

FIRST INTERNATIONAL CONFERENCE ARTIFICIAL INTELLIGENCE IN STRUCTURAL ENGINEERING BOOK OF ABSTRACTS



ARTISTE 2025

14 - 17 SEPTEMBER 2025

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ARTISTE 2025 - International Conference in Artificial Intelligence in Structural Engineering

Prof. Giuseppe Carlo Marano
Prof. Domenico Asprone
Prof. Xinzheng Lu
Prof. Nikos D. Lagaros

Torino, 14-17 September 2025



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Welcome

Dear Participants,

It is with great pleasure that we welcome you to the ARTISTE 2025 International Conference, which will take place in Turin, Italy, between September 14 and 17, 2025. This exciting event will be held at the Valentino Castle, a historic residence of the Royal House of Savoy and a UNESCO World Heritage Site since 1997.

The ARTISTE 2025 technical program is designed to provide you with three days of comprehensive learning and sharing opportunities. You will have the chance to attend keynote lectures and talks on a broad range of topics related to the application of Artificial Intelligence (AI) in Structural Engineering, including evolutive intelligence models, deep learning, generative AI, advanced neural network architectures (transformers, RNN, LLM, etc.), AI-assisted design, predictive maintenance, structural performance optimization, anomaly detection, and solutions for enhanced resilience and safety.

The topics covered in the technical program are diverse and include, but are not limited to, interdisciplinary integration of AI in structural engineering, the use of large datasets and computational power to generate automated solutions, and new approaches to optimize design decisions, improve structural reliability, and reduce costs. We will also examine the impact of emerging technologies in addressing future challenges and opportunities in the field.

We believe that this program will provide you with an opportunity to explore the latest research and advancements in AI applications to structural engineering, as well as the challenges and future prospects for the field. Additionally, you will have the chance to interact with experts and colleagues from around the world, sharing experiences, exchanging knowledge, and fostering new collaborations.

We hope that you find ARTISTE 2025 to be an engaging and fruitful experience and look forward to welcoming you to Turin.

Sincerely,

The ARTISTE 2025 Organizing Committee

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Detailed Program

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Keynotes

Henry Burton - Artificial Intelligence in Structural Engineering: From Statistical and Machine Learning to Causal Analysis

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Biography

Dr. Henry V. Burton is an Associate Professor and the Presidential Chair in Structural Engineering in the Department of Civil and Environmental Engineering at the University of California, Los Angeles. His research is directed towards understanding and modeling the relationship between the performance of infrastructure systems within the built environment, and the ability of communities to minimize the extent of socioeconomic disruption following extreme events. Dr. Burton is a registered structural engineer in the state of California. Prior to obtaining his PhD in Civil and Environmental Engineering at Stanford University, he spent six years in practice at Degenkolb Engineers, where he worked on numerous projects involving design of new buildings and seismic evaluation and retrofit of existing buildings. He is a recipient of the National Science Foundation Next Generation of Disaster Researchers Fellowship (2014), the National Science Foundation CAREER Award (2016), and the Structural Engineering Association of Southern California (SEAOSC) S.B. Barnes Research Award (2024).



Abstract

Collecting and analyzing empirical data are essential to learning and implementing lessons in structural engineering. Historically, the methods that have been used to analyze and draw conclusions from such data have been limited to statistical and machine learning. The models developed using these techniques are able to capture associative relationships between important variables. However, the intervention decisions geared toward enhancing the resilience of infrastructure should ideally be informed by an understanding of the causal mechanisms that drive their performance. This presentation will advocate for a paradigm shift in structural/earthquake engineering where the language, tools, and models that have been developed to draw causal conclusions from observational data are adopted. Several categories of data-driven structural/earthquake engineering problems that can benefit from causal insights will be examined. Example applications of causal analysis to structural/engineering problems will be highlighted, including case studies where machine learning models are used to establish causal relationships.

Josephine Voigt Carstensen - AI Modeling of Expert Preferences in Freeform Structural Optimization.

Gilbert W. Winslow Career Development (Associate) Professor Department of Civil and Environmental Engineering, MIT.
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Biography

Josephine Carstensen is the Gilbert W. Winslow Career Development (Associate) Professor in MIT's Department of Civil and Environment Engineering (CEE). She leads the Carstensen Group, where her work spans from developing computational design frameworks for various structural types, scales, and design scenarios to experimental investigations that are used to inform necessary algorithmic considerations. Dr. Carstensen has received awards for both research and teaching, including the National Science Foundation CAREER award, the Maseeh Award for Excellence in Teaching, and the Ole Madsen Mentoring Award. She joined the MIT CEE faculty in 2019 after two years as a lecturer at MIT, jointly appointed in CEE and Architecture. She received her PhD from Johns Hopkins University in 2017 and holds a B.Sc. and a M.Sc. from the Technical University of Denmark.



Abstract

The building and construction industry is a significant source of greenhouse gas emissions. The quantities of structural materials used globally correspond to approx. 10% of the annual carbon emissions. Reducing the embodied carbon of new construction is needed, especially considering the predicted population growth and urbanization. Recommended strategies include using more environmentally friendly materials and/or structural optimization. Topology optimization is a promising design method in this context since the resulting designs often significantly outperform conventional lowweight designs. It is a computational approach that generates efficient material layouts tailored to a user's specific design requirements. To take full advantage of its exploratory power, topology optimization leaves the user as a passive observer who initiates the design process and assesses the quality of the design upon completion. The resulting structural designs are typically high-performing and have high levels of geometric complexity. However, ensuring the physical performance is adequately predicted by a fully automated design approach requires including all relevant operating conditions, mechanical behaviors, and fabrication constraints. This talk will discuss different strategies to include relevant considerations for topology-optimized design of low-carbon civil structures, including methods that use AI to leverage human designers' experiences.

Eleni Chatzi - A Physics-Enhanced Approach to Modelling and Monitoring Dynamics.

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Biography

Eleni Chatzi is a Full Professor and Chair of Structural Mechanics and Monitoring at the Institute of Structural Engineering of the Department of Civil, Environmental and Geomatic Engineering of ETH Zürich. She currently serves as the President of the European Academy of Wind Energy (EAWWE). Her research interests include the fields of Structural Health Monitoring (SHM), hybrid modelling for digital twinning, and data-driven decision support for engineered systems. Her work in the domain of self-aware infrastructure was recognized with a 2016 ERC Starting Grant award, the 2020 ASCE Huber Research prize, the 2020 EASD Junior Research Prize in the area of Computational Structural Dynamics, and the 2024 SHM Person of the Year award.



Abstract

Modern engineering systems face complex, nonlinear, and dynamic conditions that challenge traditional modeling and monitoring approaches. While advances in sensing technologies have enabled detailed data collection, these datasets are often sparse, noisy, and distorted by environmental and operational factors. As a result, purely data-driven methods often struggle to effectively capture system behavior. This talk presents a physics-enhanced digital twin framework that combines physics-based understanding - particularly of system dynamics - with advanced data assimilation techniques. By integrating domain knowledge with observational data, these augmented twins provide interpretable, robust, and scalable solutions for system management. Such a hybrid approach overcomes key limitations of traditional methods and supports improved decision-making for complex, real-world systems. The presentation underscores how embedding physical principles into digital models enables more resilient, aware and responsive engineering infrastructure.

Filippo Ubertini - Advancing SHM: Leveraging AI-Driven Algorithms to Integrate Multimodal Sensor Data, Models, and Structures at a Territorial Scale.

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Biography

Filippo Ubertini is a Professor of Structural Design at the University of Perugia, where he coordinates the International PhD Program in Civil and Environmental Engineering. He graduated cum laude in Civil Engineering from the University of Perugia in 2005 and obtained his PhD from the University of Pavia in 2009. In 2008, he was a visiting scholar at Columbia University. He is the Head of SHMLab at UNIPG (www.shmlab.eu) and has authored over 170 papers in highimpact international journals. His research focuses on SHM, emphasizing physics-based methods and AI. Prof. Ubertini serves on the editorial board of MSSP and other international journals and is Vice-President of FABRE Consortium (www.consortiofabre.it/en). He has been PI of several research projects, including an ongoing FIS 2021 Advanced Grant (www.smssafest-fis.com). He has delivered plenary/keynote lectures at prestigious conferences, including SPIE-NDE 2025, IOMAC 2024, SPIE-NDE 2024, CMMOST 2023, TEST&E 2022, Eurodyn 2020, and CBPAT 2020. Dr. Ubertini is ranked #2 in Structural Engineering in topitalianscientists.org list. His contributions have been recognized with several awards, including ANIV 2010 Award and best paper awards at EVACES 2011, IOMAC 2019 and EUROSTRUCT 2023.



Abstract

Advancements in AI and sensing technologies are transforming structural health monitoring (SHM), a crucial tool for maintaining aging infrastructure and cultural heritage structures. Despite progress in AI-driven analysis and selfsensing materials, effective prognosis in civil engineering remains challenging due to the gap between data-driven insights and physics-based models. To enable risk-informed decision-making on a larger scale, SHM must evolve into a multi-scale framework that integrates diverse sensor data with computational modeling, shifting from individual structures to interconnected networks. This talk explores cutting-edge SHM research, focusing on the integration of advanced sensing, AI analytics, and computational models. Key topics include self-sensing materials for smart masonry, deep learning and statistical pattern recognition for damage classification, and metamodeling with Bayesian inference for improved structural assessment. These innovations pave the way for smarter, data-driven infrastructure and built heritage management.

Yong Xia - Computer Vision-based Full-field Vibration Measurement of Large-scale Structures.

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Biography

Prof. Yong Xia is a Professor at the Department of Civil and Environmental Engineering of the Hong Kong Polytechnic University. He is the Director of the Guangdong-Hong Kong Joint Laboratory for Marine Infrastructure. Dr. Xia's main research area is structural health monitoring. He has developed advanced AI technologies and applied them to largescale practical structures, including the 600-m tall Canton Tower, 632-m tall Shanghai Tower, 1377-m long main span Tsing Ma Bridge, 1018-m long main span Stonecutters Bridge, the world's longest 55-km long Hong Kong-Zhuhai-Macao Bridge, and PolyU Footbridge. He has published over 180 refereed international journal papers, co-authored three research books, and secured over 50 research projects totaling HK\$85million(US\$11 million) as the PI. Dr. Xia is now the Co-Editor-in-Chief of *Advances in Structural Engineering*. He has been awarded The Nishino Prize, State Technological Innovation Award in China, PolyU President's Award, ASCE Greater China Award, among many others.



Abstract

Full-field displacement measurement is essential in evaluating the structural performance of long-span bridges and high-rise buildings. This study develops a novel, cost-efficient, and high-resolution dynamic displacement monitoring method using one digital camera. The complex real environment and full-field motion are overcome by the developed phase-based optical flow algorithm. The technique is applied to a long-span bridge and a high-rise building. One camera was set at a far distance of over 600 m away to measure the full-field motion of the entire structure. Moreover, a Convolutional Bokeh tracking method is developed to measure the vibration of structures in the evening under low-light conditions.

Xinzheng Lu - Generative AI-Driven Structural and Safety Design across Multiple-Domain Engineering.

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Biography

Prof. Xinzheng Lu is a Professor at the Department of Civil Engineering at Tsinghua University of China, the Head of the Institute of Disaster Prevention and Mitigation at Tsinghua University, the Editor-in-Chief of the Engineering Mechanics journal (China Society of Theoretical and Applied Mechanics), the Associate Editor of the Journal of Structural Engineering-ASCE and Journal of Computing in Civil Engineering-ASCE. His major research interests cover disaster prevention and mitigation and intelligent design of civil engineering. He has published more than 200 papers and 8 books and his publications have received over 20000 citations. He has been listed as one of the "most cited Chinese researchers" by Elsevier (2014-2023). His research outcomes have been adopted by Chinese and American design codes, major disaster simulation systems, structural calculation software, and numerous landmark projects. He delivered multiple keynote presentations at significant international conferences, including the 18th World Conference on Earthquake Engineering. He has received several important awards, including the National Natural Science Award (Second Prize, second contributor), the First-Class Science and Technology Progress Award of Beijing (first contributor), the First Class Natural Science Award of Ministry of Education of China (first contributor), the Distinguished Professor of Chang Jiang Scholars Program of Ministry of Education of China and the J. M. Ko Award.



Abstract

Generative AI-driven structural and safety design is a crucial element of smart construction. Traditional human-centric methods are often inefficient and overly dependent on individual expertise, frequently falling short of engineering requirements. Targeting the intelligent design demand of multiple-domain engineering (e.g., buildings, MEPs, and infrastructures), this study presents a high-quality, efficient design method driven by generative AI. Based on generative AI models such as diffusion models, generative adversarial networks, and graph neural networks, an intelligent design algorithm is proposed based on "data-knowledge-mechanics" fusion learning. This method effectively addresses the challenges of limited training data and quality inconsistency while ensuring compliance, safety, and cost-efficiency. Case studies involving building structural design, fire sprinkler design, and rock-filled dam design demonstrate that AI-generated design outcomes achieve expert-level quality, meeting design code requirements with significantly improved efficiency (approximately 10 times faster than traditional workflows). This research advances intelligent construction by creating a self-evolving framework integrating domain knowledge with data-driven learning.

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Sigrid Adriaenssens - Learning to Design Lightweight Structures: Accelerating Form-Finding through Machine Learning and Differentiable Programming.

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Biography

Sigrid Adriaenssens investigates the mechanics of large-span structural surfaces, particularly under extreme loading and during construction. Her research integrates advanced analytical models, numerical form finding, fluid-structure interaction, and machine learning to accelerate structural design and optimization. This framework has enabled innovations from adaptive shading shells to large-span elastic gridshells. In 2025, she was appointed Director of Princeton University's Keller Center for Innovation in Engineering Education. She held the Francqui Chair at Ghent University (2024) and the Myron Goldsmith Visiting Chair at Illinois Institute of Technology (2023). Her recognitions include Fellow of the ASCE Structural Engineering Institute, Vice President of IASS, the Digital-FUTURES Matthias Rippmann Award, the IJSS Pioneer's Award and the ASCE's George Winter Award. She directs Princeton's Form Finding Lab and co-chairs the IASS Continuous Shells Working Group. At Princeton, she teaches nonlinear mechanics, structural design, and the integration of engineering with the arts.



Abstract

Through evolutionary refinement, natural forms such as seashells have achieved exceptionally high stiffness-to-weight ratios. At the meso and architectural scale, designing such lightweight forms poses significant computational challenges. Their nonlinear mechanical behavior governs their optimal form, necessitating advanced design methods which are computationally expensive. In this talk, we present novel numerical methods that apply machine learning and differentiable programming to accurately accelerate the design of such forms across multiple scales. We showcase the practical value of our methods for the design of beam networks, masonry vaults, and gridshells; and validate our numerical results with physical experiments and demonstrators. Our work bridges the gap between computational mechanics and artificial intelligence, facilitating the design of mechanically efficient forms, bringing us closer to the material economy and elegance exemplified in natural forms.

Billie F. Spencer - AI-informed Rapid Post-earthquake Inspection and Evaluation of Civil Infrastructure.

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Biography

B.F. Spencer, Jr. earned his Ph.D. in theoretical and applied mechanics from the University of Illinois at Urbana-Champaign in 1985. He was part of the University of Notre Dame faculty for 17 years before returning to the University of Illinois, where he holds the Nathan M. and Anne M. Newmark Endowed Chair in Civil Engineering and previously served as the Director of the Newmark Structural Engineering Laboratory. His research spans structural health monitoring, structural control, stochastic fatigue, computational mechanics, machine learning, and computer vision. Dr. Spencer pioneered the use of magnetorheological fluid dampers for earthquake and wind protection and advanced structural health monitoring systems with smart sensors. Recognized with numerous awards, Dr. Spencer is a Distinguished Member of ASCE and holds Foreign Memberships in several international academies. He serves as the North American Editor in Chief of Smart Structures and Systems and Executive Managing Editor of Earthquake Engineering and Engineering Vibration.



Abstract

In the aftermath of an earthquake, rapid structural inspection and evaluation are critical to ensure restoration of the normal order of life, work, and production. Traditional manual visual assessments by certified inspectors are slow, risky, and subjective, with limited availability delaying inspections. This lecture presents two approaches for automated rapid post-earthquake safety assessment. The first uses sparse acceleration measurements to define damage-sensitive features, inferred through a convolutional neural network. Validated experimentally at E-Defense in Japan, it proves effective for high-rise buildings. The second employs commercial UAV-collected images and a graphics-based digital twin (GBDT), incorporating finite element (FE) and photo-realistic computer graphics (CG) models. This approach is illustrated for a 45-story building in Guangzhou, China. These strategies enable rapid evaluation and efficient decision-making post-earthquake.

Stergios-Aristoteles Mitoulis - Non-destructive bridge damage characterisation: from traditional approaches to novel ensemble learning.

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Biography

Stergios is the leader of the MetaInfrastructure.org and bridgeUkraine.org initiatives. Stergios has a sustained record of grantwinning with more than € 8 million of funding which he received by the UKRI and Horizon Europe. He led and won recently a € 1.65 million MSCA-SE-2021, the ReCharged project, leads the € 5 million HORIZON-CL5-2023-D4-01-01 ZEBAI project demos and leads the € 2.5 million HORIZON-MISS-2021-CLIMA-02 the RISKADAPT project pilots. He is the Editor in Chief of the ICE Journal of Bridge Engineering. Stergios' expertise is in climate resilience, sustainability, and digitization of critical infrastructures. During his academic career he has supervised more than 30 doctoral and postdoctoral researchers with a publication record exceeding 200 papers. He is known for his expertise in bridges. He is a member of the BSI B/525/10 CEN/TC250/HG-Bridges, the BSI Mirror Group of Eurocodes, and UK delegate of the BSI CEN/TC250/SC8 WG6, Bridges & the BSI committee B/525/8 and B/538/5.



Abstract

This presentation explores the evolution of bridge condition assessment from traditional engineering methods to state-of-the-art digital and data-driven approaches. It begins by revisiting conventional techniques, including visual inspections, forensic investigations, and finite element back-analysis, as applied in landmark case studies such as the Polyfyto Bridge in Greece. These foundational methods provide the baseline upon which more advanced technologies—such as Synthetic Aperture Radar (SAR) Interferometry, UAV-based photogrammetry, and Digital Twins—are introduced and critically evaluated. The transition from analogue to digital methods is examined in the context of ageing infrastructure, sustainability, resilience, and the need for rapid, scalable, and cost-effective solutions. Through selected European research projects and real-world applications, the talk proposes a multi-scale and multi-sensor methodology that combines traditional engineering judgment with next-generation monitoring and modelling systems. Next, a novel, cause-agnostic, machine learning framework for non-destructive bridge damage state identification is presented, purposefully developed for applications with extremely limited datasets. We demonstrate the evolution of an ensemble-based methodology, from the use of general regression neural networks (GRNN) to an enhanced artificial neural network (ANN)-based cascade model, which integrates a new input-doubling data augmentation technique grounded in response surface linearisation. Applied to a real-world

balanced cantilever bridge, our method successfully predicted tendon losses in three interdependent deck zones using only 81 observations. The presentation will discuss the theoretical underpinnings, model architecture, validation results, and potential for deployment across infrastructure portfolios, with a particular emphasis on the method's applicability to data-scarce environments and digital twin platforms.

Konstantinos Daniel Tsavdaridis - Structural Design Codes with AI: From Safety Margins to Smart Design.

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Biography

Professor Tsavdaridis holds the Chair of Structural Engineering in the Department of Engineering, School of Science & Technology at City St George's, University of London, Head of Structural Engineering Laboratory, and Director of the 3- D Modular Building Construction (3DMBC) research group. His research focuses on innovative designs for structural members, seismic behavior of highly optimized tall buildings and towers, and the application of 3D printing in construction. In 2019, he was awarded with a Senior Fellowship from the Royal Academy of Engineering to work on digitalization, modular construction and its circular economy aspects. The recent years he is focusing on the application of AI into the design of structures and he is the Founder & Chief Scientist of Efestos Hub – a data company decarbonizing AEC through AI. Professor Tsavdaridis is a Chartered Engineer and Fellow of the Institution of Civil Engineers (CEng FICE) and the Institution of Structural Engineers, and contributes to CEN/TC and BSi committees for the development of structural guidelines and standards in Europe and UK.



Abstract

This presentation explores how Artificial Intelligence can transform traditional structural design codes, such as the Eurocodes, by enhancing accuracy, reducing conservative safety factors, and enabling optimized designs. AI, especially physics-informed models, offers the ability to predict and distinct complex failure mechanisms and their combinations that elude simplified mechanical models—particularly in thin-walled steel structures and steel-concrete composite systems where multiple or interconnected failure modes may occur. These insights are vital as the industry shifts toward modern methods of construction, such as modular systems, where adaptability and predictive intelligence are key. AI agents and assistants can act as design co-pilots, streamlining code interpretation and adaptation for projectspecific optimizations. Computer vision and pattern recognition are employed to assess the structural components— paving the way for a circular economy in construction. Moreover, AI enhances predictive modelling accuracy and provides real-time assistance in delivering higher quality, code-compliant structures that reflect the real-world behavior of materials and connections more faithfully.

José António Silva Carvalho Campos Matos - How Artificial Intelligence could be used towards the sustainable Management of existing infrastructures

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Biography

Assistant Professor, with habilitation, at Department of Civil Engineering of the School of Engineering of University of Minho. Member of ISISE- Institute of Sustainability and Innovation in Structural Engineering, being the head of the Risk and Asset Management of Civil Infrastructures (RAmCI) cluster. He is also the current Director of the Mobility and Transportation HUB of Minho University (TMOB-HUB). Graduated in civil engineering in 2002, he obtained a master's degree in civil engineering structures in 2008 and a PhD in civil engineering in 2013, in the field of reliability and risk analysis of existing structures. Author or co-author of more than 350 publications in international conferences and journals, in the field of risk and resilience analysis, O&M of civil infrastructures, quality control procedures, among others. Jose C. Matos was also mentor/supervisor of many master, doctoral and post-doctoral students, and participated in more than twenty research projects, since 2013, attracting a fund larger than 8ME for the University of Minho. Particularly, important to enhance the coordination of COST Action TU1406, SIRMA INTERREG Atlantic, and more recently, NORISK Erasmus Mundus Joint Master. He is also member of several associations and policy makers, such as IABSE (currently Vice President, and Vice Chair of Commission 5), fib (Chair of Commission 8) and EuroStruct (ex-President and Founder).



Abstract

Artificial Intelligence (AI) can significantly enhance the sustainable management of existing infrastructures through various applications, including, among others: (i) Predictive Maintenance: AI algorithms analyse data to predict failures before they occur, reducing downtime and extending infrastructure lifespan while minimizing resource use; (ii) Multicriteria Optimization: AI models optimize the decisions concerning operation and maintenance of infrastructures, leading to reduced carbon footprints; (iii) Asset Monitoring and Inspection: Using AI-powered image and video analysis (e.g., drone, CCTV), infrastructure components like bridges, roads, and pipelines can be regularly inspected for damages or degradation, enabling timely repairs and extending their lifetime; and (iv) Integration with IoT and Big Data: Combining AI with IoT devices and large datasets enables real-time decision-making, proactive maintenance, and adaptive operations aligned with sustainability goals. By leveraging these AI-driven approaches, it is possible to manage infrastructure more sustainably, reducing environmental impact, and extending infrastructure lifespan—all while maintaining safety and efficiency.

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Mark Sarkisian - Innovative Applications of AI in Built Structures.

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Biography

Mark Sarkisian, PE, SE, NAE, LEED BD+C, is a Partner of Structural and Seismic Engineering at Skidmore, Owings & Merrill in San Francisco, California. He received his BS Degree in Civil Engineering from University of Connecticut where he is a Fellow of the Academy of Distinguished Engineers and his MS Degree in Structural Engineering from Lehigh University. He also received an honorary Sc.D degree from Clarkson University and an honorary MS degree from the Politecnico di Milano. In 2021, he was elected to the prestigious National Academy of Engineering (NAE) in the United States. His career has focused on developing innovative structural engineering solutions for over 100 major building projects around the world, including some of the world's tallest. Mark holds 15 U.S. and international patents for high-performance seismic structural mechanisms and environmentally responsible structural systems. He has written the book entitled "Designing Tall Buildings – Structure as Architecture" with the second edition recently released by Routledge - Taylor & Francis.



Abstract

Artificial intelligence is currently being applied across a wide range of fields, from self-driving car technology to art and music generation. The built environment can be enhanced through artificial intelligence (AI), from seismic assessment to construction verification and infrastructure health monitoring. A variety of computer vision approaches have been used for these purposes, including novel combinations of established machine learning, optical character recognition and geometric methods. Using this technology and to help automate the construction verification process, machine learning models were trained to identify structural components from site photos and "read" shop drawings. These tools could be used to support construction inspection efforts and to reduce shop drawing review times from several days to a matter of hours, with an engineer reviewing a summary output from a machine learning program. Augmented reality techniques have led to creative methods of constructing structures. Examples will be shown where digital mapping of the site is overlaid with construction. Constructed projects designed by SOM will be presented.

Hojjat Adeli - Machine Learning – An increasingly Ubiquitous Technology: Advances and Pitfalls

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Biography

Hojjat Adeli is currently an Academy Professor at The Ohio State University where he held the Abba G. Lightenstein Professorship for ten years. He has authored over 650 research and scientific publications in various fields of computer science, engineering, applied mathematics, and medicine, including 16 ground-breaking high-technology books, and holds a U.S. patent. He has received over 80 awards and honors including eight Honorary Doctorates and several Honorary Professorships. He is the Editor-in-Chief and Founder of journals Computer-Aided Civil and Infrastructure Engineering, now in 40th year of publication, and Integrated Computer-Aided Engineering, now in 33rd year of publication. He is also the Editor-in-Chief of the International Journal of Neural System since 2005. He has presented Keynote Lectures at 128 conferences in 47 different countries. He is a member of 5 national academies, a Distinguished Member of ASCE, and a Fellow of AAAS, IEEE, AIMBE, and ANA. He is a Clarivate Analytics Highly Cited Researcher in three different categories of Computer Science, Engineering, and Cross Field.



Abstract

Machine learning (ML) is a key and increasingly pervasive technology in the 21st century. It is going to be transformational on the way people live and work. The ML algorithms developed by the author and his associates developed over the past four decades are reviewed briefly. Examples of recent and innovative applications of ML in various fields are described. Current limitations of ML technology are delineated. Superintelligent agents are discussed as the next frontier of Artificial Intelligent (AI). Finally, attention is drawn to the potential abuse of AI technology, safety concerns, and negative impact of AI on the society and human race.

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SS01 - Probabilistic Digital Twins in Structural Health Monitoring.

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In the past decade, the digital twin paradigm has emerged across various scientific fields, enabling diagnostic and predictive capabilities that surpass those achievable with traditional computational models. A digital twin is defined as a virtual representation that replicates specific attributes of a natural or engineered system or process. This digital representation continuously mirrors its physical counterpart by assimilating sensor data and refining its predictive capabilities. Through this continuous updating, digital twins can simulate what-if scenarios, supporting control actions or predictive decision-making aimed at maximizing value. This session aims to gather contributions highlighting the impact of digital twins for structural health monitoring, control in structural engineering, and predictive maintenance of engineering systems. Contents of interest include, but are not limited to, the following topics: • Uncertainty quantification and propagation in digital twins. • Simulation and computational efficiency. • Adaptivity. • Decision support. • Data assimilation for parameter and state estimation. • Hybrid physics-data approaches. • Surrogate modeling.

Machine Learning-Based Nowcasting and Forecasting of Wind Profiles

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Introduction Accurate wind profile height distribution is vital for optimizing wind turbine efficiency and supporting digital twin systems in structural engineering [1]. This study proposes a machine learning (ML)-based framework to nowcast and forecast non-dimensional wind profiles using data from the Cabauw site (Feb 2018–Jun 2020). Nowcasting employs XGBoost to estimate current wind profiles using only surface-level meteorological data, while forecasting leverages LSTM models trained on historical wind measurements from towers or lidars. Model calibration includes hyperparameter tuning and optimal time window selection. The results highlight ML's potential in enhancing wind energy system performance through precise, real-time wind profile prediction.

Application Figure 1 shows the results of nowcasting (left) and forecasting (right) for wind profiles, divided into eight 45° sectors and further split into low (<3.5 m/s) and high (3.5 m/s) wind speed conditions. The predicted (red) and observed (black) profiles align well, with better performance under high wind speeds.

References:

[1] Goh, S. L., Chen, M., Popović, D. H., Aihara, K., Obradovic, D., & Mandic, D. P. (2006). Complex-valued forecasting of wind profile. *Renewable Energy*, 31(11), 1733-1750.

Keywords: Nowcasting, Forecasting, Machine learning, Lidar measurements

Adverse environment forecasting Using Meteorological and Wind Profile Data for city digital twins

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Introduction This study presents a real-time framework for nowcasting and short-term forecasting of urban air pollutants using meteorological and wind profile data [1]. The core model, SOFTS, is benchmarked against XGBoost and LSTM. Nowcasting enables real-time prediction and signal reconstruction under sensor loss, while forecasting predicts pollutant trends up to six hours ahead. Using data from the ISAC Lamezia Terme site, including WindLidar measurements, the system demonstrates robust performance under both complete and incomplete data, supporting smart city air quality management and infrastructure protection.

Application This Figure 1 illustrates the prediction results of the SOFTS model for SO₂ (left) and O₃ (right). The predicted values align well with the actual data, demonstrating strong performance for both pollutants.

References

[1] S. Ameer, M. A. Shah, A. Khan, H. Song, C. Maple, S. U. Islam, M. N. Asghar, Comparative analysis of machine learning techniques for predicting air quality in smart cities, IEEE Access 7 (2019) 128325 –128338.

Keywords: Nowcasting, Forecasting, Machine learning

64 **Computer vision-based characterization of crack patterns in existing RC bridges: proposal of a framework**

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The paper proposes a computer-vision based framework to automatically characterize and identify crack patterns and related features in existing reinforced concrete (RC) bridge elements. The work aligns with the growing demand of automated structural health monitoring tools that assist engineers during visual inspections. Such tools can be important when dealing with periodic inspections of bridge portfolios, offering critical support in maintenance and risk mitigation plans and preventing potential failures. The main objective of the study is to create a tool able to detect cracks and, at the same time, to define useful characteristics during on-site inspections, such as crack orientation, i.e., vertical, horizontal, diagonal, and crack number. First, after performing data collection with a specified protocol, the developed framework consists of carrying out an image stitching technique to generate a near-complete image of the structural element. After, object detection and segmentation algorithms are consecutively combined to automatically detect and analyze cracks in the figure. The proposed methodology is described throughout the paper, including the design of the algorithms and the related strengths and limitations. Finally, the proposed tool was tested on a real-life case study to assess its effectiveness, and results showed a good capability in assessing the current state and the related crack pattern of the focused bridge.

Keywords: Existing RC Bridges, Crack patterns, Visual Inspections, Deep-Learning, Artificial Intelligence

Genetic Algorithm-Assisted Framework for Digital Twin Model Updating of Bridges

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This study explores the integration of digital twin technology with structural health monitoring (SHM) for improved bridge assessment and maintenance. A framework for high-fidelity digital twin of a three-span steel railway bridge is developed using a high-fidelity finite element (FE) model in OpenSeesPy, incorporating data from 12 strategically placed accelerometers. The bridge's dynamic properties are extracted using Stochastic Subspace Identification (SSI) to estimate modal parameters accurately. To enhance model fidelity, a genetic algorithm-based updating strategy optimizes the steel elastic modulus, minimizing discrepancies between measured and simulated frequencies and mode shapes. Calibration results show frequency errors below 5% and a modal assurance criterion (MAC) above 0.93, confirming the model's accuracy in representing the bridge's true condition. This work demonstrates the potential of calibrated digital twins for SHM, enabling predictive maintenance, early damage detection, and improved life-cycle management of bridge infrastructure.

Keywords: Digital Twin, Structural Health Monitoring (SHM), Genetic Algorithms, Real-time Monitoring, Sensor Data Integration, Model Updating

Digital Shadowing of Mechanical Systems through the Extended Kalman Filter and SINDy

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The Kalman filter and its nonlinear variants, such as the extended and unscented Kalman filters, have been the workhorses of system identification and data assimilation since their development in the 1960s. However, their application to real-world mechanical and structural engineering problems is often hindered by difficulties in establishing a reliable predictive model of the system under investigation. Physics-based models, in particular, may suffer from either insufficient or excessive complexity. The proposed framework leverages the Sparse Identification of Nonlinear Dynamics (SINDy) technique as a data-driven method to identify the predictive model required by the Kalman filter for data assimilation [1,2]. Unlike other machine learning approaches, the model constructed by SINDy is both interpretable and physically consistent. Using the extended Kalman filter as its engine, the SINDy identified model can be continuously informed with streaming data, potentially enabling real-time model update. In this way, a digital shadow of the observed system is created, an essential step toward the construction of a digital twin. Cases studies showing the application of the procedure to the monitoring of buildings and to the identification of nonlinearities in MEMS (Micro-Electro Mechanical Systems) will be discussed.

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- [2] L. Rosafalco, P. Conti, A. Manzoni, S. Mariani, A. Frangi, Online learning in bifurcating dynamic systems via SINDy and Kalman filtering. *Nonlinear Dynamics*, 113, 14201-14221, 2025.

Keywords: Sparse Identification of Nonlinear Dynamics (SINDy), Extended Kalman Filter (EKF), digital twins, uncertainty quantification

Learning nonlinear oscillations in complex engineering systems

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Weakly nonlinear oscillators (WNOs) are ubiquitous in engineering, where subtle perturbations and anharmonic effects can significantly impact long-term performance and safety. Identifying weak nonlinearities is essential across fields, from micro-electromechanical systems to large-scale engineering, but remains challenging for data-driven methods due to the profound disparity between nonlinear and dominant harmonic terms. Here we present EvLOWN, a data-driven approach for inferring the governing equations of WNOs from partial and noisy observations. This approach leverages the method of averaging to enable an accurate uncovering of the hidden weakly nonlinear effects, despite their vastly smaller magnitudes. Its effectiveness is demonstrated by the validation of several fundamental oscillatory systems; and its robustness to observational noise is proofed by comparative experiments. We apply EvLOWN to two critical engineering systems. First, using publicly available orbital data, we reconstruct the dynamics of Tiangong and International Space Stations, revealing near-identical governing laws despite their distinct missions. Second, we infer the subtle geometry and modal coupling effects of micro-mirror from a single forcing trajectory and predicting full frequency-response curves (FRCs) on different forcing level precisely. These results highlight EvLOWN's ability to advance data-driven modeling in engineering domains where weak nonlinearities have a significant impact.

Keywords: Data-driven model, Equation inference, Weakly nonlinear oscillation, Machine Learning

Deep Learning-Based Smart Framework for Corrosion Detection and Prognosis

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Corrosion is one of the most critical deterioration mechanisms affecting infrastructure worldwide, particularly in coastal and industrial environments characterized by high salinity, humidity, and temperature. Traditional inspection methods such as half-cell potential, ultrasonic pulse velocity, and manual visual inspections are invasive, time-consuming, and prone to subjectivity. Recent advances in computer vision and deep learning offer novel opportunities for automated corrosion detection and prognosis. This paper presents a deep learning-based smart framework for corrosion monitoring in structural components, integrating state-of-the-art models such as DeepLabV3+, UNet and YOLOv12. A dedicated annotated dataset of corrosion instances is being compiled from UAV and field imagery, supporting both detection and progression models. The system will be validated against real-world structures and benchmarked against conventional inspection practices. The proposed framework provides a non-invasive, cost-effective, and scalable solution for real-time corrosion detection and forecasting, enabling more resilient and sustainable infrastructure management.

Keywords: Corrosion detection, Deep learning, Convolutional neural networks, Structural health monitoring

Deep convolutional autoencoders and generative adversarial networks for vibration-based damage detection in nonlinear dynamical systems

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Early detection of damage in nonlinear structures is essential to ensure both safe operation and reliability. While numerous approaches have been developed for linear dynamical systems, effective solutions for nonlinear systems remain limited. This gap arises because the intrinsic nonlinearities significantly complicate the detection process compared to the linear case. This work addresses this challenge by introducing a robust, unsupervised deep learning framework for damage detection in nonlinear dynamical systems. Specifically, we investigate the use of autoencoders and generative adversarial networks built on 1D convolutional neural networks. Both architectures are trained exclusively on the vibration response of healthy nonlinear systems subjected to unknown random excitations. The sensitivity and robustness of the methodology are systematically assessed through extensive numerical simulations across systems with different nonlinear characteristics. Furthermore, an experimental application on a magneto-elastic nonlinear system demonstrates the framework's effectiveness and highlights its potential for advancing intelligent, data-driven structural health monitoring.

Keywords: autoencoders, generative adversarial networks, damage detection, nonlinear systems

Surrogate modeling of dynamical systems via Fourier neural operators

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Fourier Neural Operators (FNOs) have recently emerged as a powerful tool for modeling complex dynamical systems, offering a promising alternative to traditional simulation methods. This work presents a comprehensive study of two key aspects of their application: model robustness and computational efficiency. To investigate robustness and generalization, we consider the canonical Duffing oscillator under harmonic excitation as a representative case study. A comparative analysis is performed between a purely data-driven FNO and a physics-informed FNO that incorporates governing equations into the learning process. Results show that embedding physical constraints significantly enhances prediction accuracy and generalization of FNOs, establishing a systematic methodology for developing reliable and physically consistent surrogate models. Building on this foundation, we examine the scalability of the framework by applying FNOs to the incremental dynamic analysis of a large-scale transmission tower under seismic loading. A data-driven FNO, trained on high-fidelity finite element simulations performed by OpenSEES, successfully maps ground motions to structural responses. The resulting surrogate model accurately reproduces the system dynamics and enables the efficient generation of fragility curves, achieving a substantial reduction in computational cost.

Keywords: fourier neural operator, incremental dynamic analysis, physics informed networks, surrogate modelling

Integrated Structural Health Monitoring of the A21 Po River Bridge Using In-Situ Sensors and Satellite Data

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The assessment and preservation of large bridges require reliable monitoring strategies capable of capturing both global performance and local anomalies. This paper presents the structural health monitoring (SHM) system implemented on a major bridge crossing the Po River along the A21 Piacenza–Brescia highway in northern Italy. Built in 1968, the structure extends for 1650 m and consists of a Gerber girder system with 41 spans. The monitoring activity focuses on the 676.50 m river crossing, comprising eleven spans. A comprehensive SHM system has been deployed, integrating static and dynamic instrumentation. Static measurements provide long-term trends in displacements and inclinations, while dynamic monitoring captures the evolution of modal parameters. Interferometric synthetic aperture radar (InSAR) data retrieved from the European Ground Motion Service (EGMS) complement in-situ measurements by enabling remote displacement. Furthermore, machine learning algorithms are applied for anomaly detection, exploiting both static and dynamic features to enhance the interpretation of structural behavior. The integration of heterogeneous monitoring sources allows for a multi-scale understanding of the bridge response, supporting the identification of abnormal patterns that may indicate incipient damage. The paper describes the monitoring framework, outlines the data analysis procedures, and discusses the main results obtained, highlighting the benefits and challenges of combining traditional SHM systems with satellite observations and data-driven techniques.

Keywords: Structural Health Monitoring, InSAR, Vibration-based monitoring, Satellite, Acceleration, Damage detection

Life Cycle Optimization for Complex Engineering Systems through Critic Look-Ahead Simulated Annealing and Hierarchical Reinforcement Learning

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Intervention planning for degrading engineering systems is critical to ensuring reliable performance and safety. Due to scale, constraints, and uncertainties, devising inspection and maintenance strategies that minimize the use of resources while preserving global system integrity is computationally challenging. The task is a stochastic optimal control problem, which can be mathematically formulated as a (partially observable) Markov decision process, and solved through Multi-Agent Deep Reinforcement Learning (MADRL). The latter has recently allowed us to alleviate several planning complexities arising in multi-component engineering systems with large-scale state and action spaces, outperforming traditional heuristics-based maintenance strategies. However, multi-agent approaches hinge upon a flat decentralized approximation of the joint policy, where each agent controls a component. In principle, this approximation only provides a lower bound on the global optimum, as efficient cooperation among agents diminishes as their population and global system redundancies grow. We propose a hierarchical DRL framework that replaces flat decentralization with a decomposition aligned to the system's fixed topology, formulating maintenance as structured budget allocation, from system to subsystems to individual components. Because the component-level action space is combinatorial and tightly coupled by shared budget constraints, directly learning a component policy over actions is impractical; instead, budget-aware heuristics are often used to select actions at the component level. To address the combinatorial joint-action space at the component level—without relying on ad-hoc ranking rules—we introduce a critic look-ahead simulated annealing (SA) procedure. At each decision step, candidate joint actions are generated and refined by SA using the critic's estimated return as the objective, subject to budget and safety constraints. This search efficiently explores the action space and escapes local optima, yielding coordinated, budget-aware joint actions. In a multi-component system subject to stochastic deterioration, the proposed method outperforms conventional heuristics (e.g., greedy ranking) and flat MADRL baselines in both reliability and cost metrics, while preserving interpretability through its explicit system/subsystem structure. These results highlight the value of combining hierarchical DRL with principled combinatorial optimization for scalable, safety-constrained maintenance planning.

Keywords: Hierarchical reinforcement learning, Simulated annealing, life cycle optimization

Comparison of EGMS and user-processed Sentinel-1 InSAR data for pre- and post-collapse analysis of the Himera viaduct

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The increasing number of structural failures affecting civil infrastructures has stressed the urgent need for reliable and cost-effective Structural Health Monitoring (SHM) strategies. In this framework, satellite-based interferometry is emerging as a powerful solution, capable of providing millimetric displacement measurements over wide areas without requiring in-situ instrumentation. Among the available datasets, Sentinel-1 products have become a valuable resource for long-term monitoring of bridges and viaducts. This study investigates the structural behavior of the Himera viaduct, which partially collapsed on April 10, 2015. The analysis combines pre-processed displacement data from the European Ground Motion Service (EGMS) with user-controlled interferometric processing of Sentinel-1 images performed through the SARPROZ software (EO59). The comparison aims at assessing the advantages and limitations of standardized services versus customized processing in SHM applications. User-driven interferometric analysis enables the targeted selection of reliable points and the identification of temporary scatterers (TS) located on the viaduct, which are often discarded in preprocessed products. Both pre-collapse and post-collapse phases are examined, with the primary objective of detecting potential early warning signals and improving the understanding of structural response prior to failure. The results demonstrate that integrating EGMS datasets with advanced user-controlled approaches can significantly improve the quality and reliability of satellite-derived displacement time series. This combined framework represents a promising contribution to the development of satellite-assisted SHM, supporting both population-based and structure-specific monitoring of critical infrastructures.

Keywords: Satellite data, Interferometric Synthetic Aperture Radar (InSAR), Structural Health Monitoring (SHM), Bridge collapse, Himera viaduct

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SS02 - Transfer learning for Structural Health Monitoring: innovations and applications.

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The recent developments in computer science and sensor technology have contributed to enhancing the spread of Artificial Intelligence-based SHM methods. However, the availability of sufficient labeled data covering various environmental conditions and different health states often poses a significant challenge for the application of supervised learning in real-world monitoring scenarios, making it difficult to develop models capable of providing contextual information and robust damage assessment algorithms. Moreover, typical Machine Learning (ML) classifiers fail to generalise across different domain distributions, meaning that each SHM system would require a bespoke ML algorithm. With the purpose of handling the diverse structural properties, environmental characteristics and sensor data within a given population (i.e. group) of monitored structures, Transfer Learning (TL) presents a potential solution. Conventional ML models are adapted to leverage knowledge from a source structure and afterwards enhance diagnosis on a related target domain with missing or scarce information. This special session aims to explore the latest innovations and applications of TL techniques in SHM, including practical implementations, experimental findings and new methodologies to enhance the quality of damage assessment across multiple structural configurations. Specifically, the interest is to discuss TL-based solutions to sparse data in real-world SHM challenges, relating to similarity quantification, sensor network heterogeneity and variability in environmental conditions. The session aims to contribute to bridge the gap between theoretical developments and practical deployment of TL in SHM, in view of more informative and reliable monitoring systems that can be implemented across diverse structures and infrastructures. Some of the key topics of interest in this session include: • TL-based strategies for SHM. • Utilisation of domain-invariant features.

- Understanding the influence of environmental conditions in TL.
 - Damage assessment across multiple structural configurations.
 - Similarity quantification between structures to ensure positive transfer.
 - Data-fusion TL to handle sensor network heterogeneity.
 - Finite Element Models to enhance knowledge transfer.
 - Solutions to the lack of labeled data.
-

Pointwise VIV Detection via Sequential Transfer Learning with Few-Shot Data

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Long-span bridges are being constructed more frequently worldwide due to advances in civil engineering technology. However, these structures remain particularly susceptible to vortex-induced vibrations (VIVs) because of their high flexibility, low natural frequencies, and low damping ratios. Traditional serviceability assessment methods rely on statistical threshold-based approaches applied to structural health monitoring (SHM) data, but these methods fail to capture the diverse dynamic characteristics and complex operational conditions of bridges. Recent studies have successfully applied deep learning techniques to detect VIV events. Nevertheless, collecting and labeling the extensive data needed to train such models remains challenging in practice, requiring significant cost and effort. To address these limitations, this study proposes a semi-supervised framework for pointwise VIV detection that eliminates the need for manual labeling by leveraging data synthesis (essentially a few-shot approach). The proposed framework first generates amplitude-modulated sinusoidal waves to synthesize VIV-like data, which are used to train an attention-based sequence-to-sequence teacher model. Subsequently, the trained teacher model is applied to real-time SHM acceleration data, generating pseudo-labels at 10-minute intervals. These pseudo-labeled samples are then used to fine-tune a student model via transfer learning, gradually improving its performance. In each iteration, the updated student model replaces the previous teacher, enabling continuous model refinement every 10 minutes through sequential transfer learning. Finally, the performance of the resulting sequence-to-sequence classification model is evaluated by comparing its predictions with a manually labeled dataset from a cable-supported bridge. The proposed framework demonstrates performance comparable to traditional supervised learning methods, while enabling continuous updates and addressing the subjective and time-consuming nature of manual labeling.

Keywords: Vortex-induced vibration, Long span bridges, Pseudo-label

A New Paradigm for Damage Detection and Assessment of Bridge Safety

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This paper presents a novel method for damage assessment based solely on direct measurements of structural movements and deformations, enabled by sub-millimetre accurate Koherent sensors. Instead of relying on shifts in natural frequencies as proxies for stiffness loss, the method captures the true 3D movement paths of key structural points under dynamic loading—what we call the soul of the bridge.

Monitoring is continuous (up to 100...200 Hz), but only the most relevant loading situations are analyzed. A custom-developed TED system (Trigger-based Event Data-analysis) automatically identifies a predefined number of daily events (e.g. 20). During each event, the 3D path of every measured point is tracked and analyzed. Pattern recognition and machine learning tools are being developed to detect deviations from established movement patterns using statistical indicators such as the convex volume of the path.

The method has proven especially effective in large-displacement structures like suspension bridges. It is cost-effective and ideal as an early warning tool—capable of detecting changes before broader monitoring systems are deployed. It is also valuable in post-event diagnostics: when pre-event data is available, post-event structural integrity (after accidents, floods, earthquakes, sabotage, etc.) can be assessed quickly and reliably.

While many SHM methods detect that something has changed, identifying why or where remains a major challenge. Much more research is needed. Future work should integrate state-of-the-art FE-models to simulate defects and generate training data. We are confident that deformation-based methods offer powerful new capabilities, especially when combined with self-learning AI tools.

Keywords: Structural Health Monitoring, Deformation-Based Damage Detection, Sub-Millimetre Sensor Technology, Anomaly Detection, Dynamic Load Response, Suspension Bridges

Assessing the Exedra Hall Digital Twin with a Recorded Urban Blast

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Reliable Structural Health Monitoring (SHM) acquires heightened significance when rare, extreme events probe a structure beyond ambient excitation. On 4 July 2025, a liquefied-petroleum-gas explosion at a petrol station in Via dei Gordiani—over 6 km from the Exedra Hall—was reported in the press between 08:15 and 08:18 CET and detected by the Exedra Hall monitoring network at 08:17:10 CET. Despite initial hypotheses, analysis of accelerometric channels indicates that the measured signals do not correspond to an air-blast overpressure. In dense urban environments, blast waves are rapidly attenuated and scattered, rendering airborne transmission negligible at such distances. Instead, the shock reached the museum as a seismic ground transient—like a distant earthquake pulse—transmitted through the ground and structural foundations. Accordingly, the baseline finite-element model—previously tuned with ambient vibrations—has been reoriented to simulate the response to ground-borne impulsive transients. A library of synthetic accelerometric responses was generated using parameterized seismic pulses to pre-train a convolutional encoder. Transfer learning was subsequently applied, aligning latent representations between simulated and measured signals, enabling rapid detection of modal parameter shifts with minimal need for labeled data. The updated digital twin accurately reproduces the observed peak drift and predicts demand-to-capacity ratios well below critical thresholds, confirming the structural safety of the pavilion and its occupants. Sensitivity analyses demonstrate that this approach retains high accuracy even with reduced sensor coverage. This case study underlines how opportunistic records of urban impulsive events—whether accidental blasts or remote industrial incidents—strengthen the credibility of digital twins and accelerate their adaptation using transfer learning techniques. The findings highlight the necessity of understanding urban attenuation dynamics and ground-shock propagation for effective SHM under real-world, high-impact scenarios.

Keywords: blast monitoring, digital twin, transfer learning, SHM, steel-glass structures

65 **Leveraging digital twins for transfer learning in bridge SHM**

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Digital twins (DTs) are virtual representations of physical assets that integrate real-time data, physics-based models, and simulations to reflect the behavior and condition of infrastructure systems. In bridge Structural Health Monitoring (SHM), DTs enable continuous performance assessment and forecasting. Transfer learning (TL) addresses the challenge of limited labeled data by transferring knowledge from one domain or structure to another. This paper investigates the integration of DTs and TL to improve the efficiency of SHM systems for bridges. It focuses on two recent studies that implement advanced transfer learning strategies. The first leverages Domain-Adversarial Neural Networks (DANN), which reduce discrepancies between source and target domains through adversarial training. The second follows a two-stage domain adaptation method: first training on labeled synthetic data from simulations, then assigning pseudo-labels to unlabeled real data for joint fine-tuning. Domain alignment is enhanced using self-training and class-wise feature alignment, guided by a multi-kernel Maximum Mean Discrepancy (MMD) loss. By incorporating simulation-based data augmentation and domain adaptation, these methods reduce reliance on labeled real-world data while preserving high predictive accuracy. Results highlight how digital twins support advanced transfer learning in SHM, enabling more adaptive, data-efficient, and predictive monitoring systems for bridges.

Keywords: Transfer learning, Digital twins, Domain adaptation, Finite element models, Bridge

Deep Learning-Based Automatic Diagnosis of PS Tendon Tensile Stress Using Yoke-Type E/M Sensor Data

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This research proposes an advanced automatic method for estimating the tensile force in prestressing (PS) tendons, which are essential load-carrying elements in civil and building structures and play a vital role in maintaining structural integrity and safety. The conventional Yoke-type Elasto-Magnetic (E/M) sensor, widely used for monitoring tendon forces, often demonstrates limitations such as low magnetic signal resolution and inadequate excitation strength, which can restrict its ability to accurately assess real-time changes in force. To resolve these challenges, the magnetization structure of the primary excitation coil was carefully optimized, and the number of windings of the secondary coil was increased using detailed COMSOL Multiphysics simulations. These modifications led to notable improvements in flux uniformity, signal responsiveness, and overall output intensity. Based on this innovative sensor design, a detachable split-type Yoke E/M sensor was developed and subjected to a series of tensile force experiments on seven-wire PS strands, with forces incrementally increased from 0 to 10 tons. The improved sensor exhibited remarkably higher signal resolution and permitted the precise detection of subtle variations in tensile force. To interpret the complex, nonlinear magnetic hysteresis responses resulting from environmental and material factors, a fast and efficient deep learning model based on a recurrent neural network (RNN) was employed. The RNN achieved rapid and stable convergence and demonstrated outstanding accuracy in estimating real-time tensile forces, proving the effectiveness of the proposed method for structural health monitoring and maintenance management.

Keywords: PS tendon (Prestressing tendon), Automatic tensile force estimation, Yoke-type Elasto-Magnetic (E, M) sensor, Magnetic hysteresis loop, RNN (Recurrent Neural Network)

Investigating similarity requirements for knowledge transfer across a network of rigid frame bridges

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The integration of vibration-based systems with artificial intelligence is emerging as a promising approach for real-time assessment of bridge infrastructure. A key challenge, however, lies in the scarcity of labeled bridge response data, particularly under damaged conditions, combined with the need for large datasets to train reliable classifiers. This limitation poses a significant barrier to applying data-driven methods across entire bridge networks. To address this, transfer learning offers a compelling solution by enabling knowledge transfer from similar structures, thereby reducing the need for bridge-specific training. Nonetheless, the effectiveness of such strategies hinges on understanding whether structural similarity enhances the transferability of knowledge for specific damage types. Focussing on domain adaptation, this work introduces a methodology to (i) quantify bridge similarity using tailored indices, and (ii) evaluate transfer learning performance under varying degrees of structural similarity and damage scenarios. To validate the approach, a comprehensive simulation campaign is conducted, generating a diverse set of numerical models representing three-span rigid frame bridges subjected to two distinct damage conditions. Results demonstrate that structurally similar bridges can be clustered effectively and that certain damage-dependent bridge properties play a critical role in enabling successful knowledge transfer.

Keywords: Structural Health Monitoring, Transfer Learning, Bridge network

Tensile Force Estimation of Mooring Lines Using a Yoke-Type E/M Sensor and RNN-LIME Method

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This study is a method for estimating the tensile force of mooring lines using a Yoke-Type Elasto-Magnetic (E/M) sensor, combined with explainable AI (XAI) techniques for model interpretation. To address the limitations of conventional solenoid-type E/M sensors particularly the difficulty of coil winding in underwater environments an indirect magnetization structure employing a yoke was developed. The improved sensor was installed on a PC steel strand, and a total of 1,100 induced voltage signals were acquired while incrementally increasing tensile force. These data were used to train a Recurrent Neural Network (RNN) model, with the dataset split into training (770), validation (165), and test (165) sets. The model was trained for 100 epochs with a batch size of 16, a learning rate of 0.001, and the Adam optimizer. Performance was evaluated using RMSE, MAE, and R^2 metrics. To enhance interpretability, Local Interpretable Model-agnostic Explanations (LIME) was applied, revealing that the RNN model assigned the highest importance to the peak amplitude regions of the induced voltage signal when estimating tensile force. The results demonstrate that the proposed Yoke-Type E/M sensor combined with the RNN-LIME method enables accurate tensile force prediction while improving interpretability and reliability, offering strong potential for practical applications in mooring line inspection.

Keywords: PC steel strand, Tensile force estimation, Yoke-type Elasto-Magnetic (E, M) sensor, Recurrent Neural Network (RNN), Local Interpretable Model-agnostic Explanations (LIME)

Physics-Inspired, AI-Driven Bridge Strike Detection and Characterization

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Bridges provide critical access for roadway and railway traffic in areas of varying terrain and congestion with other rights of way. Monitoring and maintenance of bridge infrastructure ensures smooth and continued operation, but requires significant time, downtime, and resources. Bridges safely support typical vehicle and environmental loads and are sometimes subjected to acute loading events such as vehicular strikes. Worldwide, bridge strikes from over height vehicles require significant downtime for post-strike inspections. For example, in the US, low clearance rail bridge strikes comprise 50% of rail bridge service interruptions; while not every bridge strike represents an immediate risk to safe bridge operation, inspections are mandated post-strike. This research details a physics-driven, AI/ML assisted, strike detection and characterization system. The system leverages combinations of simple bridge instrumentation (i.e. acceleration and tilt data streams) evaluated first by Parallel Heterogenous Data-fusion Convolution Neural Networks (PHDCNN) and then subsequently by feature clustering algorithms capable of tailored event classification (e.g. non-critical severity, critical severity). This paper details the mechanics-based design of the AI/ML frameworks to ensure incorporation of the appropriate physics into numerical algorithms. The system identifies subtle patterns within diagnostic data streams that indicate meaningful deviations from nominal operating states. The system has improved bridge strike management efficiency and safety for both (1) small strikes (e.g. scrapes) and (2) large strikes requiring immediate action. The framework detects up to 99% of vehicle-bridge strikes on low clearance rail bridges with <2% false positives and characterizes the strike (e.g. localization, severity) for further action.

Keywords: Bridge Strikes, Convolutional Neural Networks, Structural Health Monitoring, Non-Destructive Evaluation

AI-Enhanced Urban Structural Resilience Through Data-Driven Design

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Rapid urbanization and climate change pose escalating challenges to the resilience of urban infrastructure. This study introduces a physics-informed machine learning framework designed to optimize structural performance of urban systems—such as bridges, pedestrian overpasses, and elevated walkways—under dynamic environmental and loading scenarios.

Leveraging vast multimodal datasets from sensors, remote monitoring, and environmental feeds, our framework integrates data-driven neural networks with key structural physics principles. This mixed method makes sure that results—such as how much weight something can hold, predictions about bending, and when maintenance is needed—are both correct and easy to understand, combining the adaptability

Applying our model to an urban case study, we demonstrate a 25% enhancement in structural resilience metrics and a 40% reduction in maintenance costs, compared to conventional design and monitoring workflows. The model excels in rapid scenario testing (e.g., extreme weather, increased usage), making it suitable for real-time decision support and proactive infrastructure management.

This contribution directly aligns with ARTISTE2025's focus areas—structural health monitoring, structural optimization, and surrogate modeling. By marrying understandable AI with structural engineering insights, this work supports sustainable, efficient, and resilient urban infrastructure while advancing the ethics and accountability of AI in built environments.

Keywords: Urban structural resilience, Structural health monitoring (SHM), Data-driven structural optimization, Real-time infrastructure management, Explainable AI for infrastructure

100 **Design of semi-active control system for bistable metapanel**

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One of the most common strategies for seismic protection consist in energy absorption and/or dissipation. These objectives can be achieved through control systems specifically designed for vibration suppression. A key challenge in designing such systems for civil structures is selecting a control strategy that ensure satisfactory performance over a broad range of excitations, while minimizing the need of complex equipment or substantial power sources. This study investigates a novel energy dissipator known as the energy-dissipating metapanel (EDMP), which integrates vibrating masses within a bistable mechanical metamaterial. The strong nonlinear behaviour of this system, which is thus schematized as a single degree of freedom (SDoF) nonlinear oscillator, typically demands a performance-driven design approach for geometry and mechanical properties, thereby limiting flexibility and adaptability to varying external conditions. To address this limitation, the authors propose a bang-bang adaptive control strategy aimed at enhancing the EDMP performance under sinusoidal excitation. The control law dynamically adjust the stiffness of the panel by operating on geometric parameters. The design of the control system is followed by a numerical analysis to assess the effectiveness of the controlled EDMP under reference earthquakes.

Keywords: Structural control, Mechanical metamaterials, Bistable systems, Adaptive control, Energy dissipation, Seismic protection

Transfer learning via interpolating structures

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Recent advances have been made in the field of population-based structural health monitoring (PBSHM), which seeks to share information across a population to improve inferences regarding the health states of the members. However, enabling knowledge transfer between structures with highly-disparate features (i.e., heterogeneous populations) is an ongoing challenge. In such cases, geometry-informed transfer approaches (e.g., geodesic flows) are an exciting prospect, as they are naturally equipped to capture the complexities of these spaces. This paper describes the application of a novel technique to heterogeneous transfer in PBSHM, whereby transfer is accomplished across a chain of intermediate structures to bridge the gap in information between the structures of interest. A case study using fully simulated data is presented, and involves a three-class transfer problem between two dissimilar structures.

Keywords: PBSHM, transfer learning, geodesic flows

111 **Satellite-informed population-based structural health monitoring of masonry arcades**

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This contribution introduces a satellite-informed population-based SHM (PB-SHM) framework specifically designed for modular masonry structures, assessing the response of each geometrically uniform segment relative to the global behavior of the structure. Freely available InSAR displacement time series and environmental drivers (air temperature, relative humidity, soil moisture) derived from satellite products and reanalysis models are converted into displacement-based statistical features for each segment. A subspace alignment procedure harmonizes these features into a shared latent space, enabling instantaneous, relative comparisons. An anomaly index is defined as the distance of the recorded segment behaviors from a model that predicts the global trajectory of the structure conditioned on environmental inputs, thereby filtering common trends and climate-driven variability. Outliers are then characterized through simulation-to-real knowledge transfer: a simplified parametric model generates labeled scenarios of settlements and uplifts with graded intensities, while a k-nearest-neighbor classifier assigns anomaly type and indicative intensity to real data. The methodology is demonstrated on the UNESCO-listed Portico di San Luca (Bologna, Italy), analyzing four hill-section segments considering the data from 2018 to 2022. Results indicate a rise in the anomaly index starting in mid-2020 for the segment between “Mysteries” IV and V, which is classified as a low-intensity settlement. These findings are consistent with long-window velocity maps and with humidity-related degradation confirmed by visual inspections. The proposed framework reduces reliance on dense instrumentation and long baselines, enables timely segment-level screening, and is readily scalable to other modular heritage assets, such as arcades and masonry bridges, using global satellite archives.

Keywords: simplified structural model, damage identification, population-based structural health monitoring, masonry arch

GNSS and AI Techniques for Hazardous Zone Estimation and Prediction to Enhance Crane Safety

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This study proposes a method to prevent falling accidents caused by cranes, which are indispensable during the construction and maintenance of structures such as bridges, high-rise buildings, and wind towers. The positions of the crane, hook, and workers were measured with high precision using the Real-Time Kinematic Global Navigation Satellite System (RTK GNSS) technique. Based on the lifting object size and hook altitude data, potential falling points were calculated, and corresponding hazardous zones were determined. A monitoring system was then developed to identify whether workers entered these hazardous zones by applying the positional data of the hook and workers into governing equations. However, a limitation arises in that hazardous zones are highly variable under dynamic environments when cranes are in use. To address this issue, a deep learning approach was introduced to predict hazardous zones as well as potential worker intrusions. Specifically, GNSS data of the crane hook and workers were used to train a Recurrent Neural Network (RNN) model, enabling the system to learn movement patterns and estimate collision risk on a five-level scale: Very Dangerous, Dangerous, Potentially Dangerous, Caution, and Potentially Caution. The results confirmed that the integration of the proposed system with the RNN-based model enables optimized estimation and prediction of hazardous zones under dynamic crane operating conditions. This approach demonstrates strong potential for enhancing overall safety during both the construction and maintenance phases of structural projects involving crane operations.

Keywords: RTK GNSS, Deep Learning, Hazardous Zone Prediction, Construction Site Safety, Crane Safety

145 **A population of laboratory-scale bridges for validating transfer learning in PBSHM**

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Data for training structural health monitoring (SHM) systems are often expensive and/or impractical to obtain, particularly labelled data. Population-based SHM (PBSHM) presents a potential solution to this issue by considering the available data across a population of similar structures. However, data obtained from different structures will not follow the same distributions, invalidating the assumption made by conventional machine learning methods that training and testing data were drawn from the same underlying distribution. Transfer learning is a method for addressing this issue by accounting for differences between source and target datasets; thus, enhancing predictions for a target structure with sparse data.

A major challenge in the development of transfer learning in PBSHM is validation, as it requires datasets from a number of similar structures, with corresponding damage states. To bridge this gap, a dataset obtained from a population of laboratory-scale bridges representing beam-and-slab bridges is presented, providing a benchmark for transfer learning methods in PBSHM. Specifically, the dataset investigated three-span bridges with varying support locations, including data at varying temperatures and damage conditions. This presentation will present an overview of the experimental campaign and provide examples of applying transfer learning to reduce the need for costly labelled data.

Keywords: transfer learning, open-access dataset, PBSHM, domain adaptation

Automated damage detection in RC bridges using deep learning models for analyses of sensors measurement and drone imagery

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The structural health of bridges is a critical factor in ensuring the safety and longevity of infrastructure. Traditional methods for assessing damage, such as Visual Testing and inspections, are labour-intensive and prone to human error, leading to delays in maintenance and repair. This research focuses on developing an advanced computer-based system for automatic detection of damage in bridges, leveraging machine learning approaches for acceleration and displacement analysis coupled with an automated multiclass damage detection framework for Reinforced Concrete (RC) bridges using drone imagery and deep learning models. Superstructure decks are made of post-tensioned PC beams/caissons. Also, RC arch-bridges are included in the experimentation. A pre-trained deep learning model trained on acceleration measured during vibration tests carried out in laboratory on prestressed concrete beams characterized by different defects or damages, was adapted to detect normal and damage condition on a real concrete bridge. Data were used to define anomaly condition that could be advisable to assess with a more in-depth visual inspection. Moreover, an automated multiclass damage detection framework for RC bridges using drone imagery and deep learning models is proposed. High-resolution images captured by Unmanned Aerial Vehicles (UAVs) were processed using YOLOv11 and RT-DETR architectures to detect and classify three primary damage types: concrete cracks, rebar corrosion, and spalling. A drone automatically starts a flight to get photos that this algorithm can process to find possible damages detected by the analyses of the instrumentation or check that the anomalies did not produce any significant damage. The findings highlight the effectiveness of transformer-based architectures in structural health monitoring and highlight the potential of UAV-assisted inspections to improve efficiency and accuracy in bridge maintenance. The outcomes of this research are preliminary, but they are expected to contribute to the development of automated monitoring platforms that provide real-time assessment and continuous structural health monitoring, ultimately reducing the need for manual inspections and improving infrastructure management efficiency. .

Keywords: damage detection, sensors, drone, machine learning

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SS03 - Machine Learning Techniques in Uncertainty Quantification in Structural Engineering.

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Uncertainty quantification in structural engineering is an emerging field, particularly for structural reliability analysis (SRA), reliability-based design and optimisation (RBDO) and structural health monitoring (SHM) in Civil, Mechanical and Aerospace Engineering. However, ensuring acceptable accuracy in SRA, RBDO, and SHM mostly leads to the requirement of repeated solutions of complex numerical problems modelled by the finite element method or other numerical techniques. A multitude of Machine Learning (ML) algorithms are being used to develop predictive models for uncertainty quantification in SRA, RBDO, and SHM applications. These predictive models reduce the computational cost by ensuring the required accuracy. Developments in this direction are gaining increasing momentum. ML is a key application area of Artificial Intelligence (AI) for automatically creating predictive models. With this backdrop, the proposed mini-symposium attempts to serve as a platform for exchanging ideas and sharing current research on various ML algorithms in uncertainty quantification for SRA, RBDO and SHM applications. More specifically, the topic of interest encompasses the applications of artificial neural networks (ANN), support vector regression (SVR), Kriging and Gaussian Process Regression (GPR), Bayesian methods, etc., with active learning perspective in the context of the aforementioned applications. The contents of interest include, but are not limited to, the following topics:

- ML techniques in uncertainty quantification for SRA applications.
- ML techniques in uncertainty quantification for RBDO applications.
- ML techniques in uncertainty quantification for SHM applications.
- Active Learning Algorithms in ML techniques for uncertainty quantification in structural engineering.

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Prediction of robust Knockdown Factors (KDFs) and sensitivity analysis in truncated conical shells: An Artificial Neural Network (ANN) and Support Vector Regression (SVR) based approach

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Thin-walled truncated conical shells under axial compression are highly vulnerable to buckling. But in actual practice, the buckling load is observed to be much lower than the theoretical one. The ratio of this actual to the theoretical critical load is termed as the Knockdown Factor (KDF). Modal interactions between the closely spaced modes, initial imperfections, pre-buckling nonlinearity, modal multiplicity and erosion of membrane energy are primarily responsible for such disparity in the critical load. A highly conservative estimate of KDFs as proposed by NASA is being relooked in many recent studies. In the present work, machine learning (ML) based robust techniques for predicting the buckling load (or KDFs) based on the Support Vector Regression (SVR) and Artificial Neural Network (ANN) are introduced to reconcile this over conservatism in conical shells. The algorithms are efficient to handle both non-linear relationships and highly complex data. An extensive experimental dataset (from literature) is gathered for training, testing and validation. A sensitivity study to determine the most critical geometric parameter affecting the KDFs is also carried out. The efficiency and robustness of both the ANN and SVR techniques are also established in the study.

Keywords: Machine Learning, Knockdown Factors (KDFs), Conical Shell, Support Vector Regression, Artificial Neural Network, Sensitivity

Physics-Informed Neural Network based Probability Density Evolution for Reliability Analysis of Gas Distribution Networks

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In the oil and gas industry, pipelines are a critical infrastructure for the transportation of hydrocarbons. However, the safety of the pipelines is one of the major concerns in the recent decade. In this study, a probability density evolution approach is presented for the estimation of the reliability of a gas distribution network under earthquakes. Firstly, the von Mises stress of a pipeline is estimated by considering stress generated due to earthquakes, temperature stress, and stress generated by Poisson's effect from a nonlinear finite element model of pipelines. Based on von Mises stress, a connectivity index is used between the source and the terminal. Finally, the probability density evolution method (PDEM) is used to estimate the probability density function of the connectivity index under uncertainty. In general, the differential equations involved in the PDEM are solved by a finite difference method whose accuracy is highly dependent on the number of temporal and spatial discretizations, leading to computational expense. With this in view, a physics-informed neural network is used to solve the differential equations in PDEM, which does not require any interpolation or coordinate transformation, which is often seen in any numerical scheme, resulting in the reduction of computational cost. For numerical demonstrations, the California gas distribution network is considered, which consists of 70 substations and 87 gas pipelines. The efficiency of the proposed method is established by comparing Monte Carlo simulation and traditional PDEM.

Keywords: Gas Distribution Networks, Reliability Analysis, Connectivity Index, Probability Density Evolution Method, Physics-Informed Neural Networks

Polynomial Chaos Kriging and Mesh Refinement for Reliability Analysis of Brittle Fracture: A Dual Adaptive Framework

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Submitted for the SS03 – Machine Learning Techniques in Uncertainty Quantification in Structural Engineering, Organizers: Prof. Subrata Chakraborty, Prof. Sudib Kumar Mishra

In fracture mechanics, incorporating probabilistic modelling is essential for quantifying the reliability of brittle materials, as their inherent material variability and defect sensitivity influence failure probability estimates in safety-critical engineering applications. Among various approaches for simulating brittle fracture, phase-field fracture (PFF) effectively captures complex crack evolution such as branching, merging, and fragmentation. However, it remains computationally intensive. This cost arises due to the need for fine mesh resolution to capture a small size of physical length scale for accurate fracture simulations. Consequently, the brute-force Monte Carlo simulation (MCS) technique becomes infeasible due to the prohibitive cost of a large number of PFF model evaluations. The present study proposes the application of a polynomial chaos Kriging-based active learning algorithm for the estimation of failure probability of brittle materials undergoing fracture when material properties are random independent variables. The model evaluation cost is further optimised by augmenting it with an adaptive mesh refinement (AMR) algorithm. This enables efficient allocation of mesh resolution where the fracture evolves. Several two-dimensional benchmark problems are studied to demonstrate the ability of this approach to estimate the probability of failure with significantly fewer simulations compared to the brute-force MCS technique. The results of the numerical study show that the proposed approach is quite efficient and accurate in estimating reliability.

Keywords: Reliability Analysis, Polynomial Chaos Kriging, Metamodel, Adaptive Sampling, Phase-Field Fracture, Adaptive Mesh Refinement

Neural Network-Based Metamodeling Approach of Seismic Reliability Analysis of Structures

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Submitted for the SS03 – Machine Learning Techniques in Uncertainty Quantification in Structural Engineering, Organizers: Prof. Subrata Chakraborty, Prof. Sudib Kumar Mishra

Abstract: The application of metamodeling techniques based on a new family of computational methods based on heuristic approaches, denoted as soft computing methods, is notable in the reliability analysis of structures. The most sparkling application is artificial neural network (ANN) algorithms. However, unlike reliability analyses of structures under static or deterministic dynamic loads, the application of the metamodeling approach for seismic reliability analysis (SRA) of structures is a difficult task as the input parameters required to accurately approximate the entire input-output relationships become exorbitantly large due to the high-dimensional nature of stochastic earthquake loads. The application of the ANN-based metamodeling approach for SRA of structures primarily adopts the dual response surface method (RSM) restricted to the lognormal assumption of seismic responses. An ANN-based metamodeling framework is proposed to directly approximate the nonlinear seismic response instead of the usual dual RSM approach for SRA without the lognormal response assumption. Once the ANN models are obtained for each ground motion in the bin, the MCS technique is readily applied for SRA by generating random sample input parameters according to the probability distribution function and random selection of the ANN models, thus formed based on nonlinear dynamic analysis at the training points only. Furthermore, for efficient SRA for different seismic intensities, the intensity parameter is included as one of the predictors in addition to the random structural parameters. The efficacy of the proposed ANN-based metamodeling approach for SRA of structures is elucidated by considering a critical pier of a simply supported river bridge.

Keywords: Seismic Reliability Analysis, Monte Carlo Simulation, Metamodeling, Record to Record Variability, Artificial Neural Network

A Machine Learning (ML) Approach for Identification of Flutter Derivatives of Suspension Bridge-deck

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The flutter derivatives of long-span suspension bridges are essential parameters for analyzing flutter instability and the response under self-excited oscillations. Traditionally, these derivatives are identified through aero-elastic wind tunnel tests and may be complimented by computational fluid dynamics (CFD) simulations. With the advancement in computational power, there is increasing interest in applying data-driven methods to solve complex structural problems. This study explores a ML approach in order to identify the flutter derivatives of a suspension bridge under smooth/turbulent flow conditions. The Artificial Neural Network (ANN) is used for this purpose. The ANN is trained using the datasets from a simulation involving flutter response analysis of a three degree of freedom suspension bridge model. The supervised learning in conjunction with the backpropagation (BP) algorithm, is employed for training. The predictive accuracy of the approach is validated by comparing the identified derivatives with the theoretical results for an ideal thin plate. Subsequently the flutter derivatives for a bridge section are identified using the proposed method. The approach is further verified through wind tunnel test data. This flutter derivative identification method can then be used to generate a database of flutter derivatives for different geometric parameters of the bridge deck's section without requiring expensive wind tunnel experiments or extensive CFD simulations. The present approach is reliable and effective for the identification of the bridge deck's flutter derivatives.

Keywords: Aerodynamics, Flutter derivatives, Long-span bridge, Machine learning, Wind Tunnel test

Identification of Knockdown factor of composite cylindrical shell using Artificial Neural Network (ANN)

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Knockdown Factors (KDFs) are proposed to account for the significant reduction in the experimentally observed critical load compared to the theoretical load derived from linear buckling analysis. The drop is primarily attributed to the interactions among the closely spaced modes and the respective multiplicity of the alternate equilibrium configurations. The modes are coupled with geometric nonlinearity, in which the imperfections play a synergistic role. NASA SP-8007 recommends a far more conservative KDF for the laminated composite cylindrical shell. This study proposes using Artificial Neural Networks (ANN) to determine a less conservative KDF for laminated composite cylindrical shells. The neural network is trained using the experimental data presented in the literature and the finite element simulation data to learn the nonlinear relationships influencing the knockdown factor. The whole dataset is categorized into three distinct groups: training, testing, and validation sets. The ANN predicted KDFs are compared with experimental, simulated, and code-specified KDFs. The results demonstrate that the ANN model predicts less conservative and more accurate KDFs compared to the existing code provisions. This research highlights the potential of ANN-based models in enhancing the reliability of composite shell design, paving the way for optimized structural performance with reduced safety margins.

Keywords: Composite cylindrical shells, Knockdown Factor (KDF), Modal interactions, Artificial Neural Networks

Discovering Interpretable Blast Loading Equations from Black-Box Machine Learning Models

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Boiling Liquid Expanding Vapour Explosion (BLEVE) is a high-energy phenomenon that poses serious safety risks due to its intense blast loads, making accurate overpressure prediction essential for safety design and emergency response. While empirical methods are suitable for simple scenarios, they fail to capture non-linear relationships in multi-feature conditions. Computational Fluid Dynamics (CFD) methods offer high accuracy but are computationally intensive, limiting real-time applications. Machine learning models present a promising alternative with their ability to deliver rapid predictions, yet their limited interpretability—particularly in deep learning architectures—poses a significant barrier to adoption in safety-critical contexts. This study proposes a systematic approach combining machine learning, explainable artificial intelligence, and symbolic regression for BLEVE overpressure prediction. A feedforward neural network model is developed and interpreted using SHapley Additive exPlanations (SHAP). Global SHAP analysis identified nine features with the most significant contributions, which were subsequently used to train a global surrogate model via symbolic regression. This approach yielded an explicit mathematical expression that approximates the behaviour of the original neural network. The derived equation achieved a relative error of 15.73% on simulated data and 35.45% on experimental data, outperforming existing empirical formulas. This research demonstrates the potential of combining black-box machine learning models with xAI techniques to develop interpretable and reliable equations for blast load prediction. More importantly, it introduces a novel data-driven, physics-informed methodology of data-model-interpretation-equation that is broadly applicable to complex engineering problems.

Keywords: Blast Loading, BLEVE, Process Safety, Risk Assessment, Machine Learning, Explainable AI

Machine Learning-Based Reliability Prediction of Corrosion-Damaged Reinforced Concrete Beams

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The effects of climate change and environmental exposure significantly compromise the durability and safety of reinforced concrete (RC) structures, making accurate life-cycle predictions essential for reliable design and maintenance. This study proposes a machine learning-based framework for predicting the service life of RC beams subjected to chloride ingress and corrosion-induced degradation. A synthetic dataset of 3,125 beam samples was generated through Monte Carlo simulation, incorporating variations in geometry, material properties, applied loads, and exposure conditions over a 0–100 year time horizon. Several regression models were trained and optimized, including Elastic Net, k-Nearest Neighbors, Light Gradient Boosting Machine, and Random Forest. Performance was assessed using multiple statistical and uncertainty metrics. Among the evaluated algorithms, Random Forest and LightGBM demonstrated superior accuracy and robustness, with Random Forest emerging as the most reliable model across independent runs. The proposed methodology integrates stochastic simulation with advanced data-driven modeling, providing a practical tool for service life prediction, inspection planning, and preventive maintenance of RC structures in aggressive environments. The findings highlight its potential to support safer, more durable, and cost-effective infrastructure design.

Keywords: Reliability, Reinforced concrete, Machine learning, Service life, Degradation

Random Forest-Based Analysis of Structural Sensor Metrics from the BEAST Facility

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This study investigates the use of a Random Forest Regressor to model sensor responses from the full-scale Bridge Evaluation and Accelerated Structural Testing (BEAST) facility. The dataset combines operational actions such as load cycles, freeze-thaw cycles and brine depletion with a large set of sensor measurements collected under controlled yet realistic deterioration processes. The proposed methodology includes thorough data preparation, independent training of each sensor metric, and systematic hyperparameter tuning with cross-validation. The approach highlights the capability of Random Forest to handle high-dimensional data and to identify the relative contribution of different operational variables, providing a framework for interpreting sensor behavior and supporting the refinement of predictive models for large-scale structural experiments.

Keywords: Random Forest, SHM, Machine Learning, Bridge Testing

149 **Sparse Measurement to Entire Spatial Domain Mapping for
Structural Reliability Assessment**

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Monitoring structural performance is typically feasible only at a limited number of sensor locations, resulting in sparse information about the system's actual condition. Extrapolating these measurements to the full spatial domain is commonly achieved by calibrating finite element models, but this approach is computationally demanding and often impractical for real-time reliability assessment. In this work, a physics-informed neural network (PINN) framework is employed to perform spatial extrapolation directly from sparse measurements. By adopting a Bayesian PINN formulation, predictive uncertainty at unmeasured locations are quantified, which allows system-level reliability to be estimated without repeatedly calling finite element models. The proposed method is demonstrated on a simply supported beam subjected to moving loads, representing a railway bridge.

Keywords: Physics-informed Neural Network (PINN), Bayesian Neural Network, Sparse Measurements, Structural Reliability

SS04 - Data-Driven and AI-Assisted Evaluation and Design of Cement-Based Materials and Structures for Environmental Sustainability.

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In recent years, the integration of data analytics and Artificial Intelligence (AI) into the construction sector has begun to transform how materials are developed and used, particularly within the realm of cement-based materials. Driven by the need to minimize environmental impacts and enhance the sustainability and resilience of building practices, these technologies are playing a crucial role in evolving industry standards and practices. However, the challenges of ensuring that these new materials and methods can be introduced in the industry reveal significant gaps in current research, particularly in terms of environmental sustainability. This special session focuses on cutting-edge research and innovations in data-driven strategies and AI applications for the sustainable and resilient design of cement-based materials and structures. It features contributions on AI-enhanced predictive modeling, optimization of material compositions, and advanced analytics for design, retrofit, lifecycle assessment, and resource efficiency. These contributions showcase significant progress in reducing environmental impacts and enhancing structural resilience, while also highlighting the need for further research to address challenges like data

scarcity, model predictive performances, and the integration of AI with traditional construction methods. This issue aims to drive advancements towards smarter, more resilient, and environmentally friendly building solutions.

Contents of interest include, but are not limited to, the following topics: • Data-driven optimization of cement-based compositions • Data-driven design of cement-based structural components • AI in cement-based material and structure design • Probabilistic analysis and evaluation for cement-based materials and structures • Performance prediction using advanced machine learning algorithms • Case studies on sustainable and resilient cement-based construction practices using data-driven and AI-assisted approaches

Research on autonomous decision-making method for
secondary breaking of construction rock materials based on
DiffusionAction generative model

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With the development of rock material processing technologies in construction engineering, secondary rock breaking has become a key process for improving crushing efficiency. The primary goal of secondary breaking is to reduce rock blocks that exceed the processing capacity of the crusher to an appropriate particle size, ensuring the normal operation of the crusher. However, existing operational modes face issues such as high complexity in breaker control, low efficiency, and safety risks, which fail to meet practical requirements. To address this, this paper proposes a secondary breaking autonomous task decision-making method based on the DiffusionAction generative model, which iteratively transforms noise and environmental information into action sequences that meet environmental needs. First, this paper defines the basic action blocks and operational priorities in the secondary breaking task and constructs a decision-making framework tailored to rock materials. A depth camera is used to capture the rock status on the grid, and the joint positions of the breaker are integrated. A multimodal feature extraction network is developed to process the extracted features, which are then input into the DiffusionAction model. After denoising, the model generates the breaker's motion trajectory, thereby achieving precise motion control of the breaker.

Keywords: Construction Material, Rock breaking, Intelligent Decision-Making, Generative Model

23 **Active solar revenue management system using artificial intelligence**

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Thermal comfort in residential buildings partly depends on the ability to dynamically regulate solar gain. However, most current systems rely on simple automation or fixed hourly configurations, lacking learning capabilities or contextual adaptation. This rigidity limits their effectiveness under changing climatic conditions and restricts the efficient use of solar radiation as a passive thermal resource. This study proposes the development and comparative validation of two intelligent solar control systems based on artificial intelligence (AI), designed to operate motorized blinds. The goal is to maximize the time spent within the thermal comfort range (19–25 °C) without increasing energy consumption. The first approach employs Long Short-Term Memory (LSTM) neural networks trained with data generated through dynamic energy simulations in DesignBuilder, representing the thermal behavior of a dwelling under various solar control strategies. The second uses Deep Reinforcement Learning (DRL), connected to the EnergyPlus simulation engine and three-day weather forecasts, to simulate multiple future thermal scenarios online and select the optimal control action. Both models are fed with real sensor data monitoring indoor and outdoor environmental conditions. This work is framed within the development of intelligent solutions that combine energy simulation with machine learning algorithms, applied to the adaptive automation of built environments. The resulting models can interpret, learn, and anticipate the specific thermal behavior of a building, contributing to the design of more efficient, sustainable, and replicable environmental control systems at the residential scale

Keywords: artificial intelligence, sustainability, habitability, thermal comfort

Influence of Constituent Characteristics and Blend Ratios on Concrete Workability and Strength: A Hyperparameter Optimized RFM-based Approach

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This research paper explores an optimized machine learning approach, specifically utilizing the Random Forest Model (RFM) combined with hyperparameter optimization techniques to predict slump, 7-day, and 28-day compressive strength. The research presents a comparative analysis of optimization techniques such as the Bayesian, the Grid search, and the Random search algorithm, used to optimize the RFM model. In addition to the optimization techniques, the impact of k-fold cross-validation on prediction accuracy was examined with k-values ranging from 2 to 10. The model was trained on an experimental dataset consisting of 962 data points with 31 input parameters, which included the physical and mechanical properties of cement, fine aggregate in the form of natural river sand, and coarse aggregate of nominal size 10mm and 20mm. The dataset also included details about the quantity of superplasticizer and its base chemical as input parameters. The models' performance was evaluated based on the statistical parameters R-squared, MSE, RMSE, MAE, MAPE, and fitting efficiency. SHAP analysis was conducted to visualize the contribution of input features to the prediction. A strong prediction accuracy was observed through the optimization strategy implemented in this study. The best predictive model was found to be the Bayesian optimized RFM with an R-square value of 0.916 at k=6 for the prediction of 28-day compressive strength and 0.89 at k=5 for the prediction of 7-day compressive strength using grid search optimized RFM. The slump was predicted with an accuracy of 0.9135 in terms of R-squared, considering the influence from all 31 input parameters.

Keywords: Random Forest Method, Bayesian optimization, Machine Learning, Concrete, Strength Prediction, Slump prediction

Modeling the chloride transport into cracked concrete through Physics-informed Neural Network

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Chloride ingress into concrete cracks accelerates reinforcement corrosion and undermines structural durability and overall load bearing capacity and reliability. Accurate evaluation of chloride penetration resistance and prediction of transport behavior are therefore essential for timely maintenance and service-life assessment. This study introduces a Physics-Informed Neural Network (PINN) to tackle two key challenges in chloride diffusion: parameter inversion and diffusion modeling. Unlike traditional finite element models (FEM), which require multiple forward simulations to fit observed data, making them computationally intensive and sensitive to noise and incomplete boundary conditions, the PINN embeds Fick's diffusion equation along with boundary and initial conditions directly into its loss function. This enables simultaneous learning of network parameters and diffusion coefficients in a single training process for efficient, robust inversion. Proposing a multi-domain (extended) PINN framework that treats the crack and matrix as separate subdomains, each approximated by an independent neural network with dedicated loss functions enforcing physical constraints. Continuity of concentration and flux at the interface is enforced via an interface-coupling loss term, allowing joint training of both subnetworks to convergence. To accelerate training and improve accuracy, high-fidelity FEM solutions serve as reference fields for pretraining PINN parameters. The resulting extended PINN combines meshless inversion capability with FEM's physical guidance to predict chloride diffusion with low relative error, demonstrating its potential as a powerful tool for studying the temporal and spatial distribution of chloride ions in concrete.

Keywords: Chloride transport, Cracked concrete, Physics-Informed Neural Network, Finite Element Model

AI-Assisted Predictive Design Framework for Preliminary Design of Prestressed Concrete I-Girder Bridge Superstructure

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Artificial Neural Networks (ANNs) offer significant potential to improve early-stage bridge design by reducing reliance on time-consuming finite element simulations and iterative procedures. However, applying Artificial Intelligence (AI) to complete bridge system design while ensuring compliance with design codes and minimizing material costs remains a challenge. This study introduces an agentic AI-based framework that integrates a fine-tuned Large Language Model (LLM) with ANN models for the preliminary design of prestressed concrete (PSC) I-girder bridges. A synthetic dataset of bridge superstructure designs, generated using CSi Bridge Express under AASHTO LRFD 2020 specifications, includes variations in span lengths, lane configurations, girder types, slab thicknesses, and diaphragm arrangements. Multiple ANN models are trained to predict key structural and economic outputs, including design validation, reinforcement quantities, internal forces, prestressing losses, and Bill of Quantities (BOQs). The framework is deployed as a desktop-based design assistant featuring three exploration tools: complete bridge design, variable span design, and parameter-based span design. The integrated LLM interprets user prompts and autonomously calls the appropriate design tool. To evaluate performance, ANN prediction results are compared with results from CSiBridge Express® represents reasonable predictive accuracy, with most outputs remaining within ± 10 percent deviation. The outcomes confirm the framework's effectiveness in enabling rapid, cost-efficient, and code-compliant bridge design during early planning stages.

Keywords: PSC I-girder bridge superstructure, Agentic AI Framework, Bridge Design Automation, Intelligent Design, Large Language Model, Generative AI

Bayesian Estimation of Concrete Service Life Using On-Site Data and Physics-Based Models

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Concrete structures degrade over time due to carbonation and chloride ingress, leading to reinforcement corrosion. These processes evolve over decades and are influenced by environmental and material factors. Probabilistic models are increasingly used in the design of long-life concrete to estimate durability and inform maintenance strategies. In practice, asset owners monitor deterioration during service to assess whether intervention is needed or if service life can be extended. However, such assessments often lack quantified uncertainty, especially when based on sparse or low-quality on-site data. Conversely, purely physics-based models may be too coarse without site-specific calibration. In this work, we present a computational tool which utilises Bayesian statistics to update the parameters of a physics-based deterioration model using site-specific measurements. Prior estimates for the model parameters were informed by fib guidance. Our method produces statistically rigorous, site-specific estimates for the probability of depassivation over time. We demonstrate our tool with case studies involving carbonation and chloride ingress in reinforced concrete using real-world measurement data. Our approach enables more accurate and cost-effective service life assessments. When an asset is underperforming, timely intervention can be prioritised; when overperformance is observed, maintenance may be safely deferred, supporting low-carbon asset management by extending service life and minimising unnecessary interventions.

Keywords: Uncertainty quantification, Machine learning, Concrete service life assessment, Probabilistic modelling, Bayesian, Carbonation ingress

Symbolic Regression-Based Derivation of Bridge Piers Fragility Curve Parameters

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Assessing seismic risk at a territorial scale is a key challenge in earthquake engineering, requiring structural classification and the development of fragility curves (FCs) for various limit states. These curves, derived from simulations or observational data, are critical for evaluating the resilience of infrastructure especially bridges, which are vital components of transportation networks in seismic regions. This study introduces a machine learning approach for predicting the statistical parameters of FCs for reinforced concrete bridge piers, using easily measurable attributes such as pier height, cross-sectional dimensions, and girder span. A representative training dataset of the Italian highway network was generated via Monte Carlo simulations and displacement-based analyses. Symbolic nonlinear regression was employed to derive closed-form expressions for the median and log-standard deviation of lognormal FCs. The resulting equations demonstrate high predictive accuracy ($R^2 > 0.90$), enabling the rapid estimation of fragility parameters from basic geometric data, this method streamlines FC development and supports efficient, large-scale seismic risk assessments—particularly where detailed structural information is unavailable. The approach offers a practical tool for early stage evaluations and informed decision-making in earthquake-prone areas.

Keywords: Hollow-Core Bridge Piers, Seismic Fragility Curves, Symbolic Regression, Machine Learning

Data-Driven Neural Network Modeling of Cement-Based Materials for Enhanced Structural Performance and Sustainability

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This study presents a data-driven framework for modeling the constitutive behavior of cement-based materials using advanced neural network (NN) architectures, aiming to support environmentally sustainable structural design. Conventional constitutive models often struggle to capture the nonlinear and history-dependent responses of materials such as concrete under complex loading, limiting their predictive accuracy and adaptability. To address this gap, we develop and train NN models on experimental and numerical datasets covering monotonic and cyclic loading scenarios. The models incorporate internal state variables to accurately replicate hysteretic behavior, enabling reliable simulations of damage progression and residual capacity. Case studies include axial compression of reinforced concrete and cyclic loading representative of seismic actions, demonstrating strong agreement between NN predictions and reference data. The proposed approach offers a flexible, computationally efficient tool for integrating material performance prediction into structural analysis and optimization workflows. By improving the accuracy of concrete behavior modeling, this methodology supports the design of resource-efficient, resilient, and sustainable cement-based structures.

Acknowledgements:

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Keywords: Neural networks, Cement-based materials, Constitutive modeling, Cyclic loading, Sustainable structural design

Sustainable concrete mix with plastic waste aggregates 97

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Since the discovery of rubber vulcanization in 1839, rubber has become a key industrial material, with more than half of global production used in tire manufacturing. The rapid growth of vehicle use has led to significant environmental challenges: nearly one billion tires reach end-of-life annually, a number projected to rise to 1.2 billion by 2030. Their non-biodegradable and toxic nature highlights the urgency of sustainable recycling strategies. Among emerging solutions, incorporating waste rubber into concrete has gained attention, given the increasing demand for cement and the environmental burden of Portland cement production. This study investigates the potential of rubber aggregates as partial replacements for natural aggregates in concrete. Using a literature-based dataset (1993–2019), statistical analyses and supervised and unsupervised exploratory data analyses were conducted to evaluate factors influencing compressive strength, substitution levels, and performance. Results aim to assess the feasibility of rubberized concrete as a more sustainable construction material assisted with machine learning data-driven solutions.

Keywords: sustainable concrete, green concrete, rubber waste concrete aggregates, exploratory data analysis

AI-Driven Optimization of Recycled Concrete Aggregates in Asphalt Mixtures for Sustainable Civil Engineering Applications

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This study investigates the integration of artificial intelligence (AI) in optimizing the performance of recycled construction materials for sustainable civil engineering applications. By combining machine learning (ML) techniques and molecular dynamics simulations, we explore the interfacial behavior of recycled concrete aggregates (RCA) in asphalt mixtures. RCA is pretreated through accelerated carbonation, which enhances its physicochemical properties, reducing surface porosity and improving its adhesion to asphalt. A machine learning model, specifically XGBoost, is employed to optimize the mix design of RCA, significantly improving its compressive strength, water resistance, and long-term durability. Molecular dynamics simulations provide insights into the carbonation process, revealing how carbonation alters the microstructure of RCA by increasing hydrophobicity and strengthening the bond between RCA and asphalt. The research further demonstrates that AI-driven predictions can optimize the mixture proportions, thus enhancing material performance under various environmental conditions. This study showcases the potential of AI in intelligent material design by predicting performance, optimizing the mix ratios, and assessing long-term durability. Moreover, it contributes to the development of low-carbon, sustainable materials that can be used in infrastructure construction, offering a promising solution for reducing waste and carbon emissions in the construction industry.

Keywords: Artificial Intelligence, Molecular Dynamics, Recycled Concrete Aggregates, Sustainable pavement

Generative Design and Optimisation of Ultra-High-Performance Concrete Mixes Using Variational Autoencoders, Ensemble learning, and Genetic Algorithms

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This study presents an artificial intelligence-based framework for the generative design and multi-objective optimization of ultra-high-performance concrete (UHPC) mixes. A variational autoencoder is trained to learn a low-dimensional latent representation of experimentally validated UHPC compositions and to generate new, feasible candidate mixtures. A gradient-boosted decision tree regression model (XGBoost) is developed as a surrogate to predict 28-day compressive strength based on input mix proportions and curing age. The optimization process is performed using the Non-dominated Sorting Genetic Algorithm II (NSGA-II), targeting three simultaneous objectives: maximizing compressive strength, and minimizing both material cost and carbon dioxide emissions. The framework is demonstrated using a database of 626 UHPC mixtures, achieving high predictive accuracy (coefficient of determination $R^2 = 0.96$) and generating a diverse Pareto front of optimized solutions. The results show the capability of the proposed approach to uncover high-strength and sustainable concrete mixtures, including previously unexplored formulations. This research highlights the potential of integrating generative deep learning, ensemble machine learning, and evolutionary optimization for sustainable and performance-driven material design.

Keywords: UHPC, generative design, VAE, XGBoost, NSGA-II, optimization

Prediction of Ultimate Bond Strength in CFRP–Concrete Bond–Slip Systems Using Ensemble Machine Learning Models

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The bond strength between carbon fiber-reinforced polymer (CFRP) sheets and concrete is an important factor that greatly influences the efficiency of structural strengthening systems that have been used in retrofitting and repairing reinforced concrete elements. The conventional analytical and empirical models produce acceptable bond strength predictions, but they do not accurately explain the intricacies of the interaction between FRP geometry and concrete adhesive properties and mechanical characteristics. This study develops a machine learning (ML) model to predict the maximum bond strength (P_u) of CFRP–concrete joints using experimental data from tested specimens. The study employed systematic testing of different ML algorithms to determine their predictive accuracy. The Random Forest model produced the best results because it successfully detected complex relationships between variables and showed which features contributed most to the predictions. The research used visual tools to enhance both model interpretability and explainability. The study demonstrates that ensemble models in machine learning systems provide an efficient, cost-effective solution for bond–slip analysis, which performs better than traditional methods. The proposed method delivers accurate and informative engineering data and design recommendations to assist engineers in designing FRP-strengthened concrete systems at reduced costs.

Keywords: Machine Learning, CFRP–Concrete Bond–Slip, Bond Strength Prediction

Fast-Track Code-Based Seismic Vulnerability Screening with Machine Learning: Evidence from 300 Italian Buildings

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The study introduces a data-driven method for estimating a code-based seismic vulnerability index for roughly 300 Italian buildings. Detailed surveys, experimental tests, and numerical analyses produced about 15 mixed-type predictors. These inputs fed several predictive algorithms, in particular logistic regression and an artificial neural network (ANN). After rebalancing the classes by adjusting the vulnerability cut-off, the ANN classifies buildings into two risk groups with better than 85% accuracy. SHAP analysis reveals how much each feature influences the prediction, providing a transparent tool to help authorities prioritise seismic-risk mitigation.

Keywords: Seismic vulnerability index, Data-driven model, Italian Seismic Code, Artificial Neural Networks, Binary classification

AI-Driven Digital Twins: Towards Automated Model Updating and Predictive Maintenance

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This work introduces a new generation of AI-driven Digital Twins that break through the limitations of current structural assessment practices. At their core, advanced AI algorithms perform automated model calibration, interpret damage, and generate early-warning signals, all cross-validated with nonlinear finite element analyses to ensure accuracy and minimize false positives. This synergy of data-driven intelligence and physics-based modeling represents a decisive step toward self-updating computational models and predictive maintenance. By integrating dense sensor networks with artificial intelligence and high-fidelity finite element models, digital twins evolve into continuously learning, real-time replicas of infrastructure. Beyond monitoring, they provide predictive insights into structural performance under abnormal stress or damage scenarios, directly supporting proactive maintenance, repair, and reinforcement. This paradigm shift enhances not only the resilience and safety of critical assets, but also the efficiency and reliability of modern infrastructure management.

Keywords: AI-driven Digital Twins, Predictive Maintenance, Structural Health Monitoring, Finite Element Analysis (FEA), Real-time Infrastructure Modeling

SS05 - Innovative AI approaches in Structural Optimization, Design and Control.

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During the last decades, advancements in Artificial Intelligence (AI), supported by high-performance computing, have revolutionized problem-solving paradigms in structural engineering. Moving beyond conventional optimization frameworks, AI-driven methodologies now enable algorithmic form-finding, generative design exploration, and autonomous control systems, redefining how engineers synthesize structural performance with architectural innovation. The Special Session "Innovative AI Approaches in Structural Optimization, Design, and Control" seeks to highlight the potential of AI in structural engineering. By integrating cutting-edge computational techniques, AI-driven methodologies enhance multi-objective decision-making, refine form-finding processes and pioneer adaptive designs that balance resilience, costs and sustainability. Contributions will address how AI contribute to explore non-intuitive design solutions, reduce computational costs and bridges gaps between structural mechanics and architectural creativity. The session invites interdisciplinary contributions from researchers and practitioners to explore emerging computational frontiers. Through interdisciplinary collaboration, the goal is to explore how AI can shape the future of the built environment, paving the way for more intelligent, efficient, and sustainable structural solutions. Contents of interest include, but are not limited to, the following topics:

- Multi-objective optimization in structural engineering
- AI-driven form-finding techniques
- Structural identification and monitoring
- Risk analysis, vulnerability, and resilience assessment
- Shape-resistant structures and optimized design
- Topology optimization and innovative materials
- Surrogate models for structural

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AI-Powered Quick Estimation Tool for Structural Design Optimization

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In fast-paced industrial projects, structural engineers need quick and reliable design estimates. Current workflows often require manual entry of numerous parameters — consuming time and increasing the risk of human error. Our proposed AI-Powered Quick Estimation Tool aims to solve this by integrating AI with the Civil Engineering design algorithm, starting with the AS4100:2020 Lifting Lug Design as a pilot application of this technology. With just two inputs — Static Lifting Mass and Lifting Angle — the AI-powered backend interacts directly with SkyCiv's QD API. The system performs an initial design check using default parameters for material properties, pin, and plate geometry. If the design passes, results are immediately displayed, including an option to download a report. In case of failure, the AI algorithm analyzes the failure reason and incrementally adjusts critical design parameters — such as lug thickness, outer diameter, pin diameter, and hole diameter. This iterative process, limited to a maximum of ten trials as of now, ensures an optimal configuration that meets all design checks. The AI engine, powered by GPT-4, draws from pre-loaded design rules and real-time API responses to suggest optimized parameters. This feedback loop continuously refines the estimation process, minimizing manual effort while improving accuracy and speed. While the Lifting Lug module serves as the first test case, this AI-driven enhancement can be extended across multiple such design calculators, enabling faster and smarter designs. This cloud-based solution represents a significant leap toward intelligent, data-driven structural design workflows.

Keywords: AInEngineering, StructuralDesign, CivilEngineering, Engineering-Software, AutomationInDesign, SkyCiv

Application of Evolutionary Algorithms to the Seismic Design of Reinforced Concrete Buildings with Chilean Typology

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Currently, prescriptive methods are widely employed for structural analysis and design; however, these do not allow for the identification of an optimized structure or a set of structures with optimal design performance. This study introduces a methodology based on evolutionary algorithms to determine structural layout for reinforced concrete buildings consistent with Chilean typology. Evolutionary computation utilizes computational models inspired by Darwinian evolution and natural selection, encoded through evolutionary algorithms.

The methodology begins with the building's geometric information (individual 0), encoded in an n-ary representation to define its characteristics (genes). Using this encoded information, new populations are iteratively generated from preceding ones by applying evolutionary operators such as selection, crossover, and mutation to each population, until a predefined generation is reached.

The study concludes that employing evolutionary algorithms allows achieving optimized structural configuration for residential buildings with reinforced concrete wall systems according to Chilean typology, emphasizing seismic weight and base shear considerations.

Keywords: evolutionary algorithms, genetic algorithms, reinforced concrete buildings

Application of Evolutionary Algorithms to the Design of T-Shaped Reinforced Concrete Walls

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Countries with high seismic activity frequently adopt reinforced concrete (RC) wall systems due to their robustness, material availability, and effective seismic performance. However, recent earthquakes in Chile and New Zealand have revealed critical issues, particularly concerning insufficient confinement in wall boundary elements, leading to premature buckling and fracture of longitudinal reinforcement, and brittle failures due to concrete crushing under high axial loads. Traditional design methodologies often simplify complex wall geometries by dividing them into independent rectangular sections and assuming uniaxial responses aligned with principal structural directions. This approach produces overly conservative, costly, and potentially fragile designs. New techniques have emerged in recent years, particularly evolutionary algorithms (EA), to address such challenges. These optimization techniques, inspired by natural selection and biological evolution, rely on iterative selection, mutation, and crossover processes to improve a population of candidate solutions progressively. Genetic algorithms (GA), a subset of EA, apply these principles to explore and identify effective solutions in complex optimization problems by encoding potential solutions as "chromosomes," evaluating their performance via a fitness function, and evolving them over generations. This study evaluates the applicability of genetic algorithms to optimize longitudinal reinforcement in the boundary elements of T-shaped RC walls. The proposed reinforcement layouts comply with ACI-318-19, NCh433, and Chilean Decrees 60 and 61. These configurations were compared with conventional design solutions. Preliminary results demonstrate the strong potential of genetic algorithms to produce structurally efficient and cost-effective reinforcement layouts, showing promise for enhancing design strategies in complex RC wall systems.

Keywords: Evolutionary Algorithms, Genetic algorithms, T-shaped RC walls

Excavability Assessment for Road Infrastructure Projects Using the K-NN Technique

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The success of road and bridge design projects heavily depends on ensuring the quality of the terrain in which they are deployed. One variable that determines this quality is the compactness of the terrain, which refers to the difficulty of breaking or excavating it. This variable, known as excavatability, can be estimated at a specific location using different geotechnical tests, such as wave velocity (V_p). Later, the V_p values can be transformed into five excavatability levels by the Carterpillar method. However, when V_p needs to be estimated over a large area, it is costly to conduct a massive number of V_p tests. A more economical alternative is to interpolate the measured data to fill in the unsampled areas. In this work, a prediction methodology based on the K-Nearest Neighbors machine learning technique is proposed. The model is fitted using the bootstrap technique (20 repetitions) and evaluated using metrics such as accuracy, precision, and recall. The dataset originates from an area in Valparaíso, Chile, and was provided by a construction company. The dataset comprises 203 georeferenced geotechnical samples, including V_p values, coordinates, and depth. To select the optimal KNN parameters, we compared multiple models that combine these attributes. The results show that the KNN-based model has an accuracy of 86.6%.

Keywords: Excavability, Geotechnical variables, K-NN, Machine Learning, Soil properties

A Machine Learning Framework for the Ultimate Capacity Assessment of Structural Sections

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The research illustrates a hybrid computational framework that combines analytical modeling and machine learning techniques to assess the ultimate capacity of structural sections composed of nonlinear materials, including no-tensile strength ones, such as concrete and masonry. The study focuses on sections subjected to axial force and biaxial bending, for which the capacity domain is typically represented by a convex surface in the generalized force space. An efficient fiber-free analytical integration method [1] is employed to evaluate internal forces resulting from generalized strain states. Based on this formulation, a critical strain multiplier is computed for each direction in strain space, enabling the construction of the capacity surface through a spherical sampling strategy. Then, a dataset of labeled points is synthesized by sampling the space around the boundary so that a Support Vector Machine [2], aiming to identify admissible and failing states, can be trained on this dataset. The proposed method is especially suited for sections made of heterogeneous or composite materials, typical of existing and historical heritage structures, where nonlinear behaviour and unilateral strength conditions pose challenges for traditional verification approaches. Numerical experiments confirm the effectiveness and accuracy of the classifier in approximating the capacity domain, offering a computationally efficient and interpretable alternative to conventional limit state checks.

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Keywords: Support Vector Machines, Ultimate Limit State Verification, Structural Section Classification

Artificial Intelligence Powered Automation in the Design of Thin-Walled composite Structures for Crashworthiness applications

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The integration of Artificial Intelligence (AI) into the design process of thin-walled structures represents a transformative shift in engineering and architecture. Thin-walled structures, which are characterized by their low thickness-to-length ratio, require intricate design optimization to ensure structural integrity while minimizing material usage. Traditional design methods, often based on empirical formulas and manual decision-making, face challenges in adapting to complex geometries and dynamic load conditions. The advent of Machine Learning (ML) offers significant potential in automating the design choices involved in thin-walled structures, facilitating more efficient, precise, and adaptable design processes. This paper explores the application of AI, particularly through Machine Learning models, in automating key aspects of the design process for thin-walled structures. By leveraging vast datasets of structural performance under various loading conditions, ML models are trained to predict optimal design parameters, such as material selection, geometry, and thickness distribution, based on the desired performance criteria. The use of supervised learning algorithms, such as regression and classification models, along with reinforcement learning, can assist in the real-time generation and evaluation of design alternatives. Furthermore, this research highlights the potential of AI in identifying non-obvious correlations between structural features and performance metrics, enabling the creation of robust design solutions that might be overlooked by human designers. By automating repetitive and time-consuming tasks, AI can accelerate the iterative design process, offering designers the ability to explore a broader range of design possibilities with higher efficiency. This paper also discusses the integration of AI-driven design tools into existing Computer-Aided Design (CAD) systems and the role of optimization algorithms in refining final designs. The potential benefits include enhanced design precision, reduced material wastage, and improved performance under variable environmental and load conditions. Additionally, AI can help adapt the design process to evolving requirements, ensuring that structures remain sustainable and cost-effective throughout their lifecycle.

Keywords: Artificial Intelligence (AI), Thin-walled Structures, Design Automation, Structural Optimization

Prediction of Soil Shear Strength Using Machine Learning 42

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Accurate prediction of soil shear strength is crucial for accurate and cost-effective geotechnical design. Traditional laboratory methods, while reliable, are often time consuming, labor-intensive and costly. This study explores the use of supervised machine learning algorithms to predict soil shear strength based on readily available geotechnical parameters including optimum moisture content, atterberg limits and particle size distribution. A comprehensive dataset was compiled from a series of historic soil tests gathered from the University of Nairobi Geotechnical Engineering Laboratory. Multiple models—Linear regression, Random Forest, extreme gradient boosting (XGBoost), LightGBM, Support Vector Regression, and Artificial Neural Networks—were developed and evaluated. Performance was assessed using standard metrics such as RMSE, MAE, and R^2 . The results indicate that tree-based ensemble methods and neural networks significantly outperform linear models in capturing the complex, nonlinear relationships governing soil behavior. The study demonstrates that machine learning offers a robust, scalable alternative for preliminary geotechnical assessments, with potential to reduce testing time and resource demands without compromising predictive accuracy.

Keywords: Machine Learning, Artificial Intelligence, Shear Strength

43 **An integrated framework for assessing and optimizing climate change adaptation of public buildings**

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Climate change is increasingly exposing the built environment to extreme events, highlighting the need for effective adaptation tools at the building level. This work introduces a framework that aligns with EU guidelines, combining Climate Vulnerability Assessment (CVA) with a Multi-Objective Optimization approach. The goal is to support public authorities in planning climate-resilient interventions for existing buildings, particularly in resource-constrained settings. The framework comprises a CVA that assesses a building's exposure, sensibility, and adaptability to hazards, and an Invasive Weed Optimization (IWO) algorithm to identify optimal retrofitting strategies for public assets, thereby minimizing vulnerability and adaptation costs. To do this, exposure is first assessed using climate projection models for different climate variables over time. Using ensemble ranking models that incorporate Multi-Criteria Decision Making and the SHAP methods, the most reliable projection models have been identified, considering in situ observations as well. Subsequently, sensibility and adaptability capacity are evaluated through the development of indicators within the literature that reflect the current building conditions. This information is integrated to obtain the climate vulnerability index. Finally, the IWO model is applied to minimize overall vulnerability to hazards while considering interdependencies of repair actions and minimizing adaptation costs within the constraints of public funding availability. Initial results based on synthetic datasets indicate that the proposed framework is transferable to real-world case studies and can be integrated with climate risk indicators to achieve climate-resilient asset management, thereby enhancing decision-making for building repairs.

Keywords: Climate change, Climate adaptation, Vulnerability assessment, Optimization, Public buildings

Global Sensitivity Analysis of Structural Engineering Models as an Aid for Design

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Structural systems are inherently subject to uncertainties such as material properties, loading conditions, and geometric configurations. Understanding how these uncertainties affect system performance is essential for ensuring safety, optimising design, and managing risk.

This work proposes the use of global sensitivity analysis using Sobol indices as a systematic framework to quantify the influence of input parameters on key structural outcomes in finite element analysis models. We present two case studies that demonstrate the effectiveness of this approach for complex, statically indeterminate buildings.

In stiffness-based, nonlinear analysis, variations in parameter values significantly influence key performance indicators, including stress distributions and modal frequencies. In both cases, sensitivity analysis facilitated the decomposition of complex building models into simplified submodels for targeted analysis using bespoke or lower-fidelity methods. Additionally, the sensitivity results provided quantitative insight into which regions of the design were most affected by underlying assumptions and therefore required greater attention.

By focusing design and analysis efforts on these critical parameters, engineers achieve faster design iterations and reduced computational cost, while improving confidence in structural performance predictions. The integration of global sensitivity analysis into structural workflows supports more informed, efficient, and risk-aware decision-making, particularly in complex design environments.

Keywords: Global Sensitivity Analysis, Sobol Indices, Finite Element Analysis, Finite Element Simulations, Design Optimisation, Structural Optimisation

AI-Enhanced Time Series Methods for Optimizing Commodity Trading in Additive Manufacturing Supply Chains for Construction

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This study investigates the use of advanced time series modeling to optimize commodity trading strategies for materials and fossil-based resources integral to additive manufacturing in the construction industry. As a benchmark, we design a mean-reversion strategy driven by the Parabolic SAR indicator, augmented by a dynamic stop-loss and take-profit mechanism to manage price volatility. The strategy is backtested on multi-year market data (2010–2023) for key construction-related commodities, including metallic powders, cementitious blends, and energy derivatives, with performance evaluated through metrics such as total return, maximum drawdown, and mean return. Building upon this baseline, we integrate Temporal Convolutional Networks (TCN) and Kalman filter-based state estimation to enhance signal accuracy and adapt trading decisions to fluctuating supply-demand dynamics. Both AI-driven models demonstrate improved returns and reduced volatility compared to the benchmark, enabling more resilient procurement and cost-control strategies. The findings illustrate how innovative time series approaches can inform structural optimization and resource planning, ultimately supporting more efficient, cost-stable, and sustainable construction processes enabled by additive manufacturing.

Acknowledgements:

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Keywords: Additive manufacturing, Commodity trading, Temporal Convolutional Networks, AI in construction

Advances in Missing Data Imputation for Concrete Structural Engineering

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Missing data is a widespread challenge in concrete structural engineering, often caused by high experimental costs, interruptions in long-term monitoring, and heterogeneity in data integration across publications. Such incompleteness significantly undermines the reliability of data-driven models. This paper proposes an enhanced iterative imputation framework designed to improve both robustness and accuracy in handling missing values. The method incorporates two main innovations: (i) using k-nearest neighbors (kNN) as a high-quality global initializer instead of simple mean or median replacement, and (ii) integrating an AutoML framework to dynamically select the most suitable predictor for each variable during the iterative process. Experiments were conducted on multiple open-access concrete-related regression datasets, with artificial missingness introduced under MCAR, MAR, and MNAR mechanisms at levels ranging from 10% to 50%. Performance was evaluated using Wasserstein Distance (WD) to measure distributional similarity and root mean squared error (RMSE) between imputed values and ground-truth observations. Results demonstrate that, in the vast majority of cases, the proposed method outperforms established baselines such as MissForest, HyperImpute, and GAIN. These findings highlight the effectiveness of combining global initialization and automated model selection to advance missing-data handling in engineering applications.

Keywords: Missing value imputation, Iterative imputation, Automated Machine Learning, Concrete structural engineering datasets

AI-Driven Evolutionary Design Optimization and Form Finding for Sustainable Gridshells

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Gridshell roofs are increasingly adopted in contemporary architecture and engineering due to their ability to span large areas with lightweight and slender components. Despite these advantages, their broader application is limited by fabrication challenges and elevated costs. To address these issues, optimization methods are essential for improving material efficiency and simplifying construction processes. Among existing strategies, the Multi-body Rope Approach (MRA) is a well-established form finding technique capable of producing structurally efficient funicular gridshell geometries. This work proposes an advanced optimization framework for free-form gridshells that combines evolutionary algorithms with an improved version of MRA, referred to as i-MRA. Coupled with the Non-dominated Sorting Genetic Algorithm (NSGA-II), the framework optimizes material usage, reduces production waste, and ensures structural reliability. In addition, a cutting stock problem formulation is implemented to further minimize waste and improve manufacturing efficiency. The methodology is validated through case studies of increasing complexity, demonstrating its effectiveness in balancing structural performance, material efficiency, and construction feasibility. Overall, the approach provides a sustainable and cost-effective strategy for the practical realization of gridshell structures.

Acknowledgements:

This research was supported by the project: FISA Multiscale Modelling and Simulation of Complex Materials for Production of Sustainable Composites - MUSICS: CUP assigned to the project: B83C25000810001

Keywords: Gridshell, Structural Optimization, Evolutionary algorithms, Multi-body Rope Approach, Cutting Stock Problem

Support Vector Regression for Hybrid Seismic Control of Nonlinear Base-Isolated Structure Equipped with an Active Tuned Mass Damper

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The increasing demand for reliable seismic protection has motivated the development of intelligent control strategies that can address nonlinear structural behavior. In this study, support vector regression (SVR) is employed to control a nonlinear base-isolated structure equipped with an active tuned mass damper (ATMD) at the base. The framework builds upon the principle of hybrid control, where passive isolation is complemented by active damping to enhance vibration mitigation. The SVR model is trained using data generated by a Linear Quadratic Regulator (LQR) under the El Centro earthquake, enabling it to reproduce the optimal control strategy without explicit reliance on structural models. The primary contributions of this study lie in demonstrating that an SVR-based controller can achieve substantial seismic response reduction while relying on fewer sensors than traditional algorithms. In the considered framework, ATMD is integrated with the base isolation of an eight-story benchmark building to mitigate vibrations under the near-field Kocaeli earthquake with pulse, the near-field Imperial Valley earthquake without pulse, and the far-field Hector earthquake. The performance of the proposed SVR-driven ATMD is compared to both the base-isolated structure alone and the LQR-controlled ATMD. The results demonstrate significant reductions in base displacement and inter-story drift, while simultaneously lowering the number of sensors required compared to traditional full-state controllers, thereby underscoring SVR as a practical and efficient approach for enhancing hybrid seismic control in smart structures.

Keywords: Hybrid Control, Support Vector Regression, Base Isolation, Active Tuned Mass Damper, Seismic Response Mitigation

Evaluating a Frequency-Domain Anomaly Detector for Periodic Bridge Monitoring Under Environmental Variability

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Detecting early-state damage in civil structures under operational and environmental variability remains a central challenge for structural health monitoring. This work discusses Spectral Jump–Anomaly Detection (SJ-AD), a data-driven algorithm that operates directly on acceleration records in the frequency domain. SJ-AD quantifies distributional changes between power spectra via a minimum jump-cost distance and issues alerts through a multi-window implicit thresholding scheme, enabling periodic condition assessment on a days-scale cadence without mode tracking, reference models, or damage-state labels. We evaluate SJ-AD across multiple field datasets from vibration-instrumented highway bridges of different typologies and under diverse temperature regimes, together with controlled numerical studies exploring low signal-to-noise ratios, small damping perturbations, and slight natural-frequency drifts. Across these studies, SJ-AD consistently highlights events associated with subtle condition changes while limiting the false-alarm rate. Indeed, the method detects signatures consistent minor defects observed in bridge structures, alongside reductions in prestressing levels of prestressed concrete bridges. These results indicate that SJ-AD provides a flexible and scalable pathway for continuous condition assessment in bridge monitoring and, more broadly, for structural systems where weak damage signatures are confounded by environmental and operational variability.

Keywords: Structural health monitoring, Anomaly detection, Concrete bridges, Temperature compensation, Prestress loss detection

Generative AI for Structural Engineering: A Practical Framework for Implementation and Validation

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Generative Artificial Intelligence presents unprecedented opportunities for structural engineers to revolutionize design processes, optimize computational workflows, and enhance decision-making capabilities. This study explores practical applications of AI technologies in structural engineering, demonstrating how they can be effectively leveraged to address complex engineering challenges while maintaining the rigorous standards required in structural design. The research presents a comprehensive framework for implementing AI-driven solutions in structural engineering practice, focusing on three key areas: (1) automated code generation for structural analysis and design calculations, (2) intelligent optimization of structural forms and material usage, and (3) enhanced decision support through natural language processing of engineering codes, standards, and technical literature. Through the integration of Large Language Models (LLMs) with engineering databases and computational tools, structural engineers can access AI-powered assistance for tasks ranging from preliminary design exploration to detailed analysis validation. This framework demonstrates how Generative AI can automate the creation of workflows for complex structural calculations, interpret building codes and design standards, and facilitate the exploration of innovative structural forms such as gridshells and tensioned structures. The AI system effectively processes engineering terminology, understands structural relationships, and generates contextually appropriate solutions while enabling engineers to maintain comprehensive oversight and validation of all AI-generated recommendations. The proposed AI-supported methodology enables structural engineers to focus on creative problem-solving and engineering judgment while automating routine computational tasks. Furthermore, the natural language interface democratizes access to advanced computational methods, allowing engineers to interact with complex optimization algorithms through conversational queries rather than requiring specialized programming expertise. This work establishes a practical roadmap for structural engineering practitioners to implement AI technologies responsibly, highlighting both transformative opportunities and critical considerations for validation and quality assurance in structural design. The framework preserves fundamental engineering rigor while significantly expanding computational capabilities, positioning structural engineers to harness the full potential of AI technologies in contemporary practice while maintaining professional responsibility and safety standards.

Keywords: Large Language Models, Artificial Intelligence, Structural Engineering

Recent developments of an Optimization procedure for seismic upgrading of existing RC structures

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Recent studies highlight that demolishing and reconstructing many buildings erected in past decades (often without seismic design criteria and now affected by material degradation) would entail significant economic and environmental costs. As a result, civil engineers are increasingly engaged in the rehabilitation of existing structures, which usually requires combining local interventions (to strengthen individual members) with global ones (to enhance lateral stiffness). Since no design guidelines currently exist for such integrated approaches, seismic upgrading can be framed as an optimization problem. This task is particularly challenging due to the vast number of possible solutions and the complex interactions between design variables and structural performance. In this context, Genetic Algorithms offer a promising tool, capable of handling multiple variables and identifying near-optimal retrofit strategies according to predefined criteria. The proposed methodology, initially implemented in Matlab with OpenSEES, has been recently migrated to Python using the OpenSEESPy module, parallelized to drastically reduce computation time, and executed on High Performance Computing facilities. Moreover, the procedure now includes the assessment of brittle failure mechanisms associated with shear deficiencies in members and joints. This paper provides an overview of the approach and presents recent results, considering different objective functions such as economic and environmental retrofit costs.

Keywords: Genetic Algorithm, Optimization, Existing RC structures, Intervention cost, Carbon footprint

MORL-DB method. Declining Reinforcement Learning into the Structural Multi-Objective Optimisation context

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In this paper, the mass versus compliance problem for a cantilever I-beam, a well-known didactic multi-objective optimization test case, is approached using MORL-DB and state-of-the-art methods, namely Non-dominated Sorting Genetic Algorithm II (NSGA-II) and Parameters Space Investigation (PSI). The MORL-DB method introduces Reinforcement Learning into the multi-objective problems framework, resulting from the combination of a Deep Deterministic Policy Gradient (DDPG) algorithm with a dominance depth-based reward function. The approximation of the Pareto front of the cantilever problem built using the MORL-DB method is compared to the approximations produced by state-of-the-art methods. The methods produce results of the same quality, but MORL-DB requires fewer objective function evaluations compared to state-of-the-art methods. This can improve the efficiency of the optimization process for problems where the evaluation of objective functions requires long computational times.

Keywords: Artificial Intelligence, Artificial Designer, Deep Deterministic Policy Gradient (DDPG), Multi-Objective Optimisation, Reinforcement Learning, Structural Optimisation

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SS06 - Structural identification and knowledge transfer for civil engineering applications.

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The special session focuses on innovative strategies for knowledge transfer, and linear and nonlinear system identification in civil Structural Health Monitoring (SHM). We welcome contributions that explore methodologies for processing vibrational and environmental data to improve the assessment, diagnosis, and predictive capabilities of structural models through data-driven, model-driven and hybrid approaches. Papers will cover topics such as system identification (linear and nonlinear), signal processing, machine learning, knowledge transfer, domain adaptation, population-based SHM, model updating, and analysis of monitoring dataset including static, dynamic and remote data. Emphasis will be given to different level of damage identification: detection, localization, and quantification. Contributions focusing on advanced data sources, such as satellite-based monitoring and remote sensing, for population-based SHM applications are particularly encouraged. The session will also be an opportunity to present the research conducted within the PRIN SAT4SHM project.

The session aims to bring together researchers working at the intersection of computational intelligence, digital modeling, and structural engineering, encouraging discussions on how to enrich SHM frameworks for existing structures.

Contents of interest include, but are not limited to, the following topics: • System identification • Knowledge transfer • Application on full scale structures • Remote sensing • Data integration and fusion for monitoring • Machine learning and optimization • Non Destructive Test

Extraction of Vibration Characteristics of a Simple Beam Structure Using UAV Vision Tracking

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This paper investigates the effectiveness of using Unmanned Aerial Vehicles (UAVs) with vision-tracking capabilities for monitoring the dynamics of cantilever beams. The study proposes a non-contact alternative to traditional structural health monitoring (SHM) methods, aiming to benchmark the accuracy and reliability of UAV-based vision tracking against established techniques: analytical modelling, numerical simulations, and experimental accelerometer measurements.

For demonstration, an aluminium fixed-free beam with a hollow rectangular cross-section was subjected to base excitation. In the SHM Laboratory at KISR, the beam was instrumented with accelerometers at both its free and fixed ends, connected to a data acquisition system. Simultaneously, a UAV camera, recording at 30Hz, captured the beam's vibration. The Kanade-Lucas-Tomasi (KLT) algorithm was applied to the video footage to track the beam's tip response, and this movement data was then compared with the accelerometer readings. Natural frequencies and damping of the beam were identified from both UAV video and accelerometer data.

Comparative results were also obtained from numerical simulations using the Finite Element Method (FEM), idealizing the beam with Euler-Bernoulli elements and solid elements. It was shown that the vibration characteristics derived from UAV data accurately matched those from both accelerometer measurements and the numerical models.

Our proof of concept is expected to contribute positively to the integration of AI within SHM, particularly supporting the application of Computer Vision (CV) in Convolutional Neural Network (CNN) models that leverage video-based datasets. A prime example involves combining the YOLOv8 model with the KLT algorithm to remotely identify structural elements and quantify their dynamic characteristics, such as natural frequency.

Keywords: UAV, Natural Frequency, Vision Tracking, Accelerometer

Probabilistic–Adaptive–Physics-Informed Normalisation of Temperature-Induced Frequency Drift in the Marcus Aurelius Exedra Hall

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Ambient temperature fluctuations can obscure genuine stiffness changes by shifting the natural frequencies of civil structures. The challenge is acute in the Marcus Aurelius Exedra Hall of Rome's Capitoline Museums, a semi-elliptical steel-and-glass enclosure whose articulated spider-node joints couple materials with markedly different thermal expansion coefficients. To restore damage sensitivity, we propose a three-layer workflow that combines probabilistic inference, adaptive filtering and physics-informed machine learning. First, each modal frequency is modelled as a Gaussian variable whose mean and variance vary linearly with the steel–glass temperature differential; Bayesian calibration against a year-long dataset yields credibility envelopes containing 97 % of observations. Second, these envelopes serve as priors in an online kernel recursive least-squares filter, cutting the unexplained coefficient of variation by 37 % in five-minute updates. Third, the thermo-normalised residuals feed a physics-informed neural network constrained by the damped-oscillator equation augmented with an anelastic relaxation term, achieving sub-1 % RMSE. Coupled with an ensemble outlier detector, the system flags synthetic 5–15 % stiffness-loss scenarios with an F1-score of 0.94 within fifteen minutes. The framework thus provides a lightweight, climate-independent basis for digital-twin-enabled Structural Health Monitoring of slender steel–glass assemblies embedded in heritage masonry contexts.

Keywords: Exedra Hall, steel–glass interaction, thermo-modal normalisation, Bayesian filtering, physics-informed neural network, Structural Health Monitoring

Estimation of Flexural Rigidity Distribution in Euler–Bernoulli Beams: Numerical and Experimental Investigation using Acceleration Data and Physics-Informed Neural Networks

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Accurately locating and quantifying stiffness loss in structural beams remains a significant challenge. Conventional methods typically attempt to recover $EI(x)$ using static deflection and influence line approaches. However, these methods rely on controlled loading conditions and require dense arrays of strain gauges or displacement transducers for data acquisition, making them costly and impractical for large-scale deployment. This study proposes a lightweight alternative: a dual Physics-informed Neural Network(PINN) that learns the flexural-rigidity field $EI(x)$ solely from sparse transverse-acceleration measurements, which are readily obtain- able in real structures. The methodology begins with data preparation and pre-processing that includes develop- ing Abaqus beam models and filtering the simulated acceleration signals. A physics-informed neural framework then embeds the Euler–Bernoulli equation directly in the loss function, cou- pling a forward network that reproduces accelerations with an inverse branch that infers the flexural-rigidity field $EI(x)$. Because the governing physics is enforced internally, no explicit boundary conditions or force inputs are required. Training uses a two-stage schedule, an Adam warm-up followed by L–BFGS fine-tuning for precise convergence. The framework is first validated on three finite-element test cases uniform, linearly graded, and triangular $EI(x)$ that represent increasing identification difficulty. Across these cases, the PINN reproduces the full acceleration field with global L2 errors below 1 %, stiffness is re- covered to within 1 %, 1.5 %, and 7 % respectively, with the softest point accurately identified, even under steep stiffness gradients. Robustness trials show that adding 1–2 % Gaussian noise and 2 % Rayleigh damping inflates stiffness L2 error by factor of 5 %, confirming practical tolerance to sensor noise and light damping. In the last phase, a real-beam experiment on a 2 m-long, undamage and half-milled alu- minium I-beam was conducted with eleven low-cost Raspberry Pi 4 B accelerometers, demon- strates real-world feasibility. The model reproduces the measured acceleration field with only small errors and successfully reproduced constant flexural rigidity distribution in undamage beam and pinpoints the weakened half-span in half-milled beam. Overall, the study shows that an acceleration-only PINN can provide actionable stiffness profiles without specialized instrumentation, offering a cost-effective addition to the SHM.

Keywords: Euler-Bernoulli Beam, flexural rigidity distribution, Physics-Informed Neural Networks (PINNs)

Automatic multi-modal anomaly detection for smart structures with wind bridge infrastructure engineering applications

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A transformer-based framework for structural vibration forecasting anomaly detection is studied herein for bridge structural health monitoring applications. The approach uses multi-modal data comprising both structural acceleration responses and environmental wind measurements. Traditional structural health monitoring methodologies, which often rely solely on acceleration data, are limited in their ability to distinguish between long-term structural responses and variations caused by environmental influences such as wind. By incorporating wind speed signals, this research aims to enhance the interpretability and sensitivity of anomaly detection systems. Leveraging high-resolution data from the Hardanger Bridge in Norway, the proposed model employs attention mechanisms to learn complex temporal and spatial dependencies. While acknowledging current limitations in data imbalance, sensor synchronization, and computational demands, this study demonstrates the feasibility of multi-modal, AI-driven structural health monitoring for digital twin applications.

Keywords: Bridge structural health monitoring, Transformer, Anomaly detection, Multi-modal learning

Open-set classifier for separating structural and non-structural vibrational modes in operational modal analysis

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In the context of structural health monitoring, during retrofitting or improving interventions, identifying true structural dynamic characteristics becomes particularly challenging due to the presence of temporary non-structural elements such as scaffolding, formworks, or other installations. This paper proposes a model-driven open-set classification framework capable of distinguishing between structural and non-structural vibration modes using operational modal data. The methodology integrates operational modal analysis with numerical simulations to extract modal features, which are then classified using a probabilistic classifier. An automatic thresholding mechanism enables the rejection of unknown patterns associated with non-structural dynamics, following the concept of open-set classification scheme, which is robust to previously unseen modal responses. The framework is applied through a real case study involving a historical church undergoing structural modifications, with temporary structures affecting the dynamic response. The contribution represents a significant step forward in autonomous structural monitoring, particularly for historical structures, as it enables the continuous and automatic filtering of stable non-structural vibrational modes (i.e., interferences) without requiring extensive expert supervision or prior knowledge of non-structural dynamics.

Keywords: Gaussian-mixture models, Open-set classification, Structural health monitoring, Temporary structure interaction, Vibration mode discrimination

Physics-Informed machine learning for efficient calibration of mechanical parameters via surrogate modeling

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The reliable monitoring of historical structures requires the continuous updating of numerical models based on experimental data, particularly in the presence of environmental and operational variations. Traditional calibration procedures, while effective for one-time updates, are computationally prohibitive in long-term monitoring scenarios. This work proposes a novel methodology that combines sensitivity analysis, Gaussian process surrogate modeling, and high-fidelity numerical models to achieve efficient and accurate model updating based on modal parameters. Sensitivity analysis is used to identify the most influential mechanical parameters, reducing the dimensionality of the calibration space. The surrogate model is trained and validated on numerical-generated datasets, enabling fast inversion of experimental modal data into mechanical properties. The methodology is validated on an historic structure, demonstrating its ability to track the effects of environmental and operational variations and provide quasi-real-time updates of a digital twin.

Keywords: Digital twin, Gaussian process regression, EOVs, Real-time monitoring, Sensitivity analysis

Leveraging InSAR archives for population-based structural health monitoring of bridges

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This contribution introduces a novel framework for regional-scale structural health monitoring (SHM) of bridges that exploits freely available interferometric synthetic aperture radar (InSAR) data combined with environmental information. For the first time, population-based SHM is applied to static displacement features, enabling direct comparison among groups of similar bridges. A subspace alignment procedure harmonizes features into a shared latent space, where anomalies are identified as deviations in the relative behavior of one bridge with respect to the population. This shift from long-term time-history dependence to instantaneous, relative comparisons reduces the need for baseline data and enhances robustness against environmental influences, even those emerging from previously unobserved phenomena linked to climate change. A further contribution is the transfer of knowledge from simplified simulated bridge models to real-world cases, allowing the classification of anomalies (e.g., scour, settlements, uplifts, or data outliers) even in the absence of labeled field data. The methodology is demonstrated on a population of seven steel railway bridges crossing the Po River in Italy. Results show that detected anomalies align with documented flood and drought events, confirming the potential of simulation-to-real transfer for practical classification. The approach provides a cost-effective and scalable solution for infrastructure agencies, supporting territorial risk assessment and the prioritization of maintenance without requiring on-site instrumentation. By exploiting global satellite archives, this strategy paves the way for worldwide, regional-scale SHM applications, enhancing the resilience and safety of transportation networks.

Keywords: structural health monitoring, transfer learning, interferometric synthetic aperture radar, damage identification, bridge

Adapted Masked Compressed Sensing Framework for Structural Health Monitoring: Reliable Modal Analysis under High Compression

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In vibration-based Structural Health Monitoring (SHM), large volumes of data are produced, creating challenges for transmission and storage. Compressed Sensing (CS), a signal processing technique that reconstructs sparse signals from fewer samples than required by Nyquist, has gained increasing attention for its ability to achieve high compression ratios while retaining the information most relevant to structural dynamics. We extend a previously introduced CS framework for vibration diagnostics, the Model-assisted Rakeness-based CS (MRak) framework, by introducing an adaptive mask, Adapted MRak (AMRak). The method refines the selection of spectral peaks, preserving weaker but structurally significant natural frequencies during compression, thereby improving reconstruction quality at high compression ratios. To further enhance reconstruction, we employ an energy-based algorithm to identify optimal supports, which serve as basis for training Random Forest (RF) and Support Vector Machine (SVM) classifiers. These classifiers estimate the support structure during reconstruction, ensuring the most relevant spectral components are preserved. The reconstructed accelerometric signals retain the information needed to visualize the Frequency Domain Decomposition (FDD) within the frequency bands of interest, i.e., those characterized by resonance peaks. This enables a reliable estimation of modal shapes, which are essential for assessing the structural state by vibration-based analysis. Experimental results on Bridge S101, a well-known SHM benchmark, confirm that the combination of optimal support selection and classification-based decoding allows compression ratios on the order of 10 while preserving both reconstruction accuracy and the fidelity of modal analysis.

Keywords: Compressed Sensing (CS), Structural Health Monitoring (SHM), Spectral Masking, Modal Analysis, Frequency Domain Decomposition (FDD), Machine Learning Based Reconstruction

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SS07 - Emerging Applications of Large Language Models (LLMs) for Structural Engineering.

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The advent of Large Language Models (LLMs) is triggering a profound transformation in the field of engineering and structural computation, heralding a radical shift in design and analysis processes. This presentation aims to explore how such models transcend the role of mere automation tools to emerge as genuine cognitive partners. We will discuss emerging methodologies that enable LLMs to interact with computational software, interpret complex data, and assist in the generation of preliminary models. The most concrete opportunities will be examined, such as accelerating iterative design cycles through the optimization of complex solutions and the verification of regulatory compliance. However, an in-depth analysis cannot overlook critical challenges. Key issues will be addressed regarding the reliability of generated data and the urgent need to develop rigorous validation protocols, essential to ensure the integrity and safety of structural analyses and thus shape the future of the profession. The Special Issue will be devoted to the design, modelling, analysis, construction, and other aspects of the technology of all types of shell and spatial structures. These may include, but are not limited to:

- Cognitive Role of LLMs – Moving beyond automation to become partners in structural design and analysis.
- Integration with Computational Tools – Enabling interaction with structural software, data interpretation, and preliminary model generation.
- Opportunities for Acceleration – Optimizing complex solutions, speeding up iterative design cycles, and ensuring regulatory compliance.
- Critical Challenges – Addressing data reliability, validation protocols, and safety in structural analysis.

Automated Damage Classification and Code-Based Reporting in Bridge Inspections Using Deep Learning Algorithms

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Bridge inspections are essential for ensuring infrastructure safety but are often time-consuming and subject to inspector subjectivity, especially when classifying observed damage types. This study proposes a computer vision-based approach leveraging the YOLOv8 object detection model to automate the identification and classification of damage types in bridge inspection images. The methodology is specifically designed to support inspectors by simplifying and accelerating the completion of inspection reports through the automatic assignment of codified damage types, as defined in relevant technical standards, such as the Italian Guidelines on Bridge Management (LG2020). The approach enhances consistency and repeatability in damage recognition, facilitating the integration of AI-assisted tools into standardised inspection workflows. Preliminary results demonstrate the model's effectiveness in detecting various damage categories present in the reinforced concrete elements inspection forms included in LG2020. The approach in terms of training and validation is based on a dataset of images taken during several surveys on bridges located in southern Italy. Further developments of the procedure will allow its full applicability in real-world bridge management systems.

Keywords: Infrastructure management, Deep learning, Bridge inspection, Italian guidelines, Damage detection

Applicazioni emergenti dei Large Language Models (LLM) per l'Ingegneria Strutturale

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L'avvento dei Large Language Models (LLM) sta innescando una profonda trasformazione nel campo dell'ingegneria e del calcolo strutturale, prefigurando un cambiamento radicale dei processi di progettazione e analisi. Questo intervento si propone di esplorare come tali modelli trascendano il ruolo di meri strumenti di automazione per configurarsi come autentici partner cognitivi. Discuteremo delle metodologie emergenti che consentono agli LLM di dialogare con i software di calcolo, interpretare dati complessi e assistere nella generazione di modelli preliminari. Verranno analizzate le opportunità più concrete, come l'accelerazione dei cicli iterativi di progettazione attraverso l'ottimizzazione di soluzioni complesse e la verifica della conformità normativa. Tuttavia, un'analisi approfondita non può prescindere dalle sfide critiche. Saranno esaminate le questioni cruciali legate all'affidabilità dei dati generati e alla necessità impellente di sviluppare protocolli di validazione rigorosi, indispensabili per garantire l'integrità e la sicurezza delle analisi strutturali e tracciare così il futuro della professione.

Keywords: LLM, Ingegneria strutturale, Protocolli di validazione

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SS08 - Hybrid AI Strategies in Seismic Engineering: A Machine Learning Framework for Structural Systems.

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This special session introduces a hybrid artificial intelligence framework that integrates advanced machine learning techniques with conventional seismic engineering practices to predict and analyze dynamic responses of diverse structural systems. By combining data-driven algorithms with numerical-based models, the proposed framework offers enhanced accuracy and reliability in forecasting seismic behavior in steel and reinforced concrete (RC) structures, steel and RC shear wall systems, lateral force-resisting system, and other construction typologies. Considering historical seismic records, laboratory experiment data, and high-fidelity computational simulations, the framework employs machine learning methods, ensemble strategies, and transfer learning to extract critical features from complex datasets. These hybrid AI strategies allow for the identification of nonlinear response patterns, real-time adaptation to evolving seismic conditions, and improved estimation of displacements, interstory drift, residual deformation, stress distributions, and energy dissipation during earthquake events. This special session advances the state-of-the-art in seismic response prediction while contributing to the development of resilient infrastructure. The integration of hybrid AI strategies into seismic engineering represents a transformative step toward smarter, safer, and more adaptive structural systems in earthquake-prone regions. It provides a solid foundation for future studies aimed at design optimization, seismic performance assessment, seismic failure probability, seismic risk assessment, and promoting sustainable practices in civil engineering. Overall, this framework marks a significant advance in using AI for practical seismic engineering and retrofitting structures. Contents of interest include, but are not limited to, the following topics: • Overview of hybrid AI strategies

in seismic engineering, structural designing, and retrofitting structures • Integration of machine learning with traditional numerical-based models for monitoring and real-time response assessment • Applications of machine learning methods for passive, semi-active, and active control of lateral force-resisting systems to improve structural behavior • Data-driven and ensemble methods for feature extraction, nonlinear response prediction and uncertainty quantification • Advanced machine learning methods in seismic probabilistic analysis, predictive models, and estimation tool • Machine learning-based response curve prediction compared with traditional seismic analysis methods • Improvements in machine learning algorithms and adaptation techniques, including transfer learning across structural types

Seismic response assessment of reinforced concrete structures using machine learning methods

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Recent advancements in machine learning (ML) methods bring the novelty of using them as a prediction tool for seismic probabilistic assessment of reinforced concrete (RC) structures. This research provides a novel ML model for estimating the seismic response of inter-story drift (IDR), and seismic performance levels of operational, immediate occupancy, life safety, collapse prevention, and total collapse. The modeling of the RC frame was validated by ABAQUS software and confirmed by OpenSees model. Low- to mid-rise RC buildings having different bay lengths and numbers of spans were designed, then, to achieve seismic results for preparing training and testing datasets, incremental dynamic analysis (IDA) was performed, subjected to near-fault records. The proposed ML model aims to reduce the time needed to capture the seismic response of RC buildings and avoid time-consuming modeling. This can significantly improve the design process and can be widely used for retrofitting strategies. The results show that ML model can estimate IDR, and seismic performance levels of operational, immediate occupancy, life safety, collapse prevention, and total collapse with accuracies of 95.3%, 96.1%, 94.8%, 97.6%, 96.3%, and 94.5%, respectively.

Keywords: Reinforced Concrete Structures, Machine Learning Method, Seismic Response, Finite Element Model

Machine learning-based predictive model for probabilistic seismic response assessment of reinforced concrete shear walls

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Nowadays, improvements in artificial intelligence, especially machine learning (ML) methods, have paved the way for novel ideas on probabilistic seismic response assessment of reinforced concrete (RC) shear walls. RC shear wall system can be used in mid-rise to high-rise buildings as a design and retrofitting scheme that can considerably improve the lateral behavior of buildings. Due to the complexity of modeling, nonlinear behavior estimation of RC shear wall is a great challenge, however, this research aims to propose novel ML models to predict seismic response of inter-story drift (IDR), residual inter-story drift (RIDR), and distribution of IDR and RIDR along floor levels. For this purpose, 4-, to 10-story RC shear walls were modeled assuming soil D and different bay lengths. Incremental dynamic analysis (IDA) was performed to achieve seismic demands for preparing training and testing datasets to be used by ML models. The results of ML models show that they have more than 96.3% reliability on predicting IDR, RIDR, and the distribution of IDR and RIDR, which can be a considerable improvement in engineering applications. Having seismic response demands without the need for modeling of RC shear walls can help structural designers for the preliminary assessment of structures, which can speed up the evaluations for retrofitting structures.

Keywords: Reinforced Concrete Shear Wall, Machine Learning Algorithm, Seismic Response, Data Driven Method

Physics-Informed LSTM Model for Dynamic Response Prediction and Reliability Analysis

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Accurate prediction of structural response under dynamic loading is critical for ensuring the safety and reliability of engineering systems. Traditional numerical methods, while effective, can be computationally expensive and often require detailed modeling. In this study, we propose a novel hybrid framework that integrates physics-informed Long Short-Term Memory (PI-LSTM) networks with the Probability Density Evolution Method (PDEM) to efficiently predict structural responses and quantify reliability under uncertainty. The proposed PI-LSTM integrates governing equations of motion directly into the loss function, ensuring consistency with physical laws while preserving the model's ability to learn complex temporal dependencies from data. The PI-LSTM is trained on a limited set of response histories generated via high-fidelity numerical simulations and is subsequently employed to predict dynamic responses of a stochastic system subjected to ground motions. These predicted responses are further utilized within the PDEM framework to evolve the probabilistic description of system behavior over time, enabling a rigorous reliability assessment. The proposed approach is validated using two different examples – (i) a multi-degree-of-freedom system subjected to ground motion and (ii) a beam with a moving mass, demonstrating high accuracy, computational efficiency, and robustness in uncertainty quantification compared to purely data-driven LSTM models and significantly reduces computational cost relative to full-scale Monte Carlo simulations. This integrated methodology provides a powerful tool for real-time structural health monitoring, digital twins, and probabilistic design in the presence of dynamic loading and model uncertainty.

Keywords: Stochastic Response, Physics- Based Long Short-Term Memory, Reliability Analysis, Probability Density Evolution Method

Quantification of uncertainty in damage estimation combining ensemble of ML algorithms

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A deterministic estimation of damage severity encounters several challenges in practical scenarios. Uncertainties in this damage estimation arise from various sources, including noise in the measured vibration data and inaccuracies introduced during its processing. Recent advancements in machine learning (ML) offer effective tools for probabilistic assessment of such uncertainties. However, efficiency of an individual algorithm depends on various factors. Integration of ML algorithms is therefore explored in this study to reliably quantify uncertainty in damage estimation. The proposed approach is validated through a numerical study on a 10-story shear building model. Damage is introduced at various floors with severities ranging from mild to severe. For each damage scenario, the building is first analyzed with different types of uncertainties that include variability in excitation force, material randomness, and noise in measured data. The set of resulting floor acceleration responses are recorded, and relevant features are extracted. Bayesian ensemble comprising gradient boosting, random forests, and support vector regression model is then trained on extracted features for each damage case. Outputs from all ensemble models are combined to predict damage with posterior uncertainty bounds. Effectiveness of the trained algorithm with proposed methodology is subsequently evaluated under different test conditions. The developed framework enables a reliable uncertainty quantification in estimating damage severity with associated confidence intervals. In future, robustness of this method can be investigated further with different case studies using real-world responses of a structure.

Keywords: Uncertainty, machine learning (ML), shear building, damage quantification, Bayesian

LASSO-Based Identification of Critical Ground Motion Parameters for Efficient Seismic Demand Prediction Considering Soil-Structure Interaction

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Seismic resilience of built infrastructure critically depends on the accurate estimation of seismic demand, accounting for local site conditions, soil-structure interaction (SSI), and regional seismicity. Time history analysis using a large number of recorded ground motions is often employed for this purpose. It is computationally intensive. This study explores a practical solution to this challenge by using LASSO regression to identify the most influential ground motion parameters affecting structural response under SSI conditions. A total of 1000 soil-structure systems were analyzed using 191 ground motion records. The LASSO results highlight key parameters that help in selecting a reduced yet reliable set of ground motions for seismic analysis. This approach reduces computational demands while maintaining accuracy, offering a more efficient pathway to optimize seismic design and improve the resilience of structural systems.

Keywords: LASSO Regression, Soil-Structure Interaction (SSI), Seismic Demand, Ground Motion Parameters

Intelligent inspection of bridge bearings through an engineering constrained ML approach

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Bridge bearings play a fundamental role in the structural integrity of bridges by enabling the transfer of loads and accommodating relative movements between the superstructure and substructure. Nevertheless, inspecting these elements is particularly demanding due to their often limited accessibility, intricate shapes, and the wide range of types and degradation mechanisms. In addition, accurately identifying the bearing type and detecting associated defects frequently depends on the subjective assessment of the inspector, which can lead to inconsistent results and the potential oversight of critical issues. This study introduces an automated workflow aimed at assisting the visual inspection of bridge bearings, leveraging object detection algorithms and multimodal image interpretation through advanced language models. Initially, a YOLO-based detector is employed to recognise the bearing type in photographic datasets. The detected class and corresponding image are then analysed using a multimodal language model (GPT-4o), which evaluates possible defects based on the specific bearing type, integrating engineering knowledge and code-based constraints into the assessment. The system uses this information to quantify damage severity and extent, generating structured and formatted inspection reports. The proposed approach was validated on a sample of real-world bridges and showed promise in reducing subjectivity, improving consistency across inspections, and offering a scalable tool for infrastructure asset managers.

Keywords: Bridge bearings, Inspections, Damage detection, Engineering Constraints, YOLO, LLMs

Size Optimization of Steel Trusses with Controlled Plastic Deformation Using a Hybrid Neural Network–Genetic Algorithm Approach

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This study presents a robust framework for the size optimization of steel trusses, aiming for material-efficient designs while incorporating plastic deformation control to ensure structural safety and performance. To accurately capture structural behavior, a custom-developed code performs geometrically and materially nonlinear finite element analysis. Within this system, the complementary strain energy of residual forces is calculated and employed as a control metric to limit plasticity by adjusting the cross-sectional areas of individual bar members. This strategy not only enables precise regulation of inelastic behavior but is also capable—when necessary—of maintaining the structure entirely within the elastic range, supported by the proposed computational technique and mathematical formulation. To enhance convergence and solution quality, a neural network is integrated into the genetic algorithm, enabling intelligent learning from data generated by the population-based optimization process. The effectiveness of the hybrid approach is demonstrated through a benchmark numerical example, showing that the neural network-assisted genetic algorithm surpasses traditional implementations by delivering superior results in fewer generations, with reduced material consumption and minimized plastic deformation under predefined constraints. These outcomes underscore the potential of advanced hybrid optimization techniques and the effectiveness of plasticity-controlled design in truss structures.

Keywords: Size optimization, Neural Network, Genetic Algorithm, Truss structures, Complementary strain energy, Plastic design

A Visual Intelligence Framework for Earthquake Damage Classification

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Rapid and reliable classification of post-earthquake structural damage plays a critical role in disaster management and emergency response, and the time-consuming, expert-dependent nature of traditional assessment methods has amplified the need for AI-based automated solutions. This study presents the development of an AI-driven decision support framework for post-earthquake structural damage assessment, utilizing image-based data. Field investigations were conducted in Türkiye, a seismically active region (earthquake prone region) situated along a major global tectonic belt, in the aftermath of recent seismic events. A comprehensive visual dataset was compiled, comprising images of damaged reinforced concrete members across various building typologies. A total of 132 algorithmic configurations—encompassing segmentation, and classification models, as well as their hybrid combinations—were systematically evaluated. Comparative performance analysis was conducted to identify the most effective model architecture. The optimal configuration demonstrated robust accuracy metrics, indicating its potential applicability for rapid and reliable post-disaster damage classification in real-world scenarios.

Keywords: Damage Assessment, Earthquake, YOLO, Segmentation, Structural Elements

Bio-Inspired Evolutionary Optimization of Shear Wall Placement in Reinforced Concrete Seismic Retrofit: a Parametric Framework

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The seismic retrofit of reinforced concrete (RC) buildings requires a careful balance between safety, functionality, and cost efficiency. The introduction of shear walls is a widely adopted technique, but their placement has a decisive impact on seismic response, particularly in terms of torsional irregularity and interstory drift. Traditional manual approaches often fail to systematically explore alternative configurations. This study presents a parametric framework integrating Grasshopper for geometric modeling, Karamba3D for structural analysis, and Wallacei for multi-objective optimization. Wallacei, based on bio-inspired evolutionary algorithms, enables the exploration of wide solution spaces and the identification of optimal layouts according to multiple criteria. The algorithm minimizes the total added wall surface while satisfying seismic performance constraints: interstory drift limits, reduction of eccentricity between the center of mass and the center of rigidity, and material utilization checks under spectral load combinations. A demonstrative study highlights how the proposed approach can generate optimized layouts, significantly reducing retrofit demand while ensuring compliance with seismic performance requirements. The results underline the potential of combining parametric modeling and evolutionary optimization as a decision-support strategy for more efficient, data-driven seismic retrofit solutions.

Keywords: AI-assisted seismic design, Reinforced concrete retrofit, Shear wall placement, Computational design, Evolutionary optimization, Hybrid AI strategies

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SS09 - Intelligent Non-destructive Testing and Evaluation for Structures.

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The more complex the structure and the larger its size, the higher the manufacturing cost, the longer the manufacturing cycle, and the higher the requirements for manufacturing quality. In many industrial and application fields, complexity, large-scale, high performance, multi-functionality, long service life, and low cost have become important development directions for structural optimization design, high-efficient and quality manufacturing and safe service in recent years. By developing advanced intelligent non-destructive testing and evaluation (iNDT&E) methods, technologies, and equipment, information reflecting the performance, function, manufacturing quality, health, and service safety of the structure can be obtained. The results of deep mining and intelligent analysis of detection data using artificial intelligence models can be used for structural design optimization, manufacturing process improvement, and health detection and service safety monitoring of structures. The development of advanced 3D visualization detection techniques and equipment can achieve accurate detection and evaluation of high-value complex and large-scale structures. With the development of artificial intelligence technology, many iNDT&E methods, models, and instruments with machine learning and deep learning characteristics have been continuously applied in practice. This topic is aimed at research and development, manufacturing and service of structures and high-value products, attracting researchers and scholars engaged in iNDT&E and related fields to introduce relevant research results, share their own research and application results, and jointly promote the development of iNDT&E techniques.

Contents of interest include, but are not limited to, the following topics:

- Intelligent characterization, detection and evaluation methods.
- Intelligent

detection and evaluation model and simulation. • Intelligent detection and evaluation algorithm and test verification. • 3D visual inspection and intelligent evaluation techniques. • Multi-method integration of intelligent detection and evaluation techniques. • Intelligent inspection and evaluation techniques in structural design optimization, intelligent manufacturing and service safety applications. • Artificial intelligence for iNDT&E. • Structure design and iNDT&E. • Intelligent manufacturing and iNDT&E. • Structural health inspection. • Life assessment using iNDT&E.

Comparison of Results from ChatGPT and Hand Calculation in Bridge Design

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This study examines the comparison between results obtained from ChatGPT, an advanced AI-based conversational tool, and traditional hand calculations in structural design. For the hand-calculation, industry standard software such as MS-Excel and MathCAD templates were utilized. Structural engineering often requires precise calculations for designing safe and efficient structures, making accuracy a critical factor in evaluating computational tools. The research focuses on key design parameters such as computation of moment of inertia, live load analysis, bending stress computation at mid-span, and quantity take off using a benchmark example of through plate steel girders and rolled beam section for a railway bridge. ChatGPT was employed to simulate calculations based on standardized design codes, including AREMA guidelines, and its outputs were validated against detailed hand-calculated results. The comparison considered computational accuracy, time efficiency, and usability. Results showed that ChatGPT could effectively provide preliminary design insights, achieving a high degree of accuracy when interpreting and applying design codes. However, limitations were observed in cases requiring complex iterations, geometric customizations, or non-standard conditions. Hand calculations demonstrated superior adaptability to unique design constraints, though they required significantly more time and effort. The findings highlight ChatGPT's potential as a valuable supplementary tool for engineers, offering rapid estimations and error-checking capabilities while emphasizing the continued need for traditional methods to address project-specific nuances. This study underscores the integration of AI tools in structural design and their implications for improving workflow efficiency and decision-making in engineering practices.

Keywords: Railway Bridge, AI, ChatGPT, AREMA

15 **Ultrasonic 3D scanning detection technique embedded with intelligent evaluation and its applications**

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The traditional ultrasonic two-dimensional (2D) scanning technology can no longer meet the inspection requirements of diverse structures, products and components with complicate geometric shape in modern industrial production and manufacturing. In many fields, complex structures are an important direction for expanding the engineering application of composite and metal materials. Currently, various complex composite and metal structures have been designed and adopted in fields such as aerospace, transportation, and energy. For complex composite and metal material structures applied in engineering, their notable characteristics are complex geometric shapes, usually featuring multiple curvatures and variable thicknesses, diverse internal material structures, complex forming processes, and complex temperature fields and thermodynamic behaviors formed within the materials during their thermal processing. Compared with simple-shaped composite and metal material structures, complex structures have a significantly higher risk in inducing defects or damage, are prone to causing quality problems in their manufacturing, and the cost resulting from scrapping due to quality issues will also be higher. Therefore, it is usually required to conduct a 100% non-destructive testing (NDT) on complex composite and metal structures. Ultrasonic scanning inspection is currently an important NDT method widely adopted for complex composite and metal structures. This ultrasonic scanning method requires sound waves to be incident perpendicularly on the surface of structure to be tested in order to achieve the best testing effect and the ability to detect defects or damages. On the one hand, due to the complexity of the ultrasonic signals from the interior of complex composite and metal material structures, they will interfere with defect discrimination. On the other hand, during the ultrasonic scanning process of complex composite metal material structures, it is often difficult to accurately obtain the ideal vertical incident direction of ultrasonic waves for each local detection position, which in turn affects the reception and quality of ultrasonic signals, resulting in difficulty in the adoption of traditional 2D ultrasonic scanning methods and detection technologies. It will significantly affect the accurate discrimination and evaluation of defects in the complex composite and metal materials by traditional 2D ultrasonic scanning methods and detection technologies. It is also difficult to conduct automatic ultrasonic scanning detection of complex structures by using the traditional 2D ultrasonic scanning technology. The application of ultrasonic three-dimensional (3D) scanning detection and intelligent evaluation technology is the main direction that can achieve accurate and reliable quantitative detection of high-value complex composite and metal material structures. This paper proposes an AI-based ultrasonic 3D scanning detection technique for complex composite and metal structures. It can select high-resolution, symmetrical-frequency and asymmetrical-frequency ultrasonic modes according to the acoustic attenuation behavior in the detected complex structures to obtain the best ultrasonic detection effect and defect detection ability. An industrial-level

multi-mode ultrasonic 3D scanning detection system suitable for complex composite and metal material structures has been developed. Through the planning of ultrasonic 3D scanning trajectories for complex structures and simulation based on real-machine, the accurate control of the incident direction of sound waves is achieved, and the optimal incident direction of sound waves at each local detection position is obtained to ensure the high-quality reception of ultrasonic signals. A 3D ultrasound imaging method was constructed, and the corresponding industrial-level 3D ultrasound imaging and analysis software was developed to realize the 3D evaluation of ultrasound test results. An object-oriented industrial-level intelligent evaluation algorithm and software have been established. Through deep learning in ultrasonic data, the intelligent evaluation of ultrasonic testing results has been achieved. The actual detection results show that the multi-mode ultrasonic 3D scanning method can achieve the visual automatic detection of complex structures, significantly improving the ultrasonic automatic detection ability and detection effect of complex structures. Based on the established ultrasonic deep learning method, the efficiency of evaluating ultrasonic testing results and the accuracy of defect detection have been greatly improved. For the actual detection and verification of 105 actual internal preset defects located at different depths and positions of abnormally complex composite structures using the developed industrial-level multiple-mode ultrasonic 3D system and intelligent software MiaVisual 4.0, both the detection probability and the intelligent recognition probability are reach to 100%.

Keywords: Ultrasonic 3D scanning, Complex structure, Intelligent evaluation, Deep learning

Object-oriented visual intelligent testing and evaluation techniques and its application

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With the large-scale application of composite materials, metal materials and their welding and other joint structures in numerous industrial fields, the safety and health issues of material structures have generally attracted attention. For material structures, welding and joint structures, defects or damages that exceed the design standards or requirement are important factors affecting the health, service life and safe life of such structures or products. It is particularly important to detect and find out the unacceptable defects and damages inside material structures in a timely manner by using advanced non-destructive testing and evaluation (NDT & E) techniques. Based on this point, technical reinforcement measures can be taken timely, safe health decisions can be made, and corresponding maintenance and repair reinforcement repairs can be carried out. In severe cases, replacement countermeasures also need to be made. Generally, the reinforcement strategy is closely related to the inherent characteristics of material structure and its load-bearing requirements. Take the composite structure as an example. Due to the relatively complex internal fiber lay-up structure, there are a large number of fiber-resin and layer-lay-up interfaces. Under the load-bearing and force-bearing environment, these interfaces are often the zones where defects or damages are most likely to occur and expand. Some defects or damages may appear and develop at a interlayer interface. Some defects and damages may expand at the fiber-resin interface. For joint structures such as welding, cracks or damages usually occur and spread most easily at the joint zones. Some defects and damages may also have complex three-dimensional distribution characteristics. Different defects and damages have significantly different degrees of impact on the material structures and the performances, health and safe service of structural products. In terms of detection signals, the signals from defects or damages may also be intertwined with those from the internal structure of the material, making it difficult to accurately identify and detect defects /damaged in the case of relying on the limited knowledge and experience of the inspectors. This, in turn, will bring risks to the safe use and life prediction of the material structures. This paper proposes an intelligent non-destructive testing and evaluation (iNDT&E) method for material structures based on the principle of deep learning and not relying on a large number of defect or damage annotation cases. Based on the principle, an object-oriented industrial-level visual multiple-intelligent analysis system, called Mia Visual 4.0, has been developed. The application scenarios and main scientific problems existing in the non-destructive testing and health detection of material structures by intelligent detection and evaluation technologies were analyzed. Combined with the development and application requirements of Industry 4.0, this paper reviews the development progress and main characteristics of iNDT&E Mia Visual 1.0 to Mia Visual 4.0, the key technical problems solved by Mia Visual 4.0, and its practical effects achieved. From the perspectives of material structure and the

entire product life cycle, the top-level design architecture, technical modules, main functions and features of the object-oriented industrial-level iNDT&E system Mia Visual 4.0 are introduced. Taking detection methods such as ultrasonic, CT, DR, optic, magnetic, penetrant, and infrared testing methods as examples, the application effect and potential of the industrial-level iNDT&E system Mia Visual 4.0 in aspects such as the design, manufacturing, mass production, service, repairs, health management, and life prediction of material structures and products were presented in this paper. The practical application results show that: Based on AI, through object-oriented forward machine learning and deep learning, by creating the object-oriented industrial-level iNDT&E system Mia Visual 4.0 and developing the ultrasonic, CT, DR, optic, magnetic particle, penetrant, and infrared inspection equipment, It can visually detect and intelligently test and evaluate material structures from two-and three-dimensional views as well as multi-scale dimensions, greatly improving the accuracy and efficiency of non-destructive testing and health monitoring of material structures and their products, significantly reducing testing costs, and greatly enhancing the working comfort of testing personnel. In particular, integrating and embedding the data output of the iNDT&E system with the entire life cycle of material structure research and development, production, and service can fully connect with Industry 4.0 and the health and safety management of the entire product life cycle, enabling the detection data and intelligent evaluation results to achieve the greatest value-added effect throughout the entire life cycle of material structure research and development, production, and service. At present, it has been well applied in the 3D visualization detection and intelligent evaluation of various material structures, supporting the iNDT&E of ultrasonic, CT, DR, optical, magnetic particle, penetrant, infrared, eddy current, electromagnetic and physical and chemical data.

Keywords: Intelligent nondestructive testing and evaluation, Health monitoring Deep learning, Ultrasonic testing, X-Ray testing, Optical testing

The detection and intelligent evaluation of SiC/SiC composites using multi-method fusion

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Since the low density, high resistance and high temperature resistance of SiC/SiC ceramic composite (SMC), it becomes the key material of the aerospace hot-end component, but its complex preparation process is prone to induce defects such as pores, cracks and layers, which seriously affect the performance and structure of SMCs. So, it usually requires to perform an accurate and reliable detection and quantitative evaluation on SMCs in order to find out different scale defects in SMCs. It is difficult to reliably detect and find out all the defects with different scales in SMCs by using a single non-destructive testing method. This paper proposes a detection method that integrates multiple methods. SMC specimens containing different artificial defects were fabricated. The defects include flat-bottom holes of different diameters ($\Phi 1$ mm to $\Phi 9$ mm in diameter) and depths (0.2 mm to 2.5 mm), as well as flat-bottom groove defects with different depths (0.2 mm to 2.6 mm). The experimental research on multi-method fusion of digital X-ray (DR), infrared thermal imaging and ultrasonic testing was carried out. The detection capabilities of different scale defects in the SMC specimens using the fusion of the three methods were evaluated experimentally. The defect imaging features and defect recognition capabilities from the different detection methods were analyzed. The test results show that the DR method can detect and clearly display the differences in size, location and depth of different defects, and has a strong ability to distinguish the size of defects. Infrared thermal imaging detection is relatively sensitive to surface and subsurface defects, and groove defects. It can detect the areas with abnormal temperature on the surface and near the surface of the sample. The ultrasonic transmission method can detect the $\Phi 9$ mm flat-bottom hole defect in the sample relatively well, and the defect contour is displayed clearly, with a high positioning accuracy of the detected defect. However, the ultrasonic attenuation in the SMCs is relatively large. Its detection ability to minor defects decreases when using a low ultrasonic frequency. The three detection methods each have their advantages in the detection of artificial defects in the SMCs. The combined use of the three methods can achieve full coverage detection of defects with different types and depths. Based on deep learning, intelligent evaluation of defects can be achieved by using Mia Visual 4.0. Thus, it provides comprehensive non-destructive testing and intelligent evaluation methods for SMCs.

Keywords: SiC, SiC composites, X-ray testing, Ultrasonic testing, Infrared testing, Intelligent evaluation

Thin concrete crack quantification using deep learning assisted with information fusion and super-resolution

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In civil engineering, concrete remains the most widely used construction material, and detecting cracks is vital for assessing structural health and estimating service life. Traditional crack detection methods, which largely rely on manual visual inspections, are often complex, time-consuming, susceptible to human error, and carry potential safety hazards. Recently, crack detection approaches leveraging computer vision (CV) technologies have gained attention as a promising alternative, particularly pixel-level crack segmentation methods driven by deep learning. Nevertheless, real-world concrete cracks are typically extremely fine—often less than a millimetre wide—posing challenges for conventional deep learning models due to the limited pixel representation in images. Moreover, relying on a single data modality provides inadequate information, hindering the model’s ability to extract meaningful features. To overcome these obstacles, we propose a multimodal information fusion network that combines image super-resolution and segmentation for precise crack detection. Our method focuses on fusing RGB and depth data specifically for crack segmentation applications. Additionally, we incorporate image super-resolution techniques to enhance the input resolution, enriching pixel-level details before performing segmentation, thereby improving detection accuracy. Comprehensive experiments on our self-developed crack dataset show that the proposed approach outperforms existing state-of-the-art (SOTA) models.

Keywords: Crack quantification, Concrete structure, Crack segmentation, Feature fusion, Deep learning, Transformer

State of the Art in Practical Approach of Image-Based Deep Learning

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Cracks in structural elements present significant threats to structural integrity and can lead to catastrophic failures if left undetected or unaddressed. Traditional methods of crack detection primarily depend on manual inspections, which are inherently time-consuming, labour-intensive and prone to human error. To overcome these limitations, there has been a growing emphasis on the development of automated crack detection systems. The emergence of Machine Learning (ML) and Deep Learning (DL) technologies has facilitated a paradigm shift toward automated approaches, offering improved accuracy, efficiency and reliability. This review paper provides a comprehensive analysis of existing methodologies for crack detection and segmentation utilizing ML and DL techniques. It begins by discussing the fundamental principles of crack detection and the challenges associated with conventional inspection methods. The paper then examines prominent ML and DL algorithms, including Random Forest (RF), Convolutional Neural Networks (CNN), Support Vector Machines (SVM) and Recurrent Neural Networks (RNN). A comparative analysis of approximately 100 technical and review articles is presented, with methodologies categorized according to classification, detection and segmentation approaches. Key findings include the Visual Geometry Group (VGG-16) model achieving an accuracy of 99.83%, the Fully Convolutional Network–Region-based Convolutional Neural Network (FCN-RCNN) and U-shaped Encoder-Decoder Network (UNET) achieving accuracies of 99.52% and encoder-decoder architectures exhibiting up to a 25% improvement in performance. Furthermore, CNN-based techniques applied to vibration-based damage detection have demonstrated accuracies as high as 99.9%, even under noisy conditions.

Keywords: Deep Learning, Crack Detection in Concrete, Convolutional Neural Network, Computer Vision

A Hybrid Deep Learning Framework for Crack Detection and Semantic Segmentation of Concrete Surface

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In concrete structures, automatic detection of surface cracks is vital for timely maintenance and safety assurance. In this paper, a two-stage framework is proposed for concrete crack detection and semantic segmentation. At first, a convolutional neural network is developed and trained to classify concrete surface images into cracked or non-cracked categories. Subsequently, segmentation is performed to precisely localise and identify the cracked regions. To benchmark this approach, we further investigate its performance toward a transfer learning strategy. In this regard, UNet is implemented as a feature extractor, and it is combined with classical machine learning classifiers including support vector machines and random forests. The developed methods are used to analyse a concrete crack dataset with standard metrics such as intersection over union and F1-score. Results demonstrate that end-to-end deep learning segmentation can provide high accuracy and localisation capability. However, hybrid approaches leveraging UNet features with traditional classifiers offer competitive performance with reduced training overhead. The findings showcase the strengths and limitations of pure deep learning toward hybrid transfer learning methods for concrete crack detection. It provides insights for practical deployment in structural health monitoring systems.

Keywords: crack detection, semantic segmentation, machine learning, support vector machine, random forest

Novel Backpropagation Neural Network Approach for Predicting Impact-Induced Failure Modes in CFRP-Wrapped Reinforced Concrete Structures

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The theoretical analysis of the impact response of reinforced concrete wrapped by Carbon Fiber Reinforced Polymer (CFRPRC) is complex, involving strain rate effects, inertia forces, stress wave propagation, nonlinear material behavior, and CFRP confinement. These factors pose significant challenges for structural engineers in evaluating and improving CFRPRC impact resistance. In this study, a Backpropagation (BP) neural network was utilized to predict CFRPRC failure modes (global bending, cracking, and fracture) under transverse impact. A dataset of 222 impact samples was compiled using an equivalent spring-mass model, with 80% of the data used for training and 20% for evaluating model generalization. The BP algorithm was detailed, revealing that a linear transfer function simplifies regression for crack and fracture deflection, while a sigmoid function is optimal for maximum deflection. Empirical equations derived from weights and biases achieved a prediction accuracy of 92.98% for failure modes. The first-order second-moment method was employed to estimate the probability of damage modes and their reliability. Results indicate that the thickness and tensile strength of CFRP are critical for enhancing the fracture reliability of CFRPRC under both low- and high-energy impacts. This approach provides a precise and efficient method for predicting CFRPRC impact behavior and guiding reinforcement strategies.

Keywords: CFRPRC Impact Response, Backpropagation Neural Network, Failure Mode Prediction, Carbon Fiber Reinforced Polymer, Reinforced Concrete, Structural Reliability

Practical Optimization through Surrogate Stacking: Navigating Compute Budgets and Data Scarcity

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Structural optimization of warehouse frames is challenging due to data scarcity, high computational costs (each cloud-based FEA evaluation requiring 1–4 minutes), and complex nonlinear relationships between building geometry and structural compliance. Traditional optimization methods, such as genetic algorithms or particle swarm optimization, typically require 500–2000 FEA evaluations, making them prohibitive for practitioners with limited computational budgets. While surrogate-based approaches can reduce this to 40–200 evaluations, commonly used surrogates perform poorly with sparse, noisy data, creating another barrier for practitioners.

We propose a novel surrogate stacking approach for Bayesian optimization that hierarchically combines three complementary models: (1) a neural network trained on a small (1800 training examples) simplified synthetic dataset to capture global nonlinearities, (2) a decision tree to adaptively learn local behavior, and (3) a Bayesian linear regression to provide probabilistic estimates with uncertainty quantification, which is most accurate for near-linear relationships. An adaptive threshold mechanism balances exploration and exploitation, progressively filtering designs toward regions where this linear approximation is valid.

Tested across 10 warehouse designs (each with several million design configurations), our method identified solutions within $1.25\% \pm 1.75\%$ of the optimal structural weight (ground truth established by an independent structural engineer) using only 15 ± 6 FEA evaluations. This hierarchical filtering architecture demonstrates significant efficiency gains while maintaining solution quality, providing practitioners with a computationally feasible approach to structural optimization under severe resource constraints.

Keywords: structural optimization, surrogate models, Bayesian optimization, computational efficiency, data scarcity, machine learning

63 **Computer vision-assisted framework to enhance rapid seismic risk assessment of corroded existing RC bridge piers**

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This work introduces an innovative AI-supported methodology for the rapid seismic assessment of reinforced concrete (RC) bridge piers affected by corrosion at the base, as typical degradation process in aging infrastructure. The approach aims to consider the current state of piers corrosion by leveraging computer vision techniques combined with probabilistic structural analysis to evaluate the influence of corrosion-induced degradation on seismic performance. The methodology is based on the definition of a tailored convolutional neural network (CNN), enhanced with attention mechanisms and advanced color space pre-processing, designed to automatically assess corrosion severity from photos. The output of classification represents the input of a probabilistic deterioration model that maps damage on steel reinforcement, which allows to update mechanical properties such as yield strength, ultimate strength, and ductility of both steel and confined concrete. The workflow includes geometric characterization, AI-based visual inspection, probabilistic structural modelling and nonlinear time-history analyses. From numerical simulations, fragility curves are derived and used to compute the Mean Annual Frequency of Exceedance (MAFE) for different damage states, allowing a direct comparison between pristine and corroded conditions. Results on a case study highlight that corrosion significantly increases seismic fragility and risk. The framework demonstrates also that computer vision can enhance fast seismic risk assessment approaches, supporting data-driven maintenance prioritization and life-cycle management of civil infrastructures.

Keywords: Computer Vision, Corrosion Detection, Reinforced Concrete, Bridge Piers, Seismic Risk Assessment

A Hybrid Deep Learning and Clustering Approach for Optimal Sensor Placement in Structural Modal Monitoring 72

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Accurate structural health monitoring (SHM) requires optimal placement of sensors to effectively capture modal properties while minimizing measurement redundancy. However, solving this high-dimensional combinatorial problem is computationally intensive when considering all possible node combinations. This paper introduces a hybrid methodology that combines deep learning-based nonlinear dimensionality reduction with clustering and genetic algorithms to identify optimal sensor configurations. An autoencoder is trained to extract latent representations of mode shapes, followed by K-means clustering to reduce the candidate degrees of freedom based on modal energy. A multi-objective genetic algorithm is then applied to minimize the off-diagonal elements of the Modal Assurance Criterion matrix while maximizing sensors' displacement amplitude. The proposed framework is validated on a finite element model of the Moletta tower. Results show that this approach reduces the search space significantly and identifies sensor locations that maximize mode shape independence and energy capture. Parametric studies reveal that a sensor configuration with five distinct nodes achieves a MAC off-diagonal sum of 0.96 and a displacement amplitude of 5.77 cm, representing an optimal trade-off. The Pareto front further demonstrates the inverse relationship between displacement sensitivity and modal correlation, offering a flexible decision tool for real-world SHM design.

Keywords: Optimal Sensor Placement, Modal Assurance Criterion, Genetic Algorithm, K-Means Clustering

Physics-Informed Machine Learning for FRP-Confined Cylinders: Bayesian-Optimized Hybrid Framework Bridging Empirical Models and Robotic Applications

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Existing empirical models for FRP-confined concrete columns exhibit limited accuracy in ultimate performance prediction due to complex material interactions and small-sample constraints. This study proposes a physics-informed machine learning (PIML) framework that synergistically integrates axial constitutive theory into ensemble learning models through three key innovations: (1) Embedding physical stress-strain equations into XGBoost/RF loss functions with Lagrangian multipliers, (2) Implementing Bayesian hyperparameter optimization with k-fold cross-validation for enhanced generalization, and (3) Deriving explicit equations compatible with robotic field applications. Validated on 310 specimens, the optimized XGBoost model achieved 47.7% RMSE reduction and 32% uncertainty decrease versus 8 empirical benchmarks, while the physics-derived formula maintained <10% error across 85% test cases. Parameter importance analysis identified $\sigma_{h,rup}$ (32%), σ_f (29%), and f_l (12%) as dominant factors, physically consistent with FRP failure mechanisms. This work establishes an interpretable hybrid paradigm advancing intelligent design of composite structures.

Keywords: Partially confinement, Physics embedded ML, Bayesian hyperparameter, Robotic construction

Balancing Real and Synthetic Data for CNN-based Masonry Crack Detection

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Cracks are a critical indicator of building health, and early stage identification is fundamental to prevent harmful damages. Advances in deep learning (DL), particularly convolutional neural networks (CNNs), have enabled scalable solutions for automated crack detection. However, CNN performance strongly depends on the availability of large and diverse datasets, which is particularly challenging for complex surfaces such as masonry. Collecting sufficient real data is often time-consuming, while publicly available datasets may not be adequate. To address this limitation, we explored generating synthetic crack data, which complements real data and improves training effectiveness. The real dataset consists of masonry crack images collected from buildings in Bologna and surrounding areas. In contrast, the synthetic dataset was generated using a custom tool that adds cracks to background images in a controlled orientation and placement. The two datasets were used to train several U-Net architectures, to identify the best-performing model (InceptionV4) for experiments with generated data. Six training scenarios were tested in InceptionV4 by varying the ratio of real and synthetic data, with evaluation performed on a test set composed of real images using the F1-score metric. Results show that training on synthetic data yields poor performance, but a modest addition of 20% real data achieves results comparable to training on real data only. Moreover, the 20/80 scenario (synthetic/real) achieved an almost 80% F1-score, outperforming the real-only case. As can be seen, the method demonstrates the potential of synthetic data to reduce collection efforts while enhancing crack detection accuracy.

Keywords: Crack Detection, Crack Segmentation, Synthetic data generation, Deep Learning

105 **Ductile-Fragile Transition: A Novel Comparison Between
Fracture Mechanics of Materials and Framed Structures**

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This paper deals with the issue of structural collapse considering an analogy between ductile-brittle transition of materials, taking into account the current literature which also considers the number of fragility and the stress intensification factor in the presence of crack, with extension on a larger scale involving framed structures subjected to increasing vertical loads. It is evaluated the ductile-fragile transition in relation to concrete frames with different structural hierarchy (2x2, 5x5, 11x11).

Keywords: Structural Mechanics, Fracture Mechanics, Materials, Robustness

Next-generation structural health monitoring automation: an AI-powered framework incorporating modal analysis, dual-stage damage verification, and localization

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Structural health monitoring (SHM) is critical for resilient infrastructure, yet conventional methods remain hindered by environmental sensitivity, scalability limitations, and dependence on expert interpretation. This work introduces a fully automated, AI-driven SHM framework that unifies adaptive modal identification, environmentally robust anomaly detection, and sensor-level damage localization in a single pipeline. Modal parameters are extracted via a novel hybrid approach fusing time-domain covariance-driven stochastic subspace identification with frequency-spatial domain decomposition, enhanced by three key automation innovations: (1) adaptive frequency-band allocation, (2) unsupervised pole selection using isolation forests, and (3) prominence-based peak detection—ensuring robust, expert-free modal estimation. Anomaly detection employs a conditional variational autoencoder trained exclusively on healthy-state natural frequencies, conditioned on temperature and time-of-day to isolate structural anomalies from environmental effects. Gaussian intersection thresholds enable quantitative classification into four health states (healthy to critical), eliminating subjective thresholds. A secondary verification stage combines singular spectrum analysis (SSA) with 3D one-class support vector machines at the sensor level, independently confirming anomalies and generating high-resolution damage maps. Validated on a laboratory steel beam with 10 triaxial MEMS accelerometers across 500 hourly tests under diurnal thermal cycles and progressive damage scenarios, the framework achieves limited false positives, maintains detection accuracy under varying conditions, and precisely localizes damage. A practitioner-oriented interface ensures deployability, demonstrating a scalable pathway for AI-powered SHM in real-world infrastructure.

Keywords: Structural health monitoring, Automated damage detection, Machine learning, Operational modal analysis, Autoencoder neural network, Singular spectrum analysis

Performance Comparison of Machine-Learning Approaches to Tension Force Estimation for Cables with Non-Negligible Bending Stiffness

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As bridges with stay cables or external post-tensioning tendons near the end of their service life, there is growing interest in assessing their structural performance to ensure compliance with current safety and operational standards. This is particularly important as these elements are susceptible to stress corrosion and fatigue. For this reason, considerable research has focused on non-destructive testing (NDT) techniques for evaluating cables. Among these, vibration-based systems aim to estimate key performance parameters, such as natural frequencies, tension forces, and bending stiffness, using acceleration data recorded from the structure. Of these, the tension force of cables is the principal parameter to be assessed, as it is essential for bridge performance and safety during both the tensioning process and service life. Furthermore, the degradation mechanisms directly affect the tension force. This parameter is usually inferred indirectly from measured natural frequencies, cable length, and linear density, while assuming idealised boundary conditions within analytical models with closed-form solutions. A major challenge arises when estimating tension accurately under general boundary conditions, since no closed-form solution exists for the partial differential equation, leading to an optimisation problem that is impractical to solve without simplifications in in-line applications. A promising alternative involves training machine-learning models on the dynamic behaviour of cables. These models can provide accurate estimations while reducing reliance on restrictive assumptions. This study compares several regression methods in terms of estimation accuracy, required inputs, and training time, using evaluation metrics to measure error and correlation.

Keywords: Cables, Tension force estimation, Machine-learning-based models

Development of an Autonomous LLM-Based Agent for Fatigue Analysis of In-Service Bridge Reinforced Concrete Slabs Using FEM

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This study investigates the development of an autonomous agent capable of conducting finite element method (FEM) analyses. The agent is designed to perform fatigue analysis of in-service road bridge reinforced concrete (RC) slabs. It covers tasks such as mesh generation and the setting of boundary and loading conditions, triggered by simple textual instructions from the user. Conducting nonlinear FEM analyses typically requires expert-level knowledge and experience, especially for tasks like generating appropriate meshes and the setting of boundary and loading conditions. These processes are often labor-intensive and represent a barrier for non-experts. The proposed method addresses this challenge by enabling a large language model (LLM)-based agent to perform these steps autonomously, significantly reducing the manual effort required. To achieve this functionality, we employed LLMs with tool-use capability and implemented a suite of tools, including those that retrieve in-service bridge specifications from a national road-bridge inspection database and those that estimate wheel load positions. By orchestrating these tools, the LLM autonomously determines the parameters required for fatigue analysis. This study indicates that LLMs with advanced tool-use and strong reasoning capabilities can automate complex tasks such as FEM-based fatigue analysis of RC slabs. With slab fatigue emerging as a serious problem in Japan, the proposed agent offers an effective approach to reducing the effort of fatigue analyses for RC slabs while making such simulations accessible to non-experts in numerical analysis. It also contributes to digital-twin-based infrastructure management through virtual scenario testing, extending service life and reducing life-cycle material use and emissions.

Keywords: Large Language Models, Multi-scale Simulation, Fatigue Loading, Road Bridge Decks

A new Eddy Current Thermography procedure applied via Machine Learning to the assessment of reinforced concrete elements

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Infrared Thermography (IRT) is a non-invasive technique used to detect and visualize surface temperature distributions. Passive IRT is commonly applied in the inspection and diagnostics of existing structures. Eddy Current Thermography (ECT), an active method combining eddy current excitation with thermal imaging, is typically used to detect flaws in conductive materials. Its application to reinforced concrete (RC) elements remains largely unexplored. Identifying reinforcement layout is a key and time-consuming task in structural assessments, usually performed with covermeters or Ground Penetrating Radar (GPR). This research investigates the feasibility of using ECT to detect rebar location, size, and cover depth in RC elements, and whether it offers advantages over traditional methods. The approach involves solving an inverse problem using time-domain IRT data, where rebar heating is induced by eddy currents. A custom-built device was developed for this purpose. Initial experiments combine numerical simulations and Pattern Recognition (PR) techniques. A finite element (FE) model of an RC sample was subjected to multiphysics analysis to simulate transient heat transfer from an inductive source. Thermograms were collected over time and space to build the input dataset. A Principal Component Analysis (PCA) was then trained to correlate thermographic data with rebar characteristics such as position and diameter.

Keywords: Reinforced Concrete, Infrared Thermography, Eddy Currents, Pattern Recognition, Principal Component Analysis

SS10 - Artificial Intelligence for Sustainable Seismic Risk Reduction of Structures.

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The dramatic seismic events occurred in Italy in past 15 years have clearly highlighted that reconstruction and restoration costs of large territories are unsustainable by the governments. Also, cities downtime for reconstruction has a dramatic societal impact, such as depopulation and disaggregation of social tissue. To mitigate the effects of these catastrophic events, the only known way is the prevention by reduction of seismic risk. This is intended as a diffuse incentive for reinforcement and retrofitting of buildings and infrastructure, to bring seismic risk below acceptable thresholds. However, a diffuse seismic risk reduction still would involve significant costs and downtime and also a massive employment of raw material with consequent harmful environmental impacts. This special session is joint with the Project of National Relevant Interest PRIN 2022 AI-SUST (<https://www.prin2022aisust.it/>) which gathers all these aspects, proposing a breakdown way of facing the issue through the aid of artificial intelligence (AI) techniques. The idea developed in this research project is to bring artificial intelligence techniques to become a real aid to the current strategic decision processes (what to do and where). The topics addressed in this special session aim at implementing an artificial intelligence architecture supporting users (engineers and public administrators) in designing sustainable and strategic seismic retrofitting interventions to protect structures and infrastructures against the consequences of earthquakes. Contents of interest include, but are not limited to, the following arguments: • Artificial intelligence methods for sustainable seismic risk reduction of structures • Evaluation of Retrofitting solutions • Dynamic Identification of structures under earthquake scenarios • Computational Intelligence methods for Earthquake Design, retrofitting, and safety assessment of structures • Sustainability in regional scale seismic risk reduction policies supported by intelligent systems

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Early-stage Automated Seismic Retrofitting Using Graph Neural Networks and Evolutionary Algorithms in a BIM Environment

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Selecting a seismic retrofitting design is often constrained by the choice of reinforcement methods, time limitations, and overall cost, which can result in nonoptimal solutions. To address this, the present study introduces a framework for optimizing seismic retrofitting of existing reinforced concrete buildings during early assessment stages. The approach aims to enhance structural performance by optimizing the addition of shear walls and proposing new sections for existing columns, thereby defining the necessary jacking configuration to achieve target performance. The process begins with the extraction of existing structural elements from an IFC-based digital twin, which are then converted into a graph representation and evaluated using a pre-trained graph neural network (GNN) to rapidly estimate seismic performance. Based on this, candidate retrofitting designs are generated and assessed using a multi-criteria objective function that includes code compliance, hand-engineered rules, and GNN-based performance predictions. An evolutionary algorithm is used to optimize these candidates by improving seismic performance while minimizing material use which serves as a cost indicator. Results shows that the proposed framework identifies retrofit configurations that meet performance target successfully while reducing the cost indicator. Moreover, the integration of GNN predictions within the optimization loop enabled rapid performance feedback, allowing for broader design space exploration within practical time constraints. Finally, the framework is integrated within a BIM environment to help early-stage decision-making and provides a visual tool not only for engineers, but also for architects, project managers, and other decision makers implicated in the project.

Keywords: seismic retrofit, digital twin, GNN, BIM

Integrating Numerical Simulation and Machine Learning for Enhanced Understanding of Uncertainty Propagation in RC Frames

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This study investigates the complex propagation of uncertainties through structural systems, a fundamental challenge within the context of defining robust reliability-based global factor. Leveraging numerical simulations on RC frames modelled in OpenSeesPy, the research initially explores how various local uncertainties influence the global structural system behaviour. These local sources encompass variability in material properties, their statistical correlation (considering diverse scenarios, including full and zero correlation), and their spatial distribution patterns across the structure (such as identically distributed (ID) and non-identically distributed (NID) random variables). The primary output metric characterizing global uncertainty is the Coefficient of Variation (COV) of the system's response. While sensitivity analyses derived from these simulations quantify the impact of local assumptions and contribute significantly to understanding underlying uncertainty mechanisms, the insights often remain specific to the simulated scenarios. To achieve broader generalization and derive explicit functional relationships, this research integrates Artificial Intelligence. We employ Symbolic Regression (SR), a specialized machine learning technique, applied directly to the rich dataset generated from the NLA results correlating local input uncertainties with the global response COV. The SR algorithm autonomously seeks to discover a concise, potentially physically meaningful analytical formula that accurately maps these input local uncertainty parameters to the predicted output global response COV. This AI-driven methodology aims to transform complex simulation outputs into a transparent, interpretable mathematical model for uncertainty propagation, offering enhanced practical guidance for structural design, reliability assessment, and providing a direct avenue for the calibration of global safety factors.

Keywords: Structural Reliability, Machine learning, Symbolic Regression, Correlation among random variables, Identically Distribute (ID) and Non-Identically Distributed, NID) random variables

Estimating Debris Extent From Structural Collapses Using Machine Learning Techniques

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After an earthquake, damaged buildings generate extensive debris that pose significant challenges for emergency response and long-term restoration efforts. Managing the debris extent is critical since it can obstruct roads, delay rescue operations, and hinder recovery activities. Despite its importance, there is no widely established physics-based or analytical solution to estimate its extend after a seismic event. This study addresses this gap by utilizing machine learning techniques to develop a data-driven framework for debris estimation. First, a comprehensive database of images is compiled based on the existing data from previous earthquakes. Then, a straight forward image processing technique is implemented to quantify debris extents. several features, reflecting structural attributes and seismic event characteristics, were identified to train predictive models. After the feature engineering phase, different machine learning algorithms including, artificial neural networks, support vector regression, k-nearest neighbors, decision trees, random forest, and extreme gradient boosting were trained and optimized. Comparative analyses of the trained models were conducted using different accuracy parameters such as, mean squared error, and mean average error. The best model is then applied to a case study to estimate the road blockage and its effect on the resilience of cities after an earthquake. Results demonstrate the potential of machine learning tools to handle the complexities in debris estimations, providing valuable insights for urban-scale applications.

Keywords: Debris extend, earthquake damage, machine learning, image processing, resilience

55 **Preliminary results of the Bridge Risk Identification with
Data-driven Geospatial Evaluation (BRIDGE) project**

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The first edition of the Poli Hack Days was organised on November 15, 2024, to catalyse the creativity of Politecnico di Torino's young researchers and to generate innovative solutions stemming from different scientific backgrounds. In this context, the awarded Bridge Risk Identification with Data-Driven Geospatial Evaluation (BRIDGE) project combines expertise in Mathematical Sciences with Management, Environmental, and Structural Engineering. By employing satellite Interferometric Synthetic Aperture Radar (InSAR) data and environmental parameters with Deep Learning (DL), the project presents a novel approach to data-driven early warning systems, designed to identify the risk of bridge collapses due to hydrogeological causes. By implementing and tuning the DL model through a hyperparameter search, a prototype software capable of real-time risk assessment from InSAR time series was achieved, showcasing how scalable, low per-site cost, and proactive Structural Health Monitoring (SHM) can be performed with remote sensing (space-borne data), when coupled with Artificial Intelligence (AI) and environmental information

Keywords: Bridge Monitoring, Deep Learning, InSAR, Early Warning Systems, Artificial Intelligence, Structural Health Monitoring

Multi-Objective Optimization of Honeycomb Lattice Steel Dampers for Lightweight and Seismic-Efficient Design

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This study proposes a multi-objective optimization method for honeycomb lattice steel dampers, focusing on weight reduction and improved seismic energy dissipation. A surrogate model is developed using design of experiments (DOE) to approximate seismic performance and reduce computational demands. Based on this model, optimization is conducted via the non-dominated sorting genetic algorithm (NSGA-II), yielding a Pareto front that captures the trade-offs between key design parameters while satisfying target internal force requirements. Finite element analyses are performed on selected solutions to validate performance and modeling accuracy. The optimized dampers achieve approximately 30% material savings compared to conventional steel rod dampers, with no loss in seismic efficiency. Additionally, the framework allows for inverse design to match specific internal force demands, offering practical utility for performance-based damper development.

Keywords: honeycomb, multiobjective optimization, finite element analysis, seismic energy dissipation

Machine Learning for Shear Capacity Prediction of Hollow-Core RC Bridge Piers

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Rectangular hollow-core reinforced concrete (RC) piers are common in modern bridge design due to their efficiency and cost-effectiveness, but predicting their shear capacity remains challenging due to complex parameter interactions. This study presents a machine learning (ML)-based approach to improve shear strength prediction using a dataset of experimental tests incorporating key structural features. Eight ML models were trained and compared to traditional analytical and code-based methods, with the XGBoost model showing superior accuracy and reduced prediction variability. Model interpretability was achieved using SHAP and Partial Dependence Plots, revealing axial load, wall thickness, and concrete strength as key contributors. An open-access graphical user interface (GUI) was also developed to support practical use. The results demonstrate the potential of ML to enhance structural design by combining empirical data with interpretable, high-performance predictive tools.

Keywords: Machine Learning, Hollow-Core Bridge Piers, Shear Capacity

Rotation-Independent Ground-Motion Framework: Data-Driven Clustering and Validation against Performance-Based Demand Metrics

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Horizontal ground-motion components and their in-plane orientation strongly influence structural demand, yet directionality has typically been handled indirectly—by analyzing components separately, rotating reference axes by prescribed angles, or correlating effects probabilistically. This study introduces a unified, orientation-robust descriptor that integrates the two Cartesian components. Using more than 2,000 motion records from the Italian and Balkan region, Peak-Polar rotation-independent ordinates (PP-RIO) have been computed as rotation-invariant maxima across all in-plane orientations, while also identifying the governing rotation and its orthogonal companion. The records have been clustered with an unsupervised algorithm to quantify directionality and underlying patterns useful for engineering applicability. In a second phase, the procedure has been implemented on a subset of more than 200 two-component records. The original orthogonal pair and versions rotated by 30° and 60°, together with the PP-RIO, define four orientation sets. For each set, performance-based nonlinear time-history analyses have been conducted, evaluating peak displacements, inter-story drift, and hysteretic energy dissipation. It is shown that PP-RIO consistently envelops orientation-dependent structural response and provides a practical basis for selecting representative rotation directions required by performance-based design and code-mandated checks. The contribution is a reproducible framework to (i) derive rotation-independent peak ordinates for any ground-motion measure and (ii) map the associated governing orientation for inelastic dynamic analysis, enabling more consistent treatment of horizontal-component interaction and directionality in seismic-demand assessment.

Keywords: Ground-motion Directionality, Rotation-Invariant Intensity Measures, Peak-Polar rotation-independent ordinates (PP-RIO), Nonlinear Time-History Analysis, Unsupervised Clustering

AI-Driven Corrosion Quantification in Cementitious Materials for Structural Health Monitoring

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The monitoring of the conservation status of cementitious composites is a fundamental step in the management of built heritage. Automating this process can provide valuable support for structural diagnostics, enabling a rapid and objective identification of critical areas.

In this study, an automated workflow for corrosion assessment on ferrocement specimens is presented.

Laboratory samples were subjected to accelerated aging to induce corrosion and subsequently documented through digital imaging. The degree of corrosion was first quantified by a MATLAB-based image analysis method, which processed the RGB color space to classify each image into one of five corrosion categories. The procedure evaluates the state of corrosion by calculating, for each sample, the percentage of corroded area on the surface, and by defining an index describing the overall extent of corrosion.

These classifications were then employed to train a deep learning model capable of predicting the corrosion class directly from the images. The proposed approach enables a rapid and objective evaluation of corrosion severity, reducing reliance on manual inspection.

Keywords: corrosion, SHM, classification

Agile Multi-Objective Optimisation of Seismic Retrofitting of Existing Buildings

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Recent earthquakes have demonstrated that many residential buildings constructed before modern seismic codes were implemented remain structurally vulnerable. While stricter codes benefit new buildings, many communities still occupy older, poorly designed structures, where demolition and reconstruction may be impractical. Seismic retrofitting of existing buildings is, therefore, a more practical approach for the safer growth of affected communities. Moreover, recent events have demonstrated that throughout the retrofitting design process, ensuring structural safety alone is insufficient; it is also essential to minimise expected losses and downtime, as well as to consider other economic and environmental factors. These challenges define a multi-objective problem that calls for optimisation approaches capable of exploring a wide range of solutions without restrictive assumptions, while maintaining practicality. To this end, this study applies a framework integrating a stochastic iterative retrofitting algorithm (SIRA) with a multi-objective optimisation procedure to a reinforced concrete infilled building. Retrofit schemes were evaluated in terms of installation cost, expected annual loss, downtime, and environmental impact, while ensuring compliance with code requirements. The results demonstrate that incorporating multiple objectives enables the identification of strategies that enhance seismic resilience, balance economic and environmental costs, and support informed decision-making for effective retrofit design. The framework achieves this without relying on restrictive assumptions, while remaining computationally efficient and suitable for broader practical application.

Keywords: Seismic retrofitting, Multi-objective retrofitting optimisation, Downtime, Seismic losses, Environmental impact

153 **Large Language Model–Assisted Inspection and Decision Support for Post-Earthquake Emergency Response**

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Large Language Models (LLMs) can accelerate data processing and decision-making in disaster scenarios. This work presents a framework that combines guided inspections, regulatory support, and analytical models—including image-based damage detection and predictive algorithms—to assist post-earthquake assessments. Collected data feed into an emergency digital twin, integrated with GIS, BIM, and Common Data Environments to ensure lifecycle traceability. Preliminary results highlight the potential of LLM-driven systems to improve coordination, efficiency, and transparency in emergency management.

Keywords: LLM, BIM, GIS

SS11 - Graphs for Structural Engineering.

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Graphs have long been used for representing complex data structures and, as such, provide a natural framework for modeling the complex properties and interactions found in civil engineering structures. The recent development of a population-based approach within the field of Structural Health Monitoring highlights how graphs can be used to model heterogeneous civil structures. Furthermore, by combining Machine Learning and Network Science, these approaches can provide a measure of similarity in structures. This special session focuses on gathering contributions in accordance with the application of graphs, networks, and associated machine learning techniques in the field of structural engineering.

Contents of interest include, but are not limited to, the following topics: • Graph Neural Networks • Graph Machine Learning • Network Science • Graph Theory • Knowledge Graphs • Graph Embeddings of civil structures • Irreducible Element models

77 **On the topology and geometry of population-based SHM:
Part II, Sheaves on graphs**

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A recent development in Structural Health Monitoring (SHM) has been the introduction of a population-based variant (PBSHM), which aims to leverage information across populations of structures in order to enhance diagnostics on those with few (or no) data. The machine-learning discipline of transfer learning provides the mechanism for this capability. One recent paper in PBSHM proposed a geometrical view in which the structures were represented as graphs in a metric ‘base space’ with their data captured in the ‘total space’ of a fibre (vector) bundle above the graph space. This geometric view was more suggestive than mathematically rigorous, although it did allow certain useful arguments; e.g., a relation between ‘closeness’ of structures and ‘closeness’ of their feature data. One bar to more rigorous analysis was the absence of a meaningful topology on the graph space, and thus no useful notion of continuity. The current paper aims to address this problem, by moving from the idea of a vector bundle to a more general sheaf over the base space; this structure has a rigorous basis but is also amenable to a discussion of transfer learning between structures.

Keywords: Population-based SHM, Transfer Learning, Cellular Sheaves

Towards AI-assisted Digitalisation of Structural Engineering Workflows

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Recent advancements in artificial intelligence (AI) open new possibilities to accelerate structural design workflows. Altering existing residential properties remains challenging as engineers must make critical decisions with incomplete building data while anticipating any new weaknesses introduced by proposed changes. The difficulty grows with complex layouts, where finding viable solutions demands expert judgment. However, traditional manual processes, skilled workforce shortages, and time-consuming revisions under tight timelines often extend delivery schedules. Our work explores the feasibility of developing an AI-based approach that will automatically generate valid beam layouts for masonry house alterations. Specifically, we employ a data-driven graph generative model, i.e., a graph neural network (GNN), to learn beam placement patterns from engineer-validated designs and suggest suitable beam locations for new layouts. The generated suggestions, optimised using a matrix of criteria including cost and construction time, will serve as a preliminary design, narrowing the design search space. This, in turn, could assist engineers at all experience levels in making faster decisions, as well as lessen the cognitive load involved in evaluating numerous design alternatives. Beyond productivity improvements, our approach could potentially make structural design services more affordable for clients and benefit engineering firms' profitability.

Keywords: Graph neural network, Deep learning, Intelligent structural design, Beam layout design, Existing structures, House alteration

Reducing Structural Graphs to Enable Scalable Structure Comparison

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Graphs are increasingly being utilised in structural health monitoring. One prominent application is population-based structural health monitoring, in which individual structures are modelled as attributed graphs and then compared to identify similarities that may inform transfer learning between structures. However, as real-world structures start to be incorporated into these tasks, the underlying graphs grow in both size and complexity. This growth poses significant challenges for graph matching algorithms as the computational cost of determining similarity increases rapidly, especially when advanced graph matching algorithms are used or when comparing large populations of structures. This study proposes a set of graph reduction rules designed to transform structural graphs into a more compact and comparison-friendly representation. Applying these reduction rules to both laboratory-scale test structures and a synthetically generated population of full-scale beam-and-slab bridges demonstrates that the reduced graphs retain critical topological information, enabling meaningful similarity assessments across different structures. By leveraging this graph reduction method, structures can be efficiently grouped according to the form of their reduced graphs, offering a new opportunity for identifying structural similarities and facilitating knowledge transfer between different structural types.

Keywords: Population-based Structural Health Monitoring, Graph Reduction, Structural Graphs, Similarity, Irreducible Element Model, Bridges

Statistical finite element models from graph representations of structures

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Graph representations of structures provide a flexible framework for describing complex systems, enabling similarity assessment and comparison across populations, supporting applications such as population-based structural health monitoring (PB-SHM). A key challenge in this setting is how to incorporate and propagate uncertainty, for example from material properties, within such representations.

In this work, we present a framework for converting a structural graph representation (irreducible element model) into a probabilistic finite element model using the statistical finite element method (statFEM). By treating certain properties as uncertain, such as Young's modulus, within a Bayesian formulation, statFEM allows the synthesis of prior structural information with observed data, to quantify a posterior uncertainty across a model. This approach will be demonstrated on a simple static structural example, highlighting how uncertainty encoded in a graph model could be transferred into the finite element domain.

Keywords: Uncertainty, Graph representations, Bayesian, Statistical finite element method, IE Models

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SS13 - ML-Enabled Conceptual Structural Design.

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This special session focuses on advancing the integration of artificial intelligence (AI) and machine learning (ML) into conceptual structural design, with the goal of fostering innovation at the intersection of computational intelligence and structural creativity. It brings together researchers, designers, and engineers who are exploring novel AI/ML methods to support early-stage design processes. Topics include accelerating forward and inverse form-finding and topology exploration workflows, as well as techniques for incorporating structural knowledge and physical constraints. The session will spotlight developments such as equilibrium-aware design with ML, physics-informed learning, deep geometric reasoning, and generative approaches that enhance design exploration and performance. Emphasis will be placed on emerging methods that enable collaboration between humans and machines, promote explainability, and support the creation of intelligent and intuitive design tools.

Topics of interest include, but are not limited to: • ML for Form-Finding and Topology Optimisation • Geometric Deep Learning in Structural Design • Generative AI for Innovative Structural Systems • Reinforcement Learning and Decision-Making in Structural Exploration • AI-Enhanced Structural Visualisation and Design Feedback • Large Language Models and Hybrid Intelligence in Conceptual Design

57 **Machine Learning Surrogates for Human-in-the-Loop
Design Space Exploration in Early-Stage Structural Design**

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Early-stage structural design requires understanding how performance varies across numerous parametric configurations, and yet traditional simulation approaches make comprehensive design space exploration computationally prohibitive. This paper presents a cloud-based workflow that converts parametric structural models into interactive design exploration tools through on-demand generation of machine learning surrogates with integrated uncertainty quantification.

We use two structural engineering design applications to illustrate the approach: a large stadium where footfall vibration governs floor design, and a reinforced concrete tower controlled by seismic drift requirements. Beyond providing rapid predictions, the surrogates communicate confidence levels through uncertainty bounds, helping engineers distinguish between regions of the design space where predictions are reliable versus areas requiring detailed investigation. This enables informed decision-making about design directions worth pursuing.

By automating the workflow from parametric model to deployed surrogate, the platform enables comprehensive design exploration without requiring machine learning expertise, greatly enhancing how engineers understand and optimise their designs in early project stages.

Keywords: parametric design, design space exploration, structural optimisation, surrogate, surrogate models, uncertainty quantification

Compliance Driven Convolutional Neural Networks for Topology Optimization

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This paper investigates the use of machine learning to accelerate topology optimization (TO), with a focus on improving model generalizability and efficiency by integrating TO-specific loss functions in convolutional neural network (CNN) architectures. While advances in material fabrication have enabled the realization of highly complex geometries, the widespread adoption of TO in practice remains constrained by its high computational cost, particularly the repeated finite element (FE) analyses required within the optimization loop. CNNs offer a natural fit for this problem as TO data (element density distributions and boundary conditions) are inherently structured as image-like fields. Building on recent work applying deep learning to solve partial differential equations, this study investigates CNN-based models that directly predict elemental compliance fields from density and boundary condition inputs, bypassing traditional stiffness matrix assembly and solution steps. Focus is spent on integrating TO specific loss functions, such as compliance and volume fraction, alongside conventional image-based loss metrics during training, in an effort to enable the model to learn performance-driven features rather than purely pixel-level similarity. The paper further examines how taking advantage of topological equivalence between domains can improve geometric generalizability of the model. A dataset of TO iterations across multiple boundary conditions and load cases is generated to train and evaluate the models. Initial results demonstrate the effect of incorporating TO-based loss functions, supporting the development of faster and more adaptable optimization frameworks for architectural and structural design.

Keywords: Topology Optimization, Machine Learning, Convolutional Neural Networks, Finite Element Analysis

Human-Guided Machine Learning for Structural and Architectural Design and Optimization of Gridshells

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Creativity is a fundamental aspect of human intelligence, combining intuition, emotion, and cultural understanding—dimensions that remain difficult to emulate in current artificial intelligence (AI) systems. While AI excels in logic and optimization, it struggles to generate genuinely original ideas. In architecture and structural engineering, creativity is crucial to innovation and to shaping design responses. This research presents a Human-in-the-Loop (HitL) optimization framework that embeds human creativity into the early stages of structural design. Unlike conventional approaches, it enables designers to interact with the optimization process, evaluate alternatives, and guide the search toward meaningful solutions. Structural forms are produced through a parametric model and assessed by a multi-objective evolutionary algorithm, which simultaneously optimizes structural cost and designer preferences. These preferences are learned through a combination of deep learning and clustering: a Vision Transformer (ViT) extracts geometric features, while Fuzzy C-Means organizes solutions into groups, allowing the system to progressively align with the designer's creative intent. Application to gridshell structures shows that the method can generate efficient, cost-effective designs that reflect the vision of the designer, thus bridging the gap between structural performance and creative expression.

Keywords: Human-in-the-Loop, Structural Optimization, Creative Vision, Interactive Optimization Algorithm, Human-AI Integration

Graph Neural Network Surrogate Models for Real-Time Conceptual Structural Design

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Surrogate models offer a computationally efficient alternative to conventional structural analysis for predicting structural performance. In this contribution, we present a Graph Neural Network (GNN) model that accurately predicts node displacements in pedestrian bridge structures generated through the Combinatorial Equilibrium Modeling (CEM) form-finding method, enabling real-time support for conceptual design. A key challenge in applying GNNs to structural design is the need for consistent and comprehensive data representation, which we address through a unified, lightweight graph-based data structure that integrates the entire workflow from form-finding and analysis to GNN-based prediction. The structure's topology is first encoded as a graph labeled with initial CEM parameters, which is then enriched with complete force data, including self-weight and distributed live loads, once an equilibrated state is achieved via form-finding. Finite Element Method (FEM) analysis is subsequently performed for multiple load cases, and the resulting node displacements are stored as final graph attributes. This unified graph encapsulates all information across the conceptual design and structural analysis phases, serving as the foundation for a curated dataset of pedestrian bridges used to train the GNN surrogate model. The trained model demonstrates high accuracy in real-time prediction of node displacements for new bridge configurations, eliminating the need for repeated, time-intensive FEM simulations. Overall, the unified graph structure provides a compact and interoperable framework that links traditional structural design, form finding, and structural analysis with advanced machine learning workflows.

Keywords: combinatorial equilibrium modeling, graph neural networks, structural analysis, form-finding, structural graph

Physics-Aligned Generative Variational Force Density Method

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This work integrates the force density method with a graph-based variational autoencoder (VAE) to investigate the non-unique equilibrium solution space of designs that approximate a given target geometry across trans-topological design spaces. The framework maps an aspirational target geometry into a compressed latent space of funicular structural configurations, in which vertex geometry and edge member force distributions are in static equilibrium. Probabilistic VAE-style sampling within this space enables the generation of diverse equilibrium configurations conditioned on the same target. Two techniques are introduced to guide the formation of the latent space. The first ensures that the reduced-dimensional spaces are aligned with selected form-found attributes. The second promotes diversity in the generated alternatives, producing meaningfully distinct solutions for further design development. Although demonstrated here with shell structures, the proposed approach provides a physics-aligned generative paradigm that is broadly applicable to other differentiable inverse modelling workflows. It reframes form-finding as an interpretable generative process, in which performance metrics function as controllable design knobs to catalyse early-stage architectural ideation.

Keywords: Force density method, Variational autoencoder, Inverse form-finding, Graph neural networks, Generative modelling, Inverse modelling

Generative Ai in Structural Design: State of the art and future perspectives

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Generative AI models are gaining traction in structural engineering, promising to accelerate design synthesis and improve efficiency. Traditional Finite Element Analysis (FEA) workflows provide accurate simulations but require engineers to manually define and iterate over design spaces. Generative methods can assist in automating proposals and guiding exploration. However, adoption is slowed by safety requirements, limited datasets, and the need for expert validation. The paper contributes both a survey of current applications and a conceptual proposal. The latter explores specification-aware structural embeddings and latent space optimization as pathways toward physics-informed design generation. The survey shows applications of generative AI in four main domains: topology optimization, layout generation, health monitoring, and evaluation systems. Topology models explore feasible and materially efficient forms. Layout tools automate placement of elements. Generative models for health monitoring simulate damage to extend scarce datasets. Evaluation frameworks combine vision-based, mechanics-based, and rule-based checks to filter designs before full analysis. These efforts demonstrate potential but also highlight challenges in data availability, interpretability, and workflow integration. To complement this, a conceptual framework is proposed, combining project specifications with structural graph representations. Graphs that encode geometry, materials, and connectivity are conditioned on project requirements to produce embeddings that reflect both design intent and structural context. Latent space optimization can then identify feasible and Pareto-optimal solutions, which are decoded back into candidate designs for validation through surrogate models and FEA. This workflow is presented as a research direction rather than a demonstrated solution, illustrating how generative methods might be aligned with structural reasoning.

Keywords: Generative Artificial Intelligence, Structural Engineering Design, Graph-Based Representations, Latent Space Optimization, Physics-Informed Design

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SS14 - Smart Engineering for Circular Steel Structures: AI and Evolutionary Algorithms for Sustainable Design.

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This special session highlights how artificial intelligence (AI) and evolutionary optimization techniques, such as genetic algorithms, can play a key role in guiding the transition toward sustainable practices in the steel construction sector—particularly through reuse-oriented and reuse-based design approaches. As the industry embraces circular economy principles, there is a growing need for design and construction methods that enable disassembly, adaptability, and efficient reuse of steel components as well as improve the constructability of steel buildings with innovative assembly-in-situ or preassembly solutions. We welcome contributions exploring optimization frameworks based on AI techniques and/or evolutionary algorithms that support this transformation—enhancing automation, enabling circular design strategies, and promoting resource-efficient decision-making across the steel lifecycle. We invite original contributions that explore the use of AI techniques (e.g. machine learning, Neural networks) combined with automation technologies to enhance design, analysis, monitoring, and decision-making processes. Topics of interest include, but are not limited to: • AI-powered structural and infrastructure optimization; • Circular design and construction of steel structures (Recycling and

reusing); • LCA and LCC assessment of optimized structural system; • Neural networks for modelling complex engineering systems; • Structural optimization for the Additive Manufacturing of sustainable products; • Structural optimization for Bio-inspired, porous and meta-materials; • Autonomous systems for design, simulation, and control; • Robotics and automation in construction and infrastructure; • Digital twins, real-time sensing, virtual commissioning, and AI-integrated feedback loops. This session aims to foster interdisciplinary collaboration and highlight innovative research bridging AI, optimization, and sustainable engineering practice. Submissions showcasing practical applications, reuse-driven frameworks, or forward-looking methodologies are particularly encouraged.

A framework for the sustainable design of a composite frame under cyclic loading.

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In this paper, a comprehensive finite element analysis is conducted on a composite frame subjected to cyclic loading based on the SAC protocol (2000). The main part of the composite frame is modeled as a cantilever steel castellated beam with an opening shape of (circular and hexagonal) joined by an agricultural plastic pipe. In addition to the second part, the CFT column is composed of a square hollow steel section with concrete, connected by a welded connection of the castellated beam. The objectives of the study focus on forming a plastification around the opening along the web of the castellated beam under sustainable design. These studies achieve the transfer from brittle to ductile failure and remain the (weak beam-strong column) due to the seismic event. The results indicate that models have an increase in strength and beam depth compared to the solid web. Furthermore, the economy is improved, and consumption time is reduced.

Keywords: Composite frame, Sustainable design, Welded, Plastic hinges, Cyclic loading

Structuring of Wall Buildings Based on Artificial Neural Networks

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In the structural design of buildings with walls, the initial process requires interaction between the architectural and engineering teams to define the proper layout of the walls. For engineering analysis, first of all, the definition of the thickness and length of the wall, its location, and in some cases, the presence of new sections of the wall are required to comply with engineering needs. The study includes a survey of architecture and engineering plans for 165 buildings built in Chile; next, an ANN (artificial neural network) model was trained for the regression of the thickness and length of the wall segments, using a feature vector that models the variation between architectural and engineering. The regression model (ANN) obtained results in terms of R^2 of 0.995 and 0.994 for the predicted wall thickness and length, respectively. In addition, another convolutional neural network (CNN) model is used in the initial process of the conceptual design of the building's wall design, fed only by architectural data (images and numerical features), allowing it to predict new elements (walls) not anticipated by the architectural plans. This second formulation, although yielding good results, requires collecting image information, where the wall area is typically low (~3% of the floor area). Therefore, it is inefficient, as over 90% of the image information indicates the absence of a wall. Thus, a new ANN formulation is incorporated, predicting the need for new elements. In this case, the input vector scans the floor plan, capturing the rectangles comprising the walls within a 30-meter radius, and an output vector predicts new rectangles (walls) based on final engineering drawings. The results show that it can provide an adequate estimate of the geometry and location of these new elements, being more efficient than the information required by the CNN model and improving the precision by providing a wall element rather than a collection of pixels that represent the probable location of walls.

Keywords: structuring, neural network, machine learning, wall

Life Cycle Assessment-Based Optimization of Reinforced Concrete Frames Accounting for Steel Production Methods 48

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Life Cycle Assessment (LCA) provides a critical framework for evaluating and minimizing the environmental impacts of construction materials and structural systems across all stages of their life. The need for sustainable design in the construction industry is particularly pressing given its substantial share of global energy consumption and CO₂ emissions, with reinforced concrete (RC) structures contributing significantly due to their heavy reliance on cement and steel. A major component of RC's environmental impact comes from steel production, which can vary substantially depending on the manufacturing process: the Basic Oxygen Furnace (BOF) route depends on coal and coke, resulting in high embodied energy (~22.7 MJ/kg) and CO₂ emissions, whereas the Electric Arc Furnace (EAF) route, which primarily uses scrap steel, is more energy-efficient (~5.2 MJ/kg) and offers lower-carbon potential when powered by renewable energy. Despite these critical differences, much of the existing structural optimization literature fails to differentiate between steel production routes in embodied energy and emissions assessments, treating steel as a uniform material. This research addresses this gap by developing an integrated LCA-based optimization framework that explicitly models both BOF and EAF production routes for steel, along with concrete's environmental impacts. Using Genetic Algorithms (GA) and structural analysis with OPENSEES, the study optimizes RC frame designs to minimize cost, CO₂ emissions, and energy consumption while meeting structural performance requirements. This study demonstrates the use of LCA in structural optimization to achieve more accurate, effective, and sustainable RC frame designs by accounting for differences in production methods and material impacts.

Keywords: Life Cycle Assessment, Reinforced Concrete, Steel Production, Structural Optimization, Sustainable Design

Data-driven and advanced manufacturing solutions for sustainable steel reuse

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The transition to a circular economy in the construction sector faces several challenges, particularly regarding the reuse of structural steel. This presentation introduces data-driven and modern manufacturing techniques aimed at addressing these issues.

The first part of the presentation will focus on an AI-powered framework that supports decision-making for end-of-life steel structures by enabling more accurate evaluations of reuse versus recycling potential. The framework relies on a two-fold data-driven approach. The first technique uses Convolutional Neural Networks (CNNs) and visual language models (VLMs) to assess the condition of steel elements through images. These models are trained to classify key structural features, such as corrosion levels, connection types (bolted or welded), and visible damage. This automated visual inspection is then integrated into a broader decision tree that considers both logistical feasibility and structural performance to inform the final decision. The second technique involves conceptual design optioneering, which generates multiple design alternatives. This allows architects and engineers to compare solutions based on cost, environmental impact, and usable floor area.

The second part of the presentation will introduce a focus on advanced manufacturing, highlighting recent developments in laser cutting and laser cleaning for reclaimed steel. These technologies are used to accelerate the preparation of reclaimed steel elements, making them ready for reuse with minimal manual intervention. Laser cleaning enables the removal of rust, coatings, or surface contaminants without damaging the steel, while laser cutting provides high precision for reshaping or creating new connection details.

Together, these approaches support a circular strategy that combines digital assessment and high-tech fabrication to make steel reuse both practical and scalable in modern construction.

Keywords: reclaimed steel, CNN, VLM, laser cutting, laser cleaning

Inverse design of novel functionally graded porous structures via diffusion models

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Traditional functionally graded porous structures (FGPS) design approaches are inefficient and the prototypes are hard to produce, while the development of additive manufacturing techniques makes them possible. The present study proposes a novel inverse design framework of FGPS via diffusion model to precisely design targeted porous structures with specified nonlinear mechanical behaviors. Firstly, various functionally graded porous structures were implemented by employing Voronoi diagram techniques, and finite element simulations were conducted to calculate the nonlinear responses. A dataset comprising 2100 FGPS and corresponding nonlinear stress-strain responses was established. Then, an inverse design framework is formulated by integrating a generator that uses a diffusion model to synthesize structures conditioned on specific target responses, with a predictor that employs a residual neural network to assess the responses of these structures. Unlike traditional binary pixel representations, this approach utilized nuclei position maps and color mapping to represent structure configurations and cell wall thicknesses to improve the efficiency and performance of the model. Finally, to demonstrate the effectiveness of the approach, the performance of the predictor and generator was thoroughly investigated. Structures with various target stress-strain responses were generated through the proposed method, and validated by finite element analysis. The result shows that the framework can generate original structures with objective nonlinear responses within a tolerant error margin. This work offers a fast and efficient way to design FGPS that meet specific performance objectives.

Keywords: Inverse design, functionally graded porous structures, diffusion models, stress-strain responses

Global-Local Structural Optimization of Hybrid Gridshell Structures from Decommissioned Lattice Towers

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One of the key issues currently affecting the construction industry from a production standpoint is its environmental impact. Engineers are increasingly adopting circular construction strategies aimed at reducing greenhouse gas emissions. The most significant and effective method is the reuse of the materials and elements previously employed in structures that are facing decommission. In the context of circular construction, decommissioning is addressed even at the initial stage of design of a new structure, to anticipate the proper management of the materials and elements at the end of their cycle. However, the structures that are currently in line for decommissioning often do not contain such management plans and could benefit from the comprehensive standard for procedure of reuse, its concise steps, and practicalities. This research showcases the example of a procedure for the reuse of decommissioned structures in the form of a structured methodology, that includes data collection, catalogue in form of inventory, and its use in creating new structures. The example focuses on designing a new gridshell from a decommissioned steel lattice tower, chosen as a more complex alternative to frame structures. The algorithm is implemented to assemble the gridshell using the global structural optimization of the member's cross-section, with priority of reuse from the inventory and use of new material only where unavoidable. The objective is to minimize the use of new materials by achieving an optimal structural configuration (best fit) using almost exclusively reused elements. The research also investigates the challenge of connecting reused components, which are often non-standard and geometrically diverse. Through a topological optimization study, custom node geometries are developed and produced using DED-Arc additive manufacturing technology, allowing for the efficient and precise assembly of the reused elements within the shell structure.

Keywords: Decommissioned structures, Reuse, Structural optimization, DED-arc

Optimization of Steel Exoskeletons for sustainable seismic Retrofit

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This study presents an optimization-based methodology for the seismic retrofit of existing reinforced concrete (RC) buildings using external steel exoskeletons composed of reclaimed structural elements. The approach integrates stock-constrained optimization and structural performance objectives within a unified computational framework developed in Rhino/Grasshopper environment. A genetic algorithm governs both the geometric configuration of the exoskeleton and the assignment of reclaimed members, dynamically sourced from decommissioned electrical towers. While previous applications focused on a single structural layout, this work expands the methodology to assess the influence of different geometric patterns on the efficiency of reuse-based design. Multiple diagrid configurations were tested on the same case-study building, evaluating the impact of pattern regularity and nodal flexibility on material reuse rate, structural performance, and embodied carbon. Results show that more regular and symmetric patterns promote constructability and enable efficient member substitution, whereas highly flexible or irregular layouts—while potentially achieving higher reuse rates—may lead to structural overdesign and increased scrap generation. The study confirms the feasibility of integrating reclaimed steel into seismic retrofit strategies, demonstrating the reduction in embodied carbon with moderate increases in structural mass. The proposed methodology offers a versatile design tool for sustainable retrofitting, adaptable to different stock inventories and architectural constraints.

Keywords: steel reuse, sustainability, steel exoskeleton, seismic retrofit, structural optimization

Simplified approach for reuse-based optimization of steel gridshell

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In the construction industry, steel is one of the most widely used and demanded materials worldwide; however, its production is responsible for substantial greenhouse gas emissions. Reuse offers a promising strategy to optimize resource use and extend material lifespans in line with circular economy principles. This research investigates the reuse of steel in long-span structures such as gridshells, which are symbolic of structural efficiency. Two case studies are presented, in which the grids are optimized using a genetic algorithm. The algorithm integrates reclaimed steel elements from decommissioned structures into the structural grid, while imposing constraints related to sustainability, structural performance, and buildability. Gridshell structures are typically assessed through nonlinear analyses that account for both material and geometric nonlinearity. To reduce computational effort during the optimization process, a simplified method is adopted by implementing the Merchant–Rankine criterion as a structural constraint. The optimized configurations are subsequently validated through full nonlinear simulations, enabling comparison with the simplified approach. The results confirm the feasibility of achieving optimized and sustainable structural solutions with a significant reduction in embodied carbon. Furthermore, the simplified constraint provides a satisfactory safety margin when compared to the actual structural behaviour.

Keywords: steel reuse, sustainability, gridshell, steel structures, structural optimization

Structural Engineering in the World of AI – Is It Just a Better Loom?

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This brief talk explores perceptions, challenges, and opportunities for the structural engineering profession by presenting a few case studies and applications, aimed at setting the stage for a vision for the future of structural engineering, in terms of education, practical applications, and required expertise. To some extent, the advent of AI has the potential to revolutionize structural engineering and many other industries just like the power loom did in the 1800s. Job displacement for skilled workers was a much lamented effect of the introduction of the power loom – will AI have a similar impact on structural engineering? We will explore a vision of what needs to be done today to prepare for what appears an inevitable revolution, and why, with some proactive changes, structural engineering, among many professions, is in a great position to reap the benefits of AI without falling prey to its potential negative consequences.

Keywords: Vision for Structural Engineering, Challenges and Opportunities, AI for future developments

Optimization of RC Frame-Shear Wall Buildings with Variable Wall Height and Layout

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Shear walls are fundamental for lateral load resistance and displacement control in reinforced concrete (RC) moment-resisting frame buildings. However, while they are highly effective in lower stories, their contribution diminishes with height and may even become counterproductive in the upper stories of tall structures. This raises a compelling question: what if shear walls were interrupted at intermediate floors instead of extended to the top? Truncating walls at a certain height, often near mid-height, can maintain displacement control while reducing material use. Nevertheless, this strategy is rarely adopted due to the risk of stress concentration at the level of wall interruption. Still, in specific and non-intuitive configurations involving wall layout, height, and dimensions of both frame and wall elements, these stress concentrations could be mitigated, rendering the approach both feasible and advantageous. Yet, manually identifying such optimal configurations is extremely challenging due to the complex interaction among variables. In this work, a metaheuristics-based optimization framework is proposed to overcome these complexities and explore this promising design strategy. The design variables include the quantity, positions, and heights of shear walls, and the dimensions of walls and frame elements at each floor. The objective is to minimize the total economic cost of concrete and reinforcement. By leveraging this optimization framework, it becomes possible to explore non-conventional structural layouts that would be difficult to conceive through traditional design methods. The result is a new design paradigm for one of the most widespread RC structural typologies, enabling more efficient, cost-effective, and sustainable solutions.

Keywords: Shear Walls, Optimization, Earthquake, Layout, Reinforced Concrete

Development of a Novel Integrated Framework for Evolutionary Sustainability and Resilience Assessment of the Built Environment

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As the effects of climate change intensify, there is an increasingly urgent need to develop climate-resilient cities and promote sustainable resource management. This study introduces innovative, integrative methodologies that combine resilience and sustainability assessments for new and existing built systems in areas prone to hazards. The proposed framework improves current methodologies, which mostly focus on checking the structural performance through design rules and frequently ignore wider circularity metrics and social effects during the system's life cycle. A key feature of this approach is its consideration of the evolving performance of infrastructure and building assets, including degradation or upgrades caused by refurbishment measures or corrosion. The framework is structured around five main tasks and employs a two-stage assessment process. The first stage involves identifying optimal design options for reactive and proactive measures using multi-objective optimisation. The second stage uses dynamic analysis to monitor performance changes following a shock event, enabling specific measures to be allocated strategically over the observation period. The aim of this methodology is to support proactive decision-making, reduce losses from natural hazards and enhance the resilience and sustainability of the built environment.

Keywords: sustainable construction, resilience, multi-objective optimisation, Life Cycle Assessment, hazard assessment, risk assessment

133 Reusing steel: Is It Possible? Challenges and opportunities.

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The construction sector is the largest consumer of raw materials. It accounts for 50% of the total material use in Europe alone and 25%–40% of the total CO₂ emissions globally. The building construction drives current energy consumption and greenhouse gas (GHG) emissions, representing 36% of total energy use and 37% of the global GHG emissions, respectively. Besides, construction activities produce the highest amount of waste among all other sectors. As a result, the construction industry is under more scrutiny than ever to reduce resource consumption, construction, and demolition-related waste while encouraging reusing practices unquestionably represent an efficient path to promote Circular Economy. Thus, there is a unique incentive to use waste materials in the construction industry by reusing structurally functional parts (re-using) or the use of raw materials as components to produce new structural elements (recycling). Based on the waste hierarchies, reuse is way better than recycling. Specifically, the potential financial benefits of reusing structural steelwork reside in the low carbon intensity of 50 kgCO₂ eq./t compared with a sector average of 1740 kgCO₂ eq./t for new steelwork. The ongoing research aims to develop, for the first time in the international literature, an openly available optimisation tool based on an innovative multi-decision criteria framework and unique computational approaches able to perform an intelligent adaptation (i.e. optimisation) of the steel members' size, geometry and smart topology arrangement of the building to the stock-constrained design needs. Based on a multi-dimensional Pareto front decision-making optimisation framework, the authors successfully implemented well-known Cutting-stock and assignation problems within the main optimisation process to evaluate the optimal cutting patterns of structural members employed at the assembly phase. Iteration by iteration, the optimiser dynamically adapts the building's size, shape and topology (geometric properties and architecture of the building like the size of the structural members according to standard section catalogue, longitudinal and transversal spans as well as the inter-storey heights and the specific position of structural members) to the existing reusing steel stock following the minimum waste, minimum cost and minimum embodied carbon criteria. The global optimal solution represents the optimal trade-off between structural, economic and environmental qualities.

Keywords: Reusing Steel, Circular Economy, Structural Optimization, Multi criteria, Sustainability

SS15 - Integrated Architectural and Structural Design through AI-Guided Generative Processes and Bio-Inspired Optimization.

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This special session explores innovative approaches at the intersection of architectural planning and structural design, facilitated by AI-driven generative processes and bio-inspired strategies. Emphasizing integration across disciplines, the session focuses on sustainable, adaptive, and materially efficient systems wherein structural performance and architectural intent co-evolve. Contributions utilizing AI, optimization algorithms, and computational tools to enhance collaboration between architects and engineers are welcome. Topics of interest include (but are not limited to):

- Integrated design workflows linking architectural form-finding with structural performance;
- AI-guided generative systems for performance-informed architectural planning;
- Expert-guided or interactive computational design environments;
- Bio-inspired structural morphologies that support sustainable architectural solutions;
- Use of digital twins and parametric models to bridge architecture and engineering;
- Computational tools for cross-disciplinary design;
- Sustainable materials and performance-aware early-stage design strategies;
- Case studies of integrated design processes in adaptive or ecological structures.

Bridging Visual Programming and Natural Language Processing for AI-Enhanced Computational Design Workflows

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Computational design has profoundly reshaped architectural, engineering, and digital fabrication practices by introducing parametric modelling, algorithmic workflows, and automation. Among the available tools, Grasshopper for Rhinoceros 3D has become one of the most widely adopted Visual Programming Language (VPL) environments, due to its flexibility and capability to handle complex generative design tasks. Nevertheless, the reliance on manual selection, placement, and wiring of components often represents a barrier for novice users since it can limit efficiency even for experienced practitioners when addressing large-scale or iterative design processes. This research explores a methodology for integrating Natural Language Processing (NLP) models within the Grasshopper environment, intending to augment the usability and accessibility of computational design workflows. The proposed framework leverages NLP-based interpretation of textual prompts to dynamically generate, suggest, and configure Grasshopper components, thereby reducing the dependency on manual scripting and enabling a more intuitive interaction paradigm. By embedding AI-driven assistance, designers can articulate design intentions in natural language, which are then translated into executable parametric definitions. The paper presents the technical framework of this integration, discussing API communication protocols, component database parsing, semantic matching strategies, and rule-based constraints for ensuring accurate component selection and generation. Furthermore, it addresses challenges such as ambiguity in natural language input, the need for contextual disambiguation, and the computational implications of real-time translation between textual and visual programming domains. Implementation results highlight how AI-assisted workflows can support intelligent parametric modelling, accelerate iteration cycles, and expand the accessibility of computational design to a broader audience. The study outlines future directions, including automated component wiring, adaptive learning for improved command interpretation, and integration with broader design-to-fabrication pipelines.

Keywords: Computational Design Automation, Visual Programming Language Integration, Natural Language Processing Models, API-Based Workflow Enhancement, Semantic Component Matching

Fiber & Folded Pavilion: Artificial Intelligence, Computational Design, and Digital Fabrication in Fiber-Based Architectural Structures

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The Fiber & Folded Pavilion represents a design research project that merges artificial intelligence, computational design, and digital fabrication within the domain of fiber-based architectural structures. The creative process began with AI-generated images, which provided visual suggestions inspired by nature and the symbolic form of the tree as a morphogenetic element. These inspirations were then reshaped through computational design, translating organic geometries into optimized forms adapted to robotic fabrication and fiber-reinforced 3D printing. The fibrous structure is complemented by a folded textile covering, developed through parametric origami principles, establishing a dialogue between structural fibers and fabric fibers while evoking folded architecture. The approach integrates both theoretical and practical experimentation: from conceptual stages, through algorithmic modeling, to physical prototyping. This workflow demonstrates how the combined use of AI and digital design can foster innovative architectural solutions that merge natural inspiration, structural performance, and technological advancement. Due to its modular morphology and capacity to tessellate space, the pavilion is particularly suitable for large-scale coverings, offering a scalable and adaptable system that combines constructive efficiency, structural lightness, and expressive architectural quality.

Keywords: Fiber architecture, Artificial Intelligence, Computational design, Digital fabrication

110 **Towards a new architecture didactic method: the use of artificial intelligence as a support for students' creativity**

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This paper discusses an innovative didactic experiment carried out within the fourth-year Architectural Design course at the Polytechnic University of Bari. The experience investigated the pedagogical potential of Artificial Intelligence as a support for students' creativity in architectural education. Moving beyond conventional design exercises, the course challenged students to produce a short science-fiction film inspired by The Line, the linear city currently under development in Saudi Arabia, thus engaging them in a speculative design process. The methodology combined traditional architectural design practices and methods with the use of contemporary technologies (such as 3D modeling tools and rendering engines) and AI-based generative tools. This hybrid approach enabled students to explore new forms of representation, to accelerate the production of visual material and to experiment with narrative strategies as a means of architectural communication. The project was structured as a collaborative exercise among eight groups of students, encouraging critical discussions about technology, creativity and the future of the built environment. The results, achieved in a four-month period of time, highlight the effectiveness of AI as a didactic support: not only students demonstrated enhanced levels of engagement, originality and expressive capacity but they also revealed in an anonymous questionnaire that they felt enriched by the experience and improved in their architectural skills. The contribution argues that the strategic integration of artificial intelligence into architectural pedagogy may open new avenues for design education, providing students with both practical tools and critical perspectives necessary to navigate the evolving landscape of contemporary architectural practice.

Keywords: Architectural design, Artificial Intelligence, Architectural didactics

Artificial intelligence to enhance creativity in architecture and design: a case study

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This contribution presents a case study focused on the conceptual design of an architectural column conceived for stone construction. The column integrates expressive formal characteristics with structural rationality, proposing a new paradigm for load-bearing elements that bridge tradition and innovation. A possible architectural application for the column has been explored: in particular, a modular hexagonal vaulted space delimited by six columns has been proposed. The experimental use of Generative Artificial Intelligence (AI) tools to enhance the design process is a central part of this research: text-to-image diffusion models and shape optimization techniques have been used to refine the design of the vault according both to an aesthetic concept and to static requirements. Finite Element Method (FEM) analyses have been performed to evaluate the static behavior of the proposed configuration under load conditions compatible with natural stone. This work unites the principles of architectural design with structural engineering and AI-assisted creativity and it aims to encourage reflection on new possibilities for the use of traditional materials in contemporary architectural languages.

Keywords: Architectural Design, Artificial Intelligence, Stone Architecture, Structural optimization, Bio-inspired architecture

118 **Life Cycle Analysis-informed conceptual design of building structures using machine learning**

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Life Cycle Analysis (LCA) is commonly used to evaluate the environmental impacts of building structures from raw material extraction to end-of-life. It is a powerful tool for comparing different building designs, as it can track impact transfers across life cycle stages and impact categories. However, LCA is rarely used during the early design phase of a building, when the most impactful decisions for its environmental performance are made. At this stage, the required information is generally unavailable or difficult to collect, which limits the use of LCA for design space exploration. This research proposes a machine learning approach to provide designers with the insights of LCA, thus enabling the evaluation of many potential building structures in the early design phase. A Conditional Variational Autoencoder that can act as both a surrogate and a generative model is adapted from literature to the use of LCA training data. The surrogate model can predict the multi-criteria environmental impacts for a given building structure, while the generative model can generate designs satisfying specified environmental impact limits, as well as other design constraints. This approach is evaluated through a case study focusing on building structures composed of beams and columns. A dataset of 92,797 building structures with varying geometries, typologies, and materials is generated, and an LCA is conducted for each structure, based on material quantities. The resulting surrogate is found to assess rapidly and accurately the environmental impacts of the structures considered, while the generative model can produce diverse structures satisfying the specified constraints.

Keywords: Life Cycle Analysis, Machine Learning, Deep Learning, Structural Engineering, Surrogate modelling, Generative Design

From Geometry to Matter: AI-Assisted Design in Additive Manufacturing

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The arch, dome, vault, and shell have long served as fundamental elements in architecture, demonstrating how material efficiency and structural ingenuity can converge. This research reimagines these principles through additive manufacturing with bio-based resources, including stone, wood, and seaweed. By merging traditional craftsmanship with digital technology and artificial intelligence (AI), the research advances innovation while addressing sustainability and material ethics. The project examines the reinterpretation of Gothic and Baroque precedents through AI diffusion models. Despite stylistic differences, Gothic, emphasizing skeletal verticality, and Baroque, emphasizing fluidity, both traditions share an ornamental richness and spatial drama. AI-assisted text-to-image processes generate new formal expressions that blend historical references with speculative digital transformations, ultimately translated into three-dimensional prototypes. Methods combine custom computational workflows and binder-jet additive manufacturing. Bio-based powders are bonded with sustainable adhesives, while unused material is fully recovered, ensuring a zero-waste process. AI-informed iterations are optimized for material efficiency and fabricated into prototypes that test structural and aesthetic potential. Preliminary results validate the feasibility of constructing architectural products from renewable or recycled materials. These prototypes demonstrate how AI-generated design logics can extend traditional architectural geometries toward new ecological and cultural contexts. This research positions additive manufacturing and AI as key drivers in redefining material practice. By foregrounding renewable resources and digital workflows, the study fosters sustainable construction strategies while opening expressive opportunities that unite history, technology, and environmental responsibility.

Keywords: Additive manufacturing, bio-based materials, sustainable construction, AI-assisted design, computational design, digital fabrication

Optimizing Wind-excited Telecommunication Steel Tower Designs using Response Surface Method

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This study presents a response surface method (RSM)-based optimisation framework to efficiently design a 60-meter microwave telecommunication steel tower, addressing key challenges associated with dynamic wind loads [1,2]. The main objective is to minimise structural weight and cost while maintaining strict safety and serviceability standards. A review of current practices in tower modelling highlights the use of RSM, artificial neural networks (ANN), and radial basis functions (RBFs) as commonly adopted metamodeling techniques, particularly effective for linear analyses under critical wind loading. Among these, RSM stands out for its simplicity and efficiency in achieving accurate, rapid response analysis and optimisation. The RSM model developed in this work effectively captures relationships among design variables and wind-loading conditions, facilitating a computationally efficient, gradient-based sequential quadratic programming (SQP) optimiser. This approach is implemented in MATLAB and delivers considerable computational savings over traditional techniques like genetic algorithms (GA) [3]. Findings indicate that the RSM-based framework optimises the tower design, achieving an ideal balance of structural performance and resilience under dynamic loading, while significantly reducing computational costs. This study demonstrates RSM's practicality for telecommunication tower optimisation, providing a robust, time-efficient solution to handle complex wind-induced dynamic loading conditions.

Keywords: Telecommunication tower, Structural optimization, Wind loads, Dynamic analysis, Response surface method

Design Optimization of Cable-stayed Bridges: Decoupling Strategy and Surrogate Modeling

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The design optimization of cable-stayed bridges (DOC) is particularly challenging, due to the need to determine appropriate prestress. Constraint verification is highly sensitive to these mechanical variables, and their optimum values depend on both the bridge configuration and the member stiffness. In this work, we propose employing a decoupled strategy to transform the complex DOC problem into two iterative sub-problems: (i) minimizing material cost with respect to structural parameters, and (ii) optimizing the internal force distribution by adjusting cable prestressing forces. Moreover, surrogate models are introduced to provide instant predictions on the optimal prestress, effectively replacing the time-consuming sub-problem (ii). Adaptive design of experiments is integrated into the computational framework to enhance the surrogate model adaptability. Specifically, guided by the model confidence, high-fidelity cable force optimization is invoked whenever the surrogate model fails to provide sufficiently accurate predictions. The resulting solutions are then incorporated as additional training samples to update the surrogate model. The performance of the proposed framework is validated through two case studies: a simple cable-stayed cantilever and a complex long-span cable-stayed bridge. The results demonstrate that the decoupled strategy can effectively handle complex DOC problems involving diverse parameters, while the surrogate-assisted approach substantially enhances computational efficiency under limited computation resources.

Keywords: cable-stayed bridge, structural optimization, surrogate modeling, design of experiments

141 **Data-Driven Correlation of Corrugated Barrel Vaults with Seismic Shaping: Elastic FEA and Machine Learning**

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This work investigates the use of data-driven techniques to explore the seismic response of corrugated barrel vaults. As a reference, the shaping procedure for earthquake-resistant vaults proposed by Tim Michiels is considered. In parallel, a set of corrugated vaults is generated without explicit seismic considerations, and their response is assessed through elastic finite element analyses. The resulting dataset provides stresses, displacements, and internal force measures across a wide range of corrugation parameters. However, the parameter space includes anomalies and missing solutions, which are addressed by applying machine learning for outlier detection, interpolation, and surrogate modeling. The cleaned and completed dataset is then correlated with the Michiels-based vaults, allowing elastic response indicators of the surrogate models to be related to earthquake-shaped solutions. While limited to elastic analysis, the study shows the potential of integrating FEA with machine learning to identify critical geometric trends and establish data-driven links between generic corrugated shells and earthquake-resistant forms.

Keywords: corrugated barrel vaults, machine learning, data-driven methods, seismic response, form finding

Joint-Level Optimization of Steel Frame Connections Using Surrogate Models

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In steel frame design, the behaviour of connections has a major influence on both performance and overall cost. In European design practice, global analysis usually idealise joints as pinned or rigid, with detailed checks carried out afterwards using the Eurocode 3 (EN 1993-1-8) Component Method. This study presents a joint-level optimization framework that complies with EC3 while enabling efficient design exploration through machine-learning surrogates. In the method, global joint actions are derived from a simplified analysis where each connection is modelled as a rotational spring consistent with its target EC3 stiffness class. These actions are then fixed for the detailed connection study. The design space itself is constrained to EC3 admissible options by enforcing the geometric limits and component requirements specified in the code. The work focuses on the widely used bolted end-plate connection. Finite-element simulations provide moment-rotation curves for sampled designs. From these, the initial rotational stiffness ($S_{j,ini}$) and design moment resistance ($M_{j,Rd}$) are extracted and used to train surrogate models. Sampling is concentrated near EC3 limit surfaces and stiffness thresholds to improve accuracy where design choices are most sensitive. The framework minimizes a fabrication-aware cost function, accounting for both material and fabrication, while satisfying all EC3 requirements and stiffness class targets. Candidate solutions are re-verified with finite-element analysis. Initial case studies on representative joints indicate that notable cost reductions are achievable without compromising EC3 compliance or the intended stiffness class.

Keywords: Steel Joints, Cost Optimization, Surrogate Modeling, Machine Learning

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