## 9th International Workshop on Structural Control and Monitoring

# 9IWSCM 2024

## Theme: Fusion of Physics & Data for Structural Control & Monitoring

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# Book of Abstracts

Chair of Structural Mechanics & Monitoring

ETH Zürich

# Working Group 1

## Digital Twins and Hybrid Simulation

**Giuseppe Abbiati**

Aarhus University, Department of Civil and Architectural Engineering

### Optimal Design of Cyber-Physical Hydrodynamic Experiments for Floating Structures

The development of innovative offshore structures frequently involves the use of scaled models tested in ocean basins to assess hydrodynamic loading in severe sea conditions. This approach faces two main challenges. Firstly, for floating structures having a mooring system with a large footprint, the geometric scaling factors required to obtain meaningful results are not affordable due to today's basin size limitations. Additionally, wind loading can seldom be included, and its scaling laws are incompatible with that of hydrodynamic loading. Cyber-physical testing (a.k.a. hybrid testing) has emerged as a promising solution to overcome these limitations. This method combines physical and numerical models through substructuring. Specifically, it involves testing a physical model of the floating structure while the rest of the mooring system, superstructure, and wind loading are simulated numerically. SINTEF Ocean has pioneered the development of cyber-physical testing in the hydrodynamic field, employing cable-driven parallel robots to integrate the physical and numerical components seamlessly. This paper addresses the problem of estimating hydrodynamic loads on floating structures in waves. It introduces the application of statistical optimal experimental design to tune the parameters of the numerical substructure of the cyber-physical model. The goal of the optimal experimental design is to minimize the uncertainty of the hydrodynamic loading model estimated from the experimental data. The methodology is applied to a numerical case study based on the INO Windmoor floater, which is designed for a 12 MW floating offshore wind turbine. Optimal experimental design is applied to minimize the uncertainty of identified added mass and damping.

**Elif Ecem Bas**

R&D Test Systems

### Digital Twins for testing of large wind turbine components

Testing of large wind turbine components plays a central role in delivering reliable yet cost-effective technology. However, these experiments are often lengthy and costly. Fatigue testing of a wind turbine blade might take up to 12-14 months, whereas highly accelerated lifetime testing of a nacelle demands 6-8 months. The exchange of simulation models and data between OEMs and test facilities is a critical factor in the planning of an experimental campaign. In fact, OEMs are typically very protective of their industrial secrets, and sharing such sensitive information may constitute a threat. It follows that the use of simulation models to enable more effective experimentation is not pursued efficiently. Digital twins are emerging as a key enabling technology to improve the operation & maintenance of test benches for the wind industry. A digital twin combines physical systems and their digital models into a cyber-physical system to provide functionalities that physical or digital assets cannot independently attain. The seamless integration of the test bench with digital models offered by a digital twin is expected to simplify the implementation of hybrid numerical-experimental testing methodologies such as virtual testing and hardware-in-the-loop testing. We describe the development of the DIGIT-BENCH digital twin, which is being developed by R&D A/S Test Systems and Aarhus University to serve large-scale test facilities for the wind industry. The digital twin utilizes FMI-based co-simulation to enable physical/digital components to be coupled in an industrial-secret-friendly environment. It is demonstrated on a 2-degrees-of-freedom test bench installed at Aarhus University.

**Frederik Nordtorp**

Aarhus University

**A Hybrid Testing Framework for Wind Turbine Mechanical Components**

As wind turbines continue to increase in size, hybrid testing is emerging as a key-enabling solution for experimental assessment of their large mechanical components. Hybrid testing is conducted using a hybrid model which combines physically tested and numerically simulated components. In this work, the Kane method is proposed to formulate the equation of motion for the hybrid model of a wind turbine rotor system where one single blade is physically tested. The Kane method allows for formulating the equation of motion of multi-body-dynamic models efficiently and, therefore, it is widely used in state-of-art simulation software. The hybrid model of the rotor is successfully implemented on a single-degree-of-freedom test bench with a cantilever steel beam serving as the physical substructure. The performance of the implemented hybrid model is assessed through a comparison with a pure numerical simulation of the same system. The main finding of the study emphasizes the efficiency of incorporating physically measured restoring force as model parameters while formulating the equation of motion of a hybrid model.

**Youchan Hwang**

Seoul National University

**Improved Wind Tunnel Testing of Bridge Deck Models with Vertical Real-Time Aeroelastic Hybrid Simulation**

To overcome the challenges of accurately expressing the wind-induced forces exerted on a bridge cross-section, a Real-Time Aeroelastic Hybrid Simulation (RTAHS) system has been developed. This system directly measures the wind-induced forces through wind tunnel experiments and solves the motion equations based on the measured forces to control the movement. In the force measurement process, given the complex structural shape of the bridge cross-section, a method employing load cells is preferred over using wind pressure sensors. However, measuring wind-induced forces with load cells presents the challenge of effectively removing the inertial forces that arise when the experimental model vibrates. In this study, the existing method of calculating the forces induced by wind on actual bridge cross-sections from load cell measurements was enhanced and applied to the RTAHS system. When conducting RTAHS experiments on actual bridge section model, the increase in the actual experimental mass ratio relative to the target mass input in the hybrid system led to the occurrence of unstable vibrations. Measures were implemented to remove these vibrations and ensure the stability of the experiments. The primary cause of instability was identified as the forces generated by additional vibrations between the load cells and jigs attached between them. To counter this, an accelerometer was affixed at the center of the model to account for and eliminate the vibration frequency components, thus addressing the additional vibration problem. This newly applied method for inertial force removal was validated by comparing the vibration results through vibration experiments on an actual bridge model.

**Ivan Arakistain**

TECNALIA Research and Innovation

**Predictive-Cognitive Maintenance for Advanced Integrated railway Management**

Railway systems play a vital role in modern transportation and Predictive-Cognitive Maintenance (PCM) has emerged as a transformative approach in the context of Advanced Integrated Railway Management for ensuring the safety and reliability of these systems. PCM leverages data analytics and machine learning to optimize railway system maintenance. This requires effective structural health monitoring (SHM) using low-cost sensor devices. This paper presents a prototype solar-powered wireless sensor node with a 3-axis MEMS accelerometer and energy-harvesting for monitoring rail track vibrations. A microcontroller runs embedded machine-learning models to preprocess the vibration data after train crossing. Abnormal vibrations, indicative of defects, were detected in real time using the TinyML inference at the edge. Instead of raw data, only the model results were wirelessly transmitted to a digital twin in the cloud. The digital twin aggregates data across the rail network for system-level assessment of the RUL and maintenance planning. This edge computing approach minimizes wireless transmission and cloud storage compared to raw sensor streaming. Embedded ML enables real-time damage detection, whereas the cloud digital twin enables system-level prognosis insights. The solar-powered platform enables long-term remote monitoring at low cost without wiring or battery changes. A full-scale physical model was used to validate the edge node prototypes against calculation models and wired accelerometers for impulse loads. In summary, this work proposes an edge computing and embedded ML approach for SHM that integrates cloud-based digital twins to enable the predictive-cognitive maintenance of railway infrastructure. Wireless nodes demonstrate potential for low-cost, automated rail health monitoring.

**Patrick Brewick**

University of Notre Dame

**Distributed Fiber Optic Sensing for Enhanced Digital Twins**

A variety of sensing modalities and sensor technologies are used to monitor the health, assess the condition, and quantify the life span of civil infrastructure. Among the more recent technologies utilized for health monitoring applications are fiber optic sensors, which are emerging as a popular choice for monitoring non-standard structures such as pipelines, offshore platforms, and marine structures. The current state-of-the-art in fiber optic technologies can embed numerous sensing points along a single, continuous fiber, creating a distributed sensing system that can contain thousands of points. These distributed sensing systems hold great potential for digital twin applications as they provide by the measure density and volume needed to inform virtual representations of desired structures. Our group has been working on a variety of applications of distributed fiber optic sensing systems to different structures. This work has included developing methods for estimating deflections and pressure from strain measurements, performing Bayesian model calibration using distributed strain data, and providing quantification of structural reliability. Results will be shared from an investigation into the cargo deck deflections of a class of hovercraft, wherein an idealized plate model of the cargo deck was calibrated based on distributed strain data. This study utilized a hierarchical Bayesian scheme that considers both the model parameter uncertainty and the prediction error variance to account for measurement noise and inherent variability of inferences made with data from different craft. Preliminary results will also be shared for a new investigation into estimating dynamic properties from distributed strain data.

# Working Group 2

## Structural Vibration Control

**Yoshiki Ikeda**

Kyoto University

### Unified Description of Passive Structural Control Based on Pole Allocation

The pole allocation method, which is widely used in control engineering, has been applied to a multi-degree-of-freedom lumped-mass damped shear model. The method is applicable not only to active/semi-active control but also to passive control. Through the selection of appropriate model parameters, the model can represent an earthquake-resistant structure, a base-isolated structure, an interstory-isolated structure, or a passively-controlled structure with a tuned mass damper, viscous dampers or a joint damper. The application determines that there is a mathematical equation governing the vibration of buildings. This equation is referred to as either a unified or governing equation. It automatically constrains the variations in the structural parameters and control devices by specifying the poles, and aids in physically understanding the control performance with an expression of the trade-off relationship in the control effect. Consequently, the introduced closed-form equation helps improve the trial-and-error design for passive control. The pole allocation method is related to the performance-based design in structural dynamics, because the application starts by assigning a control target to the vibration modes. The unified description is integrated with the fixed-point theories for tuned mass damper or joint damper. The integration directly links the structural damping with the damping of each damper, because the fixed-point theories do not provide the structural damping effect; rather, they provide the optimum damping coefficient for each damper. The proposed simple method is useful at the preliminary design stage to predict additional structural damping without dynamic analysis.

**Jan Høgsberg**

Technical University of Denmark

### Tuning of Proportional Position Feedback for Piezoelectric Vibration Control

In piezoelectric vibration control, the classic concept of Positive Position Feedback (PPF) may be conveniently applied, because piezoelectric patches, laminates or stacks can be used for both sensing and actuation. In its simplest form, the PPF control filter is governed by a cut-off timescale and a proportionality parameter. In design procedures, the negative proportionality parameter of the PPF is commonly chosen as the governing tuning variable, while the time scale is adjusted to place the filter cut-off relative to the targeted resonance of the structure. However, as demonstrated from a mechanical analogy, a very simple tuning expression is derived by instead considering the filter timescale as the variable tuning parameter, while the proportionality parameter adjusts the apparent structure stiffness. This alternative approach to the control tuning and design results in very simple expressions that provide guidelines for the balance between the time scale and gain parameter. The accuracy of the tuning expressions is verified by simple numerical results, while first experimental results are presented for bending vibrations of a cantilevered beam.

**Carlos MC Renedo**

Universidad Politecnica de Madrid

**Current challenges on Human-induced Vibration control on pedestrian structures: controller design, modelling and integration and implications of human-structure interaction phenomena**

Current architectural trends and the increasing use of lighter and more sustainable materials such as timber and recycled steel are transforming pedestrian structures (footbridges and floors) with an ever more lightweight and slender nature. This is degrading their dynamic performance when subjected to human-induced dynamic loading, and consequently, the vibration serviceability is becoming not only an increasing sizing criterion, but a difficult problem to address by structural engineers. When aiming to improve the dynamic behaviour of these structures, designers usually encounter ultra-lightweight structures in which human-structure interaction (HSI) phenomena play an important role. Accounting for HSI is essential for an accurate prediction of the dynamic response and to avoid oversizing the structural elements. In this context, the design of vibration controllers (integrated into the original design or added as retrofitting solutions) is a solution that enables keeping the lightweight and sustainability of these structures while enhancing their dynamic response. Additionally, the consideration of the HSI avoids the oversizing possible damping devices. The design, modelling, and integration of damping solutions (such as viscoelastic, viscous, or constrained layer dampers) into the structures, is a challenge by itself. On the other hand, the design of inertial controllers (such as tuned mass damper or its upgraded solutions such as semi-active and active mass dampers) results more complex on these structures as the influence of HSI is not negligible. This implies that important detuning problems and not negligible structural damping may complicate the optimal design of these controllers. Hence, the effective design of vibration controllers is a clear topic of interest for the further enhancement of the structural design of pedestrian structures.

**Chunwei Zhang**

South China University of Technology

**Rolling and Swing Vibration Control of Infrastructural Systems**

This talk will present the recent research and development of structural active vibration control technologies by Prof. Zhang’s group at multiple institutions, including SCUT, SUT and QUT in China. Particularly, the Active Rotary Inertia Driver (ARID) control system for rolling and swing motion and vibration of various marine infrastructure systems will be discussed, from theory to experiments, prototype and practice.

**Songye Zhu**

South China University of Technology

**New-generation structural vibration control strategy enabled by electromagnetic devices: Think outside the box**

Applications of active vibration control that normally correspond to superior control performance are generally hindered by their large power consumption. Nevertheless, considering structural vibrations can be inherently regarded as kinetic power sources, a novel self-powered active electromagnetic controller capable of simultaneous energy harvesting and actuation processes is proposed and subsequently developed. Besides the introduction of its topology, working mechanism, and power analyses, the proposed device has been deployed to the vibration isolation of a single degree of freedom (SDOF) system subjected to ground motion by imposing an classic active control algorithm, while remaining self-powered. Both analytical and experimental validations are performed to cross-verify its feasibility. The developed self-powered active vibration control will pave a new way for next-generation structural vibration control strategies.

**Łukasz Jankowski**

Institute of Fundamental Technological Research, Polish Academy of Sciences

**Reinforcement learning and damage-aware structural control**

This contribution discusses a semi-active control technique intended for mitigation of structural vibrations. The control law is implemented using the machine learning technique of reinforcement learning, that is in a repeated trial-and-error interaction between the control agent and a simulated environment. Such an approach allows to omit the stage of deriving the optimal control in an analytic way, which is often difficult in nonlinear, semi-actively controlled systems. A specific implementation of the Deep Q Learning (DQN) approach is applied, which promotes control robustness with respect to structural damages. A dedicated network architecture allows the network to be damage-aware, and a specific training procedure involves not only the observations, control actions, and rewards, but also the current health status of the structure. A numerical example is provided involving a shear-type building model subjected to a seismic excitation. The actuator takes the form of a tuned mass damper (TMD), which is semi-actively controlled by changing the level of viscous damping. The optimally tuned classical passive TMD is used as the baseline reference damping system.

**Zoran Rakicevic**

Institute of Earthquake Engineering and Engineering Seismology (IZIIS)

**IZIIS-Dynamic Testing Laboratory – Gathered Experience and Knowledge in the field of structural control**

Shaking table experiments are a technically justified and economically well-founded approach for obtaining valuable information in the field of earthquake engineering. When utilized effectively, they can serve as a suitable substitute for observing how structures behave during actual earthquakes. Incorporating this knowledge into design standards and codes before earthquakes occur can significantly reduce potential economic losses and the loss of human lives. Over the past five decades, shake tables have played a pivotal role in experimental research within earthquake engineering. Through the realization of 40 projects, IZIIS has extensively contributed to the development and experimental tests on systems based on new technologies – different systems for seismic isolation, passive systems for structural control, dampers for different purposes, application of new materials for repair and strengthening. Two representative projects will be discussed and presented. Both related to devices developed by European company for vibration control solutions and tested on our shake table. One related to the effectiveness of Prestressed Damping Devices (PDDs) in mitigating structural responses to seismic forces and establishing an optimal design and placement procedure for these or similar devices in earthquake-resistant structural design. The other is for Preloaded devices (PD)as a complement and control devices to base control system for seismic isolation.

**Kyriakos Chondrogiannis**

DABUG, ETH Zurich

**Structural Damping via Negative Stiffness**

Attenuation of mechanical vibrations is an interesting task that becomes particularly challenging for civil engineering applications. Novel concepts can demonstrate considerable prospect in advancing the current landscape of protective approaches. To this extend, one can vision a structural system not only as the unit to be protected, but also as the means of influencing dynamic behaviour. By appropriately controlling the properties of a structure, attenuation of vibrations can be achieved. To this end, one unique property that can be conveniently incorporated is that of negative stiffness. Negative stiffness elements can be integrated to a multi-storey structure with the purpose of shifting its dynamic characteristics. Appropriate manipulation of a storey's stiffness can lead to energy localization, protecting important parts of the system. An intriguing phenomenon that can be realized in use of negative stiffness, is the increase of the damping ratio, while damping capacity is unaltered. This counterintuitive effect has been examined analytically and further verified by means of experimental tests. It is physically demonstrated that appropriate deployment of mechanical configurations can yield to unique properties, serving the purpose of vibration attenuation. Innovative concepts, combined with practical implementations can advance the conservative sector of civil engineering in adopting new technologies for structural protection.

# Working Group 3

## Structural Health Monitoring

**Branko Glisic**

Princeton University

**Three research examples: passive wireless 3D sensing, hybrid data analytics, and economic benefits of SHM**

Pioneering deployments of sensor-based Structural Health Monitoring (SHM) were realized approximately one hundred years ago. Since then, the research, developments, and applications were continuously growing, and pushing the boundaries of the field. At the present day, SHM is recognized as mature, and with some limitations, it has become widely accepted and implemented by practitioners. Nevertheless, SHM still represents a vibrant research and development domain, as several challenges still need to be met. As an illustration, this presentation includes examples of recent advancements in three branches of SHM. The first example concerns research on new battery-less embeddable wireless sensors for distributed multi-parameter monitoring (displacements, strain, cracking, temperature, and humidity) within the large volumes of construction materials, such as concrete or pavement courses. Sensors use the properties of mutual radiofrequency communication channels as the encoding parameters; sensors' performances are tested and presented. The second example is related to development of hybrid, physics-informed data-driven data analytics, that enables reliable and accurate evaluation of structural performance and health condition. Applications to long-term strain and temperature data, and the discoveries enabled by the hybrid data analytics are presented, including evaluation of reliability of sensors, separation of individual strain constituents such as elastic, thermal, and rheological strain, detection and characterization of unusual structural behaviors, and improvements of predictive analytical models. The third example of research included in this presentation is related to evaluation of economic benefits of SHM, with some preliminary results regarding the introduction and application of survival analysis for that purpose.

**Yolanda Vidal**

Universitat Politècnica de Catalunya

**AI for Structural Health Monitoring of Offshore Wind Turbine Jacket Platforms**

This work leverages supervised and unsupervised AI approaches to detect damage in offshore wind turbine jacket supports using only accelerometer data. Methodologies studied include autoencoders, transformers, Siamese neural networks, support vector machines, and principal component analysis. Models are trained and validated on vibration data from a laboratory down-scaled replica of an offshore wind turbine with jacket support under normal operation, and seeded damage scenarios. Capabilities in detecting damage located in the jacket support across various operating states are analyzed. Results provide insights into the efficacy of vibration-response-only AI models in assessing the structural health of the turbine jacket support.

**John Vazey**

EngAnalysis

**Insights from the Antipodes**

Australia has some fairly unique challenges in sparse population, distributed assets, a lot of heavy vehicle movements with mining and a risk adverse administration. This talk briefly highlights some of the recent work locally to indicate where utilities are finding value in structural monitoring. The talk will also present some of the challenges and failures with an emphasis on the business aspects of delivering SHM solutions.

**Daniele Zonta**

DICAM, University of Trento

**Bayesian data fusion of satellite InSAR and terrestrial measurements for enhanced structural health monitoring of bridges**

This study introduces a novel structural health monitoring approach by integrating Interferometric Synthetic Aperture Radar (InSAR) and topographic measurements using a Bayesian data fusion technique. Focusing on the Belprato 2 Viaduct, affected by a extremely slow-moving landslide, the research demonstrates how combining diverse monitoring datasets can overcome the limitations of traditional methods that rely on single data sources. The integrated approach enhances the accuracy and temporal resolution of displacement measurements providing a three-dimensional monitoring of the bridge movements. This study validates the effectiveness of the data fusion approach through a detailed comparative analysis, showing significant improvements in detecting millimeter-scale displacements critical for early identification of structural vulnerabilities. Future research will explore the incorporation of additional data types, aiming to refine the accuracy and utility of structural health monitoring practices.

**Carlos Moutinho**

Faculty of Engineering of University of Porto

**Customized sensors for continuous monitoring of long-span bridges: a contribution from CONSTRUCT/FEUP**

Driven by recent technological advances in the area of sensors and microcontrollers, new data acquisition systems have emerged for static and dynamic monitoring of Civil Structures and Infrastructures. In addition to generally having a more attractive cost compared to traditional solutions, they can be more flexible and easily customizable for specific applications. Furthermore, they can simplify the installation process, minimizing the use of cables spread across structures, and facilitate maintenance and repair operations. In this context, this presentation aims to describe real-world applications of this technology involving continuous static and dynamic monitoring of several long-span bridges. Three case studies are related to steel and concrete arch bridges that crosses Douro River in Porto. Another case study focuses on the dynamic monitoring of the cables of the suspension bridge that crosses the Tagus River in Lisbon. Details related to the developed customized sensors are provided, which consist of accelerometers, strain gauges, displacement sensors and temperature sensors. The main results relating to the research on these structures are presented and discussed, validating the effectiveness and suitability of the used technology, and contributing to more structures being instrumented in the future at more attractive costs.

**Xiaoyou Wang**

The Hong Kong Polytechnic University

**Improving machine learning model adaptation or generalization for structural damage detection**

Machine learning (ML) models face performance degradation when migrating to datasets with different distributions from the training data. This challenge limits their applications to structural health monitoring because many structures may have the same topology but different sizes, whereas recollecting labeled data to retrain models is expensive and time-consuming. Domain adaptation (DA) and domain generalization (DG) techniques have been developed towards the out-of-distribution problems. DA aims to minimize the feature shift and extract domain-invariant features by adapting the feature distributions between the source and target domains, thus, the labeled source domain can assist in the classification of the unlabeled target domain. By contrast, DG aims to learn a predictive model that can extract invariant features across source domains and then generalize to related but unseen target domains. The difference between DA and DG methods is whether unlabeled target data participates in the model training. Towards the structural damage detection problems where both feature and label shifts exist, we will develop customized DA and DG methods to improve the ML model adaptation or generalization across different structures. Numerical and experimental examples will be used to demonstrate that the developed methods outperform state-of-the-art DA or DG methods in damage detection of both mechanical and civil structures. The methods can be extended to related tasks in other fields.

**Charikleia Stoura**

ETH Zürich

**On-board monitoring of railway bridges from acceleration data of passing trains**

The global railway network sprawls across more than a million kilometers of tracks, with plans for further expansion underway. This expansion aims to promote rail transport as an eco-friendly solution to meet the increasing demands for mobility. A substantial portion of these tracks runs over bridges, which must adapt to heightened mobility needs and faster travel while bearing heavier loads. At the same time, bridges worldwide are aging, leading to structural deterioration. This dual challenge underscores the importance of monitoring the structural health of bridges, aiming to uphold the safety and quality of railway networks by identifying changes in their structural behavior. Traditional Structural Health Monitoring (SHM) relies on stationary sensors attached to bridges, offering direct data assessment but posing limitations in inspecting multiple bridges efficiently. Alternatively, mobile vibration-based sensing, employing sensors on passing trains, shows promise in gathering data from various bridges with just a few on-board sensors. Moreover, running sensor-equipped trains frequently enables continuous data collection, providing insights into bridge deterioration trends. To this end, a methodology that extracts bridge modal frequencies from train-acquired acceleration data is presented. This drive-by monitoring approach aims to assess the remaining bridge lifespan and prompt repairs when damage occurs, ensuring the safety and reliability of railway transport.

# Special Session

## Vision based SHM

**Yongchao Yang**

Michigan Technological University

**Super-sensitivity Full-field Measurement of Structural Dynamics**

The sensitivity of incoherent optical methods using video cameras (e.g., optical flow and digital image correlation) for full-field displacement measurements, defined by the minimum measurable displacements, is essentially limited by the finite bit depth of the digital camera due to the quantization with round-off errors. Quantitatively, the theoretical sensitivity limit is determined by the bit depth *B* as $\delta p = 1/(2^B - 1)$ [pixel] which corresponds to a displacement causing an intensity change of one gray level. In our recent study, we explore the possibility to break such a sensitivity limit by leveraging the random noise in the imaging system with a natural dithering to overcome the quantization. We present our recent study on the quantification of such a theoretical sensitivity limit and the development of a spatiotemporal pixel-averaging method to achieve super-sensitivity full-field measurements of vibration (displacement) of flexible structures. We will present and discuss the numerical simulation and laboratory experiment studies. We also derive a mathematical model for the achievable super-sensitivity, which is found to be quantitatively determined by the total pixel number for averaging and the noise level.

**Gang Liu**

Chongqing university

**Mode extraction on wind turbine blades using improved phase-based motion estimation**

The structural dynamic characteristics are important to ensure structural safety, and the modal parameters are important indicators to assess the vibration properties. The natural frequency of wind turbine blades and effective mode shape provide a reliable basis for avoiding wind turbine resonance, damage identification, and localization of the structure, respectively. Traditional modal analysis requires physically connected wired or wireless sensors such as accelerometers mounted on the structure. Although these sensors are reliable, their installation is time-consuming and labor-intensive for structures corresponding to large wind turbine blades. Low-cost and highly flexible digital video cameras offer the possibility to measure modal information with high spatial resolution. However, most of the existing photogrammetric methods stop at motion displacement extraction, which does not enable high-resolution modal information extraction, and very few studies have been conducted to extract high-resolution structural modal information directly from video images. In this study, a visualized high-precision modal information video measurement extraction method is developed, which enriches the field of applying video images to extract structural modal information. The high-resolution single-mode vibration formulas of structures in images are theoretically derived from the phase perspective to provide a high-precision modal information basis for structural damage identification and localization. The proposed modal identification method is applied and validated on a scaled-down tower model.

**Yang Xu**

Harbin Institute of Technology

**Structural Damage Diagnosis by Computer Vision with Limited Supervision**

The successful development of computer vision and deep learning techniques has recently revolutionized structural health monitoring (SHM) for civil infrastructure. Multi-source monitoring and inspection data are projected into a high-dimensional feature space, and data-driven models are established to map the relationships between inputs and outputs and dig out embedded structural behaviors and implicit physical mechanisms. However, the model performance highly relies on the extensive amount and diversity, intra-class completeness, and inter-class balance of training data, and the generalization ability on scarce data with specific features and particular patterns is challenging under real-world scenarios. This talk aims to overview recent advances in structural damage diagnosis by computer vision with limited supervision. First, a unified mathematical framework of few-shot learning is formulated with error analysis of conventional supervised learning. Then, a taxonomy of metric learning-based, optimization-based, transfer learning-based, and generative model-based methods is summarized. Finally, various applications of computer-vision-based structural damage recognition and condition assessment under real-world scenarios are present following a small-data regime.

**Sunjoong Kim**

University of Seoul

**Unpaired Image-to-Image Translation for Cable Vibration Detection from Low-Visibility CCTV Images**

This study focuses on monitoring excessive vibrations in the stay-cables of long-span bridges using cost-effective surveillance cameras (CCTV) commonly employed for traffic monitoring. Overcoming the challenge posed by hazy and low-visibility CCTV images, this research employs an unpaired image-to-image translation algorithm to dehaze these images and improve their visibility. We validate the effectiveness of our proposed framework using sequential CCTV images captured from a real cable-stayed bridge under harsh environmental conditions. The proposed approach demonstrates superior performance compared to conventional computer vision algorithms operating without the inclusion of an image translation process.

**Yong Xia**

The Hong Kong Polytechnic University

**Phase-based optical flow technique for full-field vibration measurement of long-span bridges using a single camera**

Displacement measurement is necessary for performance-based design and assessment. However, conventional sensors measure the displacement either in a contact manner or without sufficient resolution and accuracy. This study develops a cost-efficient and high-resolution dynamic displacement measurement using the phase-based optical flow technique with one camera only. Two challenges, namely, the complex environment and full-field motion, are overcome. The technique is applied to the 1377 m long Tsing Ma bridge. One camera was set at a distance of over

600 m from the bridge. The measured full-field dynamic displacement of the bridge has a good agreement with the GPS data in both time and frequency domains.

# Special Session

## Physics Informed approaches

**Alice Cicirello**

University of Cambridge

**Physics-enhanced machine learning strategies for SHM applications under limited information**

This contribution will review three recent approaches developed within the Data, Vibration and Uncertainty group based on Physics-enhanced Machine Learning to tackle Structural Health Monitoring challenges under limited information. The first approach belongs to the physics-guided ML strategies and enables one to identify and account for data spatial and temporal correlations in probabilistic model updating of expensive-to-evaluate models. The second approach belongs to the Physics-encoded domain ML strategies and enables the identification of discontinuous nonlinearities in dynamical systems using a Physics-Enhanced Sparse Identification when a limited number of input-output measurements is available. Finally, a physics-informed ML strategy is presented for disentanglement representation learning with physics-informed variational autoencoder. Each approach is going to be illustrated via a benchmark case study, and open challenges will be discussed.

**Yuequan Bao**

Harbin Institute of Technology

**Mechanics-informed machine learning for structural health monitoring**

In recent years, machine learning theory has provided a new way to discover the service performance and safety of structures through deep mining of monitoring data. This paper mainly introduces machine learning methods for big data mining and analysis in SHM. Firstly, the principle of mechanics-informed machine learning is discussed. Then, the mechanics-informed machine learning method for data anomaly diagnosis, modal identification, time-varying modal analysis, structural damage identification, and structural reliability evaluation are discussed. Finally, the application in actual structures are presented.

**Audrey Olivier**

University of Southern California

**Bayesian quantification of uncertainties in data-driven and hybrid models for SHM applications**

Appropriate utilization of structural health monitoring data for actual decision-making requires robust quantification of uncertainties present in the data and models. Sensing data is noisy, collected under varying environmental conditions, and availability of data greatly varies depending on the damage level yielding highly imbalanced datasets. Bayesian methods can be leveraged to disentangle aleatory and epistemic uncertainties and – through their intrinsic trade-off between data (likelihood) and prior -- offer an interesting path to integrate physics intuitions within machine learning schemes to create hybrid models. While Bayesian inference is now routinely used to quantify uncertainties in physics-based models, their use within advanced machine learning frameworks or on-line identification algorithms for dynamical systems, of particular interest to SHM applications, is both technically and computationally challenging. In this summary, I will present some recent work from our research group on integrating robust Bayesian uncertainty quantification in physics-based, data-driven and hybrid models for structural health monitoring applications.

**Ananth Ramaswamy**

Indian Institute of Science

### Physics Based Health Monitoring Methods Applied to Estimate Long Time Loss of Prestress in PSC Girders and Slabs

Prestress losses occur in concrete structures due to long-time creep and shrinkage in concrete, and stress relaxation in prestressing strands. This can result in compromising the safety of the structure. The existing formulations for creep and shrinkage modelling in concrete are empirical in nature, which have been developed based on a particular set of measured data. Existing models for shrinkage and creep predictions in the codal provisions and in the standard recommendations do not agree in a best possible way with the available experimental results reported in the literature, as the existing models have been developed based on an arbitrary selection of experimental data sets among all the available data sets. Statistical variations are present in the creep and shrinkage models, in the parameters of these models, in the shrinkage and creep mechanisms, in the environmental conditions, and in the in-situ measurements. A coupled hygro-thermo-mechanical formulation is used to model the physics associated with creep and shrinkage in concrete structures in the present work. Uncertainty tools based on a probabilistic framework are used to model the possible variations in the input variables in the hygro-thermo-mechanical formulation. A distance measure based global response sensitivity analysis is adopted to identify the parameters having maximum impact on the output responses. Uncertainties in the selected set of important variables are reduced using Bayesian inference and short-time measured responses. For validating efficiency of the uncertainty reduction technique adopting Bayesian inference and global response sensitivity, the predictions of creep and shrinkage in concrete are compared with a few experiments from the North-Western University (NU) data-base. The uncertainty reduction technique is then used to predict the long-time prestress losses in post-tensioned concrete beams and slabs cast in the laboratory.

**Antonio Palermo**

University of Bologna

### A strain-to-displacement operator for damage identification in railway bridges

Railway bridges are pivotal for the transportation system due to the limited redundancy of the railway network. However, their aging is a growing global concern as many have already exceeded their design life. As such, structural health monitoring (SHM) systems have been implemented to assess the state of health of these structures. Still, most SHM systems process heterogeneous data types individually, thus highlighting their inherent limitations. For instance, dense sensor networks are generally required for a robust identification of damage-sensitive features. Also, low-budget sensors have a limited sensitivity suitable for monitoring the effects induced by a high level of loads, which may be nonstationary and not comply with the typical assumptions of operational modal analysis. Moreover, the measurements are affected by temperature fluctuations, which need compensation methods that may contribute to propagating errors. To alleviate some of the above issues, we propose a novel damage index for railway bridges based on sparse synchronous strain and displacement data collected at the passage of trains. The approach utilizes a transformation operator that maps strains into displacements in a data-driven fashion without prior structural knowledge and with no parameter selection. The displacement prediction error is proposed as a robust damage index, insensitive to the vehicle loads and temperature effects. Numerical simulations and experimental data of a steel truss bridge demonstrate the effectiveness of the proposed approach.

# Special Session

## Practical Applications & Challenges

**Ivan M. Diaz**

Universidad Politecnica De Madrid

### Vibration-based NDT of external post-tensioning tendons in bridges: challenges on field applications and machine learning methods for data treatment and anomaly detection

External post-tensioning tendons are key structural elements in bridge engineering since they are vulnerable to corrosion and fatigue. There is a clear demand of: i) NDT systems for detecting anomalies in post-tensioning systems, and ii) the development of cost-effective continuous monitoring structural health monitoring systems (minimum number of sensors). Vibration-based techniques allow simultaneously the tracking of their natural frequencies and the estimation of their tension forces. It has been demonstrated that higher frequencies are more sensitive to damage. Additionally, due to the non-negligible bending stiffness and the present of boundary conditions different from pinned supports, the continuous tendon force tracking is another challenge to cope with. The main problem, under the usual case of short taut external tendons, is that there are not analytical solutions for the natural frequencies and they should be derived numerically by solving an implicit transcendental equation with make difficult to continuously track the tension force through model updating. Additionally, an optimization problem has to be undertaken. Machine learning-based clustering and regression offer interesting tools to tackle most of the difficulties on the SHM of external tendons: i) spectral doublets (due to different moment of inertia depending on the direction, the frequency coupling from adjacent segments and the presence of bracing systems), ii) significant frequency variation due to temperature changes that may mask potential damage , iii) selection of principal/significant performance indicators to be tracked, iv) automatic detection of abnormal tendons in multi-span bridges with a huge number of tendon segments, and v) detection of abnormal tendon segments within a multi-span tendon considering friction losses and anchor sets.

**David Garcia Cava**

The University of Edinburgh

### Embracing long-term performance: Mitigating Environmental and Operational Variabilities in Time-Variant Structures

Mitigating the impact of Environmental and Operational Variability (EOV) on continuous data-driven methodologies is essential for extracting Damage Sensitive Features (DSFs), which depict the dynamic properties of structures independently of their associated EOV. In the context of long-term monitoring applications, there are numerous structural states that exhibit similar behavior but cannot be generalized with a single model (whether data- or physics-based) due to the inherent time-variant nature of structure evolution. Addressing such scenarios necessitates methodologies with adaptable models that can capture the interdependencies between EOV and DSF at various stages of structural evolution. The challenge lies in determining when distinct structures can be considered pseudo-similar, thereby sharing the same underlying physical properties. This identification is crucial for assessing whether information can be effectively transferred to better represent the dynamics and associated EOVs corresponding to each time-variant state in the structure's evolution. In light of these considerations, I aim to share recent advances and engage in discussions with colleagues regarding developments in research focused on mitigating EOVs in structural dynamics and health monitoring applications.

**Jian Guo**

Southwest Jiaotong University

**SHM for crossing-sea bridges construction and operation**

In complex marine environments, the crossing-sea bridges face various typical load excitation with the extreme and non-stationary effect, which directly affects the safety and reliability of crossing-sea bridges construction and operation. How to monitor and identify the typical loads through precise methods is a very challenging task. Especially under high temperature, high salt, and high humidity conditions, previous testing techniques and perception methods need to improve durability and the ability to information target acquisition. Basing on test research on-site, the shortcomings of existing loads identification are analyzed. The development achievements of real-time monitoring methods for typical loads of crossing-sea bridges in complex marine environment are introduced. It is pointed out that further in-depth research on typical load models of ocean bridges is needed in the future, which will provide a basis for engineering construction and maintenance.

**Bartlomiej Blachowski**

Institute of Fundamental Technological Research, Polish Academy of Sciences

**Neural network based compressive sensing and its application to SHM of civil infrastructure**

Data fusion and multi-type sensor placement in structural health monitoring (SHM) are promising techniques for reliable estimation of current condition of the civil infrastructure. Unfortunately, in large scale structures equipped with a variety of sensors one needs to address the transmission and storage challenges associated with big data gathered during measurements. One way to avoid the overwhelming amount of information is to reduce the spatial resolution and optimize distribution of sensors. The other way is to reduce sampling frequency over a heterogeneous network of sensors. Compressive sensing (CS) is an efficient tool for reducing the sensor sampling rate, which is especially important in structural health monitoring of civil infrastructure. However, practical issues with the sampling and reconstruction algorithms prevent vast development of CS in real world engineering structures. Deep learning (DL) allows better flexibility of CS for adapting the sampling matrix, reconstructing the signal, and learning from the compressed samples. While the integration of deep learning and compressive sampling received recently significant research interest, it has not yet fully clarified what kind of neural networks architectures are best suited for such problems. In this paper main types of neural architectures will be discussed and preliminary results for the implementation of DL based-CS on tied-arch bridge equipped with heterogeneous network sensors will be presented.

**Aleksandra Bogdanovic**

Ss. Cyril and Methodius University in Skopje

**IZIIS experience in structural monitoring for more resilient and sustainable structures - Case study, Ohrid, N. Macedonia**

The continuous and cost-effective operation of structures relies heavily on their proper maintenance and management. To implement optimal management strategies for existing structures, it is crucial to accurately assess their current and future safety. Therefore, the monitoring of structures can be considered a necessary prerequisite for ensuring their safe and efficient functioning under anticipated hazardous conditions during their operational life. Despite the methodology initially used in their design, the conditions of structures change over time due to various external factors and rare extreme events such as earthquakes, strong winds, and floods. The results of real-time structural monitoring, involving the recording, measurement, and processing of data (including vibration records resulting from ambient or other dynamic excitations) in real-time, with the ability to access this data via an internet connection at any time will be discussed. The behavior of the structure is monitored under normal operational conditions, as well as during and after seismic events, if any occur during the specified monitoring period. This approach allows for the timely detection and identification of structural damage, as well as the determination of its current state and suitability for continued use. The recorded data are analyzed using various system identification methodologies to obtain essential information about the structure and its performance. Data processing involves mathematical and software solutions, with an emphasis on methodologies developed at UKIM-IZIIS. Ultimately, this research aims to facilitate the development of a more effective and cost-efficient strategy for the continuous monitoring and maintenance of structures.