Foreword

# Expectations for the practical application of structural sensing research

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## 1. Introduction

The construction industry faces the imperative to transition to a stock-oriented society rather than a consumer-oriented one. At the same time, there is a growing need to evaluate and diagnose deterioration in numerous structures constructed during Japan's period of rapid economic growth. In addition, demand for diagnosing, repairing, and strengthening infrastructure and buildings damaged by natural disasters is increasing. These challenges have driven a wide range of research and development activities. Meanwhile, sensing and measurement technologies for both laboratory experiments and field applications have advanced significantly. My expertise lies in the diagnosis, repair, and strengthening of civil engineering and building structures. My research has covered measurement and analytical techniques for structural health assessment using a variety of sensing devices and methodologies. I have also investigated adhesive bonding technologies and repair and strengthening methods employing fiber-reinforced composite materials. Furthermore, my research has focused on sensing technologies for evaluating the preload of bolted joints, which will be introduced later in this paper. Based on findings from these studies, the following sections discuss sensing technologies and their potential applications in mechanics.

## 2. Structural Sensing and Health Assessment

In the context of structural sensing for health assessment, it is essential to identify the information required for the assessment, the underlying physical phenomena, and the methods, including sensing and measurement devices, used to capture those phenomena[1]. It is also necessary to determine whether the required information can be obtained with the desired level of accuracy and whether it can be acquired in a practical and cost-effective manner. Figure 1 shows an example of the information to be obtained and the corresponding methods employed in structural sensing. It should be noted that this example was prepared solely based on the author's perspective, and the number and types of items may vary considerably depending on the target structure and assessment objectives. In recent years, Internet of Things (IoT) infrastructure and devices have advanced significantly and become increasingly sophisticated. These technologies are frequently incorporated into structural sensing and health assessment systems. Measurement data required for assessment can be transmitted through existing communication infrastructure using a variety of wired and wireless communication technologies. In addition, online storage systems can be used for data storage and processing. These approaches are expected to improve the usability, reliability, and scalability of assessment systems. The integration of communication infrastructure into sensing systems is expected to become increasingly prevalent across a wide range of industrial applications.

## 3. Sensing of Structures Reinforced with Fiber-Reinforced Composite Materials

Researchers have developed methods to repair and strengthen structures using fiber-reinforced composite materials, with particular emphasis on carbon fiber-reinforced polymer (CFRP). CFRP has an elastic modulus comparable to steel and excellent strength characteristics[2]. When CFRP is applied to repair or strengthen existing structures, load transfer is often achieved through adhesive bonding. However, if debonding or delamination occurs at the bonded interface, the load-transfer mechanism may

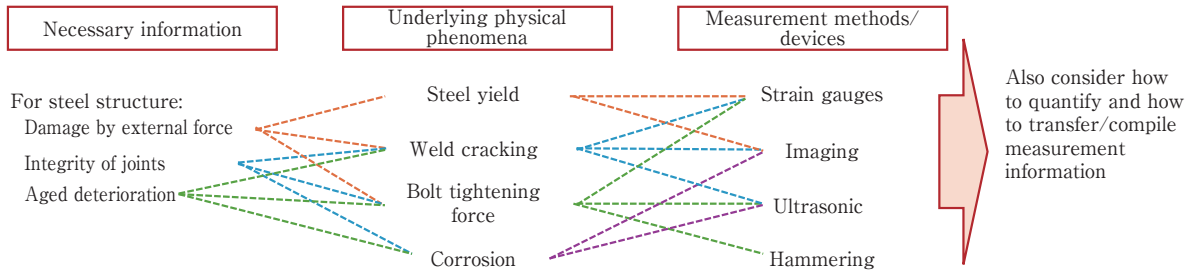


**Fig. 1** Structural sensing methods

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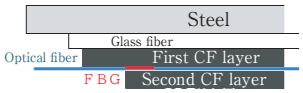
be compromised. Therefore, it is essential to accurately evaluate the strength and integrity of the adhesive bond. I have been conducting research on sensing methodologies that account for the damage mechanisms of fiber-reinforced composite materials. In particular, the study investigates the feasibility of damage detection using optical fiber sensors[3]. Similar to optical fibers used in telecommunications, these sensors are highly resistant to electromagnetic noise and capable of transmitting data over long distances. Furthermore, owing to their small diameter of approximately 0.2 mm, optical fiber sensors can be embedded within fiber-reinforced composite materials. Their extremely small size minimizes their influence on the material's mechanical properties.

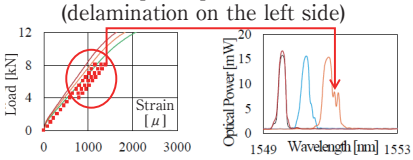
Optical fiber sensors can measure strain based on several operating principles. Among them, the fiber Bragg grating (FBG) optical fiber sensor used in this study provides measurement accuracy comparable to or higher than that of conventional electrical resistance strain gauges (hereinafter referred to as "strain gauges"). In addition, multiple sensing points can be installed along a single optical fiber.




FBG sensor embedded in the CFRP layers

Setup for applying bending force

Example of post-fracture
(delamination on the left side)




FBG sensor output (detection of tensile-side strains attributable to cracks)

**Fig. 2** Sensing of CFRP bond repair by FBG sensor

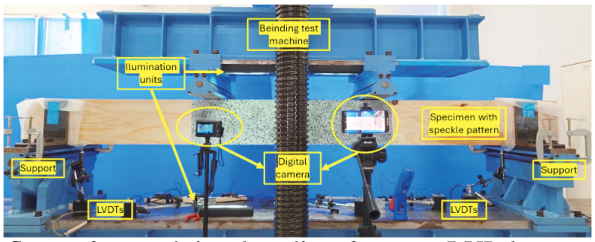
Figure 2 shows an example of the proposed sensing method. As illustrated in the figure, a CFRP laminate was bonded to a steel member to form a strengthened specimen. An FBG optical fiber sensor was embedded in the CFRP to measure strain distributions within the composite material. The FBG sensor can detect non-uniform strain distributions over its sensing length and reflect them in the measurement results. Consequently, even micro-scale damage within the CFRP can be identified. For example, when microcracks or similar defects develop in the CFRP, localized strain concentrations occur around the damaged region, and the sensor can detect these changes.

As shown in Figure 2, the sensing method successfully detected multiple dominant strain components and their evolution during repeated cycles of bending-load application and removal. These results suggest that the proposed method can be used for the structural health assessment of strengthened structures.

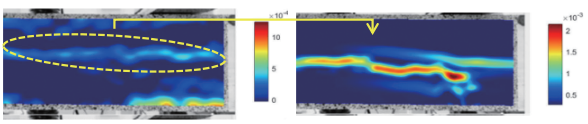
Furthermore, Reference 4 reported successful measurement of internal strain (and corresponding stress) in reinforced concrete members by embedding optical fibers into grooves machined in reinforcing bars. This technology is expected to evolve into a sensing technique that minimizes interference with the monitored structure's behavior. Additional information on structural sensing using optical fiber sensors can be found in Reference 5. Readers interested in further details are encouraged to consult that reference.

## 4. Determining Macroscopic Behaviors Using Digital Image Correlation

Wood-based materials have recently gained increasing popularity as structural materials. These natural materials impose a relatively low environmental burden and are lightweight and easy to process. These advantages have contributed to the widespread use of engineered wood products, which are manufactured by bonding small-section members or laminating thin veneers with adhesives to create structural elements with larger cross-sections. Researchers, including the author, have been investigating strain distributions on the surfaces of wood-based materials by analyzing images captured before and after deformation. This approach allows the identification of strain concentrations and the estimation of crack initiation sites[6]. Figure 3 shows an example of strain-distribution measurement in laminated veneer lumber (LVL) using digital image correlation techniques. Prior to its application, the correspondence between strain-gauge measurements obtained during material testing and strain values estimated through image correlation was verified. The results demonstrated that the method can accurately identify regions of strain concentration, which often serve as the initiation points of cracking. Therefore, it is a useful structural sensing technique for damage detection and prediction. Furthermore, when potential damage locations cannot be identified in advance, it is necessary to evaluate the overall structural behavior rather than local responses alone. In such cases, this method is effective because it enables a comprehensive assessment of the global




Setup for applying bending force to LVL beams



Strain concentration at the fracture point detected even at low loads

**Fig. 3** Damage sensing in wood-based structural materials through image examination

condition of the structure. However, several challenges remain. These include selecting appropriate surface patterns and image resolutions to ensure reliable image correlation, as well as establishing methods for long-term monitoring and evaluation. Further research and development are therefore required to improve the practicality and applicability of this technique.

## 5. Use of Strain Gauges and Their Transducers

Strain gauges are among the most widely used sensors for measuring strain and stress in materials and structures. They are inexpensive, easy to use, and available in a wide range of configurations. In addition, many commercially available transducers employ strain gauges to convert strain measurements into displacement, force, or load. Strain gauges are widely recognized as standard tools for stress analysis and evaluation. Established methodologies exist for selecting appropriate gauge dimensions (gauge length and width) and for accommodating various surface and environmental conditions. The potential applications of strain gauges and strain-gauge-based transducers are virtually unlimited and depend largely on the creativity and ingenuity of the user. I believe that strain-gauge systems are also valuable tools for developing new measurement technologies. In fact, my experience in this area was one of the reasons I was invited to contribute to this technical review. Defining a measurement objective, designing a sensor or device to achieve that objective, and validating its performance are valuable experiences for engineers and researchers engaged in engineering and manufacturing.

Strain gauges measure deformation through changes in electrical resistance and can be used to determine strain, stress, displacement, and load. When strain measurements are converted into load values, it may be necessary to eliminate bending effects or evaluate them separately[7]. In the former case, axial-force components can be extracted by averaging the outputs of two or more appropriately arranged strain gauges, as illustrated in Figure 4. Researchers, including the author, have developed and evaluated a washer-type sensor for measuring bolt axial force using strain gauges for applications in both construction and mechanical systems[8]. Although strain gauges are generally used to measure local strain, they can also be employed to evaluate average strain over relatively large regions, depending on the measurement configuration. These practical advantages are the result of decades of technological development and accumulated experience in strain-gauge applications. I am convinced that selecting, installing, and utilizing strain gauges appropriately for a specific measurement objective will further expand the possibilities of structural sensing and health monitoring.

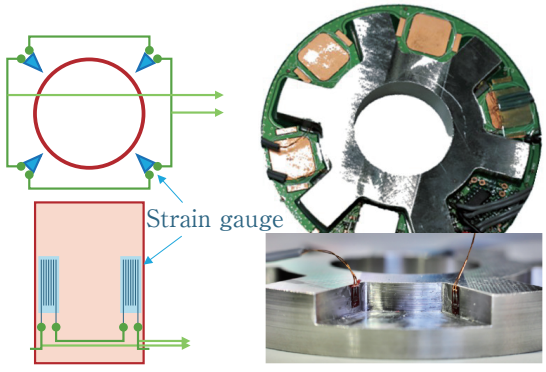



**Fig. 4** Example of a strain gauge-type transducer

## 6. Closing Remarks

In this article, I discussed structural sensing with a focus on my research activities. In particular, I described the objectives of structural sensing and the rationale for selecting appropriate sensing technologies and devices. In light of workforce shortages, the transition to a stock-oriented society, and the growing emphasis on preventive maintenance, structural sensing has significant potential to support the sustainable management of social infrastructure and the many assets essential to economic activity. Effective utilization of this technology requires a thorough understanding of the advantages and limitations of available sensing devices, as well as the appropriate use of modern information and communication technologies. I hope that the examples and discussions presented in this article will contribute to further advances in structural sensing and its practical applications. With this expectation, I would like to conclude this article.

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