INTRODUCTION TO STRAIN-BASED STRUCTURAL HEALTH MONITORING OF CIVIL STRUCTURES

BRANKO GLIŠIĆ

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Introduction to Strain-Based Structural Health Monitoring of Civil Structures

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Branko Glišić
Princeton University
Princeton
United States

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To my spouse Tanja and daughter Lana, to our extended family in Serbia, Croatia, North Macedonia, and Sweden, to our friends, and to all SHM enthusiasts.

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Preface

Importance of safe and reliable civil structures and infrastructure, or simply "structures," has been well ascertained in every society throughout human history, which is confirmed by many still-standing and still-in-use historic and old structures. Experiences teach us that many centuries-old structures survived to present day thanks to, of course, the quality of their design and construction, but also proportionately, if not more critically, thanks to preservation activities performed throughout their lifetime, including inspections, maintenance, repairing, and retrofitting or repurposing.

Over the centuries, in-person inspections have been, and still are, an invaluable source of information on structural performance and condition and have been often used as the trigger for informed preservation activities. Modern Structural Health Monitoring (SHM) was born about a century ago with the idea to complement in-person inspections and address their limitations using advanced technologies. And while progress in applications was slow during the twentieth century, revolutions in informatics, communication, and computing technologies enabled research, development, and more widespread application of SHM in the last 30 years and made SHM in general mature, viable, and, with some limitations, mostly related to cost-benefit evaluation policies, accepted among practitioners.

Strain-based SHM has been at the forefront of SHM applications on real structures due to importance, quality, and versatility of information provided by this type of monitoring. Yet, at the time of the inception of this book, both researchers and practitioners whose work involves strain-based SHM could not find fundamentals or comprehensive overview of the technique in a single reference; rather, they would have to search the information in multiple sources – books, manuals, guidelines, scientific articles, etc. – that are often presented at higher level and written with focused technical language, which can often be non-intuitive and difficult to understand for wider populace of readers, especially for beginners but frequently for advanced readers too.

Hence, the aim of this book is to address this issue, i.e., to provide a single reference book with the fundamentals of strain-based SHM that can be used by both beginners and advanced users interested in strain-based SHM. That is the reason why the book builds its contents from very broad and introductory topics toward very specific and practical subjects.

Chapters 1 and 2 of the book provide a general introduction to SHM, SHM systems and subsystems, and their specifications; while the readers experienced in SHM can skip these two chapters, they can still find a good overview of logistics of implementation of SHM that they might find useful. Chapter 3 is dedicated to strain sensors; an overview of the most frequently used strain sensors is provided, along with their advantages, shortcomings, and summaries of best performances. Hopefully, this chapter helps the reader identify technologies suitable for their applications.

Chapter 4 deals with the errors and uncertainties in strain measurements and provides basic methods for their assessment and evaluation. Errors and uncertainties due to properties of measuring subsystem are presented first, followed by presentation of errors and uncertainties introduced by specific sensor features such as thermal compensation, gauge length, spatial resolution, sensor packaging, and the manner of installation of sensor. Depending on the case, these errors and uncertainties are analyzed either quantitatively or qualitatively.

Chapters 5, 6, and 7 provide practical approaches for model-based analysis of monitored strain at local, global, and integrity scales, respectively. Chapter 5 gives first an overview of strain, sources of strain such as loading, temperature, and rheological effects, constitutive equations for typical construction materials, and analytical models for strain distributions in beams under the assumptions of linear theory. Then, the same chapter provides analytical expressions and criteria for detection of unusual structural behaviors, such as damage or deterioration, and applies them at the local scale. Chapter 6 expands the expressions and criteria to groups of sensors and global scale, and Chapter 7 to integrity scale while mostly focusing on crack detection and characterization as the most fundamental type of damage. The book closes with Chapter 8 that provides a summary and future perspectives.

Chapters 4, 5, 6, and 7 are extensively illustrated with examples taken from real-world applications. Particularly in Chapters 4, 5, and 6, there are numerous tables with data taken from real projects that are given alongside the equations and algorithms for data analysis, so the readers can apply the equations and algorithms, perform the analysis on their own, and compare it with the results presented in the book. In my opinion, the possibility for readers to practice data analysis using real-world examples makes this book especially useful and probably unique on the market. However, as a disclaimer, while all problems presented in the book were solved and the solution verified at least once, there may still be some errors present; in that case, please contact me so I can make corrections and make available corrected solutions to the readers.

For readers interested in more advanced topics of strain-based SHM, I strongly recommend the book I co-authored with one of my mentors, my former employer, and dear friend, Dr. Daniele Inaudi, *Fibre-Optic Methods for Structural Health Monitoring*. While that book has some common points with this one, it contains principles for creation of monitoring strategies for numerous types of structures and extremely rich set of real-world applications.

My involvement in strain-based SHM started at the Swiss Federal Institute of Technology in Lausanne (EPFL) when I built my first batch of fiber-optic sensors and embedded them in hybrid, steel-concrete specimen; since then, my passion for strain-based SHM has only grown, and my awe for its performance has been fulfilling my professional life. I hope that this book, which encompasses experience from more than a quarter of a century of my work in strain-based SHM, will transmit my admiration for the technique and serve not only educational and professional purposes but also inspire future research and applications.

Princeton (New Jersey, USA),
Valjevo (Serbia), and Rijeka (Croatia)
July 2023

Sincerely,

Branko Glišić
bglisic@princeton.edu

Foreword

I am honored to have been invited to write the Foreword to *Introduction to Strain-Based Structural Health Monitoring* by Dr. Branko Glišić of Princeton University. It is not every day you get asked to write a foreword by a luminary like Branko, so of course, I said yes! Not only is this foreword an opportunity to introduce an outstanding book on strain and its role in assessing structural health, but it is also a way for me to pay Branko back for everything I have learned from him over the years.

I was first introduced to the magical world of structural health monitoring when I was a graduate student at Stanford University in the late 1990s. At the time, the nascent field and the small research community forming around it were just beginning to define what we today would define as "structural health monitoring." A quarter of a century later, I am amazed by the dramatic progress this field has made with structural health monitoring, now a well-established, interdisciplinary field devoted to developing sensing and decision-support systems that can be used to detect deterioration in structures to ensure their safety. For me, the beauty of structural health monitoring lies in how it can be generalized and applied to so many types of "structure": some obvious like airplanes and bridges, and some not so obvious like metallic implants in human bone. Today, the field is vibrant and alive with innovation. Essential to building momentum in structural health monitoring is the diverse group of young students, researchers, and practitioners across the globe entering the field to contribute their talents to ensure safe and efficient structures for societal use. This future generation will be well served by Branko's *Introduction to Strain-Based Structural Health Monitoring* which provides a comprehensive and elegantly designed overview of strain sensors and their use to assess structural health and performance.

Those readers who enjoy music will appreciate the term "oldies but goodies" which refers to legendary hits that remain very much relevant and popular to millions. The topic of this book is strain, which is the most basic form of structural response measurable – for certain, an "oldy but goody" measurement. While the piezoresistivity of conductive materials has been known since the 1850s, the era of strain measurements really launched in 1938 with the invention of the strain gauge by Simmons and Ruge. Strain is a fundamental structural response to its environment and an essential modeling parameter in the field of engineering mechanics. Ironically, structures are designed based on concepts of stress, yet stress is a conceptual abstraction that is immeasurable. In contrast, strain can be measured with stress inferred from strain using constitutive models. Hence, strain has a special place in the field of structural health monitoring given its relationship to estimating the stress used to determine structural performance relative to engineering limit states. Strain has been a challenging measurement to reliably collect in structures over decades of service, especially when using low-cost metal foil gages that can only measure strain at single points where damage may or may not be detectable. This has encouraged the field to explore other sensing modalities for structural health monitoring. More recently, exciting innovation in strain sensing has once again renewed

dramatic interest in strain-based structural health monitoring. Innovations like distributed strain sensing using fiber optics and smart appliques that can map strain over large surfaces are driving that interest.

Branko's *Introduction to Strain-Based Structural Health Monitoring* provides readers with a complete overview of strain and its potential to empower practical structural health monitoring solutions for real-world structures. The book's greatest feature is how it offers readers a complete structural health monitoring framework in which strain sensors can be applied. His review of the available strain-sensing technologies that have evolved over three generations of innovation offers readers a complete understanding of the strengths and weaknesses of these sensors when applied to real-world systems. Equally novel is the articulation of how to incorporate strain measurements into damage detection methods at various length scales ranging from the local to the global and integrity scales.

Without question, Branko is offering readers one of the most comprehensive books I have ever read on strain measurements and their use in diagnosing structural health. He impressively provides a delicate balance between theory and practical application, a skill he uniquely possesses due to his leading innovation as both an academic and practitioner. His years serving as lead engineer at SMARTEC SA, which at the time was one of the global leaders in long-gauge and distributed fiber-optic sensors, provide Branko with a unique understanding of how structural health monitoring works in complex operational structures. For those readers who are fans of *Fibre Optic Methods for Structural Health Monitoring* co-authored by Branko with another field luminary, Dr. Daniele Inaudi, you are sure to not be disappointed with *Introduction to Strain-Based Structural Health Monitoring*. I am sure you will enjoy the read and learn as much as I did from this titan of the structural health monitoring field!

Durham, North Carolina
July 2023

Jerome P. Lynch, Ph.D., F.EMI
Vinik Dean of Engineering
Fitzpatrick Family University
Distinguished Professor of Engineering
Duke University

Foreword

Retrospectively, I must recognize that a proper textbook on strain health monitoring of civil structures was long due, particularly one addressing the matter with method and clarity. I have been offering a SHM course at the University of Trento since 2013. While preparing the teaching material for the first year, I remember struggling to develop a consistent syllabus suitable for civil engineers: at that time, SHM, and particularly civil SHM, was still a discipline composed of a vast, heterogeneous, sparse material with no all-encompassing reference textbook that students could use as a guide.

Of all the available bibliography, recommended readings to the students were, for instance, Ewins' "Modal Testing" for vibrational methods; Wenzel's "Health Monitoring of Bridges" for case studies; Melchers' "'Structural Reliability" for evaluating structural safety based on monitoring information. Then there was Glišić and Inaudi's "Fibre Optic Methods," much more than a book on fiber-optic sensors, as the title would suggest. What made Prof. Glišić's book different was its rigorous quantitative approach, based on continuous mechanics, to data interpretation and monitoring design – a germinal version of what You will find, fully developed and matured, in the present book.

So, 10 years on, has the civil SHM panorama changed? In terms of number of textbooks: a lot. In terms of method: not that much, to be honest. Still today, the layman tends to see SHM as a magic tool that You install on a bridge or a building and wondrously tells You whether this bridge or building is safe thanks to unspecified technological wizardry.

Even practitioners and parts of the academic community do not always get the logic of monitoring right. In a 2014 paper, Prof. Glišić and I observed a civil engineer paradox: engineers use a rigorous quantitative approach when dimensioning structures but usually the rule of thumb when designing monitoring systems. It should come as no surprise that a civil engineer is (normally) very good at designing a bridge or a building. The objective of structural design is probably obvious to most: dimension structural members to ensure stability under design loads. Designing a structure, the good engineer sticks to a well-established process, often acknowledged in standards and codes: define the design loads; calculate the member's stress demand by structural analysis, using a structural model (e.g., a finite element model); dimension the members to the required demand; assess that the capacity is greater than the demand.

Let the same good civil engineer design a monitoring system, and most likely, their approach will be heuristic, based on common sense or experience rather than on quantitative analysis. It looks like the average engineer does not grasp the objective of monitoring and does not master its underlying logic.

Effectively, SHM is about acquiring data using sensors to understand the condition state of a structure. A monitoring is well designed when it allows inferring the state of the structure with few

or no uncertainty. Uncertainty management is the keyword: reducing the uncertainty of structural state knowledge is the goal of SHM.

Monitoring design should follow a rigorous design process similar to structural design: define the target accuracy of the structural information meant to be learned through monitoring; calculate the required accuracy (demand) of instrumental data using uncertainty propagation analysis; choose the sensor technology to meet the required demand for accuracy; assess whether the expected uncertainty (capacity) is better than the target demand.

One of the breakthroughs of this book is to finally frame the problem of monitoring performance under the right light. Whereas the structural design objective is to achieve stability with an appropriate level of safety, the object of monitoring is to learn the state of the structure with an appropriate level of confidence. Uncertainty management and structural analysis play a crucial role in this process.

Notably, Chapter 4 is entirely dedicated to uncertainty analysis and error propagation. In logical terms, structural health monitoring (SHM) is formally identical to the metrology problem of indirect measurement, where the measurand is indirectly estimated based on observation of other physical quantities linked to the measurand. Similarly, Chapter 5 approaches the problem of monitoring data interpretation from a rigorous mechanics-based standpoint.

Another side of this book that deserves praise is its practical cut. For the very few who don't know him, Prof. Glišić is much more than the clichéd Princetonian academic. He features a unique industrial expertise in SHM, having matured initially as an R&D manager at Smartec SA between 2000 and 2008 and then as one of the most dynamic applied scientists in our community. In his successful career, he accomplished hundreds of SHM projects worldwide, addressing bridges, buildings, historic construction, dams, and lifeline facilities. His unparalleled first-hand experience is evident in this book, where every theoretical step is supported and made clear with plenty of case studies and real-life examples.

During my past visits to Princeton University, I have had the privilege to personally appreciate Prof. Glišić's rare teaching capabilities. His Structural Health Monitoring course, offered since 2009, is possibly the first regular graduate course on SHM for civil engineering launched in the US. By reading this book, practitioners, academics, and students alike will all acknowledge Prof. Glišić's extraordinary communication skills: He is a truly inspiring educator, capable of conveying his genuine enthusiasm for SHM with rigor and ease.

Even if there is still a long way to go before consolidating a proper common syllabus in Civil Structural Health Monitoring, this book, and the message it carries, is a fundamental milestone toward this goal. In short, I very much welcome a textbook on civil SHM that finally gets it right – Good job, Branko!

University of Trento
Italy

Daniele Zonta, Ph.D.
Professor, Department of Civil,
Environmental, and
Mechanical Engineering

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I would like to acknowledge and deeply thank numerous selfless individuals – students, colleagues, friends, and family members – as well as various institutions – professional associations, agencies, schools, and companies – whose availability, support, collaboration, professionalism, kindness, and patience, in one way or another, influenced the creation of this book.

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About the Author

Prof. Branko Glišić received his degrees in civil engineering and theoretical mathematics from the University of Belgrade, Serbia, and PhD from the EPFL, Switzerland. After eight years of experience at SMARTEC, Switzerland, where he was involved in numerous Structural Health Monitoring (SHM) projects, he has been employed as a faculty member at the Department of Civil and Environmental Engineering of Princeton University, where he is currently serving as the Chair of the Department. His research is in the areas of SHM, smart structures, heritage structures, and engineering and the arts.

Prof. Glišić's research includes advanced sensing techniques: long-gauge and distributed fiber-optic sensors, 2D sensors based on large area electronics, and 3D sensors based on radio-frequency devices and ground penetrating radar; advanced data analysis for diagnostics, prognostics, and decision-making based on structural analysis, machine learning, and hybrid physics-informed machine learning; documentation, integration, and visualization using virtual tours, information modeling, and augmented reality; smart, kinetic, deployable, and adaptable structures; holistic analysis of heritage structures; and engineering and the arts in general. His application domains include concrete, steel, and masonry structures: bridges, buildings, pipelines; smart structures for coastal protection; and historical buildings, monuments, a university course and sites.

Prof. Glišić is the author and coauthor of more than 100 published papers, short courses on SHM, and the book *Fibre Optic Methods for Structural Health Monitoring*. He is a Council Member and Fellow of ISHMII, voting member of ACI Committee 444, and member of several other professional associations and journal editorial boards. Prof. Glišić is recipient of several awards, including the prestigious SHM Person of the Year Award, the ASCE Moisseiff Award, and Excellence in Teaching by E-Council of Princeton's School of Engineering and Applied Science.

1

Introduction

1.1 Structural Health Monitoring – Basic Notions, Needs, Benefits, and Challenges

Civil structures and infrastructure (simply referred to as "structures" in the further text) form our built environment and affect human, social, ecological, economical, cultural, and aesthetic aspects of societies. They are essential for the well-being and security of the people; vitality of the economy; and prosperity, sustainability, and resilience of society. This is especially emphasized in the twenty-first century, as for the first time in history, more than half of the world's population lives in urban areas, while climate change threatens with more frequent and more devastating hazardous events. Consequently, not only resilient design and quality construction are required from engineers but also sustainable management and durable and safe exploitation of structures.

In the course of their lives, structures are subjected to adverse changes in their structural health conditions and performances due to potential damage or deterioration induced by environmental degradation, wear, fatigue, errors in design and construction, and episodic events such as earthquakes, floods, strong winds, or impacts. Damage and deterioration can lead to malfunction and in extreme cases failure of the structures, which in turn can have significant adverse consequences in terms of life losses and injuries, worsening of general public well-being and security, and material losses for individuals, society, and economy. For instance, the collapse of the I35W Minneapolis Bridge is a sad reminder of the catastrophic consequences of structural failure: the loss of 13 lives while 145 people were injured; the unavailability of the river crossing generated economic losses of US$ 400,000 per day for road users. In addition, losses for the Minnesota economy were estimated at US$ 17 million in 2007 and at US$ 43 million in 2008 (DEED 2009). The cost of rebuilding the bridge was approximately US$ 234 million (MnDOT 2009).

The aging of infrastructure is, in general, a major concern for societies. For example, the American Society of Civil Engineers (ASCE) estimated that if the deterioration trends related to surface transportation infrastructure continue, annual costs imposed on the US economy will increase by 351%, i.e., to $520 billion by 2040, and it will cost the national economy more than 400,000 jobs (ASCE 2011).

Structures are subjected to adverse changes, and their integrity and performance may be compromised over the time for some of (but not limited to) the following reasons (Glisic 2009):

- There is no ideal construction material: initial defects always exist, and they represent potential initiation points for damage and deterioration.
- Damage and deterioration induced by wear and environmental degradation, such as

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  - Excessive external static or dynamic loadings (e.g., the material reaches critical levels of stress or strain or critical levels of buckling stability).
  - Repetitive or cyclic dynamic loading (e.g., the material is exposed to fatigue).
  - Stress concentrations (e.g., at the location of abrupt cross-section changes, dents, grooves, inclusions, welds, forging flaws, material porosities, and voids).
  - Excessive or repetitive thermally generated loads (i.e., stresses due to temperature variations and gradients).
  - In concrete: Damage due to early age deformation, drying shrinkage, freeze–thaw cycles, sulfate attack, alkali–aggregate reaction, chloride penetration and corrosion in reinforcement bars (rebars), etc.
  - In steel: Local buckling (bowing), cracking due to stress corrosion or fatigue, loss of material (and capacity) due to corrosion, etc.
  - Changes in the condition of foundations due to scour, erosion, liquefaction, differential settlements, etc.
  - Etc.
- Natural or human-induced episodic events such as
  - Earthquakes, storm surges, and tsunamis.
  - Strong winds (e.g., hurricanes, tornados, and typhoons).
  - Accidents involving fire, impact, or explosion.
  - Etc.
- Changing operational and environmental conditions:
  - Old structures were not designed for modern load demands, and the latter can result in damage and deterioration of the former.
  - Changes in the environment may impose new loads that did not exist at the time of the design and construction of the structures (e.g., strong wind); these loads can result in damage and deterioration of the structures.
- Unintentional design, construction, and maintenance imperfections or errors.

Thus, it is desirable to assess the health condition and performance of structures in order to mitigate risks, prevent disasters, and plan maintenance activities in an optimized manner. For this purpose, ideally, a modern structure should be able to "generate" and "communicate" information concerning the changes in its health condition and performance to responsible operators and decision makers, in-time, automatically or on-demand, and reliably. To achieve this, a modern structure should be equipped with a "nervous system," a "brain" and "voice," i.e., it has to be subjected to structural health monitoring (SHM), which is continuously in operation and able to sense structural conditions.

The concept of SHM can be understood from comparison with the nervous system of the human body. An unhealthy condition of the body or exhaustion of performance is detected by the nervous system in the form of pain or tiredness. Nerves in the involved areas are activated, and the information is transmitted to the brain, which analyzes the data. A person realizes that they are ill or exhausted and addresses a doctor in order to prevent further degradation of health or performance. The doctor undertakes detailed examinations, establishes a diagnosis, and proposes a cure.

The SHM, similar to the nervous system of the human body, should be able to automatically detect unusual structural behaviors (e.g., damage, deterioration, and lack of performance), characterize them (ascertain the times of occurrence, localize them and quantify them, or rate them), and report them, providing an important and actionable information for engineers and managers who are responsible for the monitored structure. The similarity of SHM and the nervous system of humans is schematically presented in Figure 1.1.