IN-LB	Inch-Pound Units
SI	International System of Units

Structural Health Monitoring Technologies for Concrete Structures—Report

Reported by ACI Committee 444

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Reported by ACI Committee 444

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This report gives an overview of structural health monitoring (SHM) technologies for concrete structures. Data processing, analysis, and interpretation are not addressed in this document.

Keywords: sensors; structural health monitoring (SHM); structures; technology.

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CHAPTER 1—INTRODUCTION AND SCOPE

1.1—Introduction

The objective of this report is to introduce structural health monitoring (SHM) technologies and their applications to concrete structures. SHM entails the use of instruments and sensors to monitor changes of structural performance. Monitoring structural performance may ensure proper functioning and safety during the service life of a structural member or system. A wide variety of technologies are used to monitor the response of a structure. The response data, together with other data such as loading, environmental conditions, and other inputs, provide more complete information about the structural performance in terms of structural behavior or condition. Because these technologies have different operating principles, measure different quantities, and exhibit different strengths and limitations, the user must be informed how each technology can and should be used to maximize the value of an SHM system. The information gathered from an SHM system may effectively support rational decision-making processes regarding maintenance and repair of an existing structure.

1.2—Scope

The scope of this report is to provide an overview of SHM as applied to plain, reinforced, and prestressed concrete structures; introduce the physical phenomena that may be monitored and for what purpose; and provide a detailed discussion of established and emerging SHM technologies. This report does not discuss specific methods of data collection, storage, transmission, filtering, analysis, and interpretation. The intent of this report is to inform engineers, owners, and other SHM technology users about available sensor technologies, including the physical principle upon which each is based; equipment and sensor descriptions; method(s) of deployment; strengths and limitations of each technology; summary of availability and degree of acceptance in practice; and to identify relevant guidance or standards for use where they exist. Section 3.1 contains a discussion on the purpose and role of SHM, a broad overview on designing an SHM system, and general considerations for selecting SHM technologies. A table is provided in Section 3.1.3 to guide the reader to the appropriate technology sections in the document (Chapter 4). Section 3.2 presents the fundamental behavior (nonlinearity, non-homogeneity, cracking, and time dependency) of concrete structures to assist the reader in understanding the specific challenges associated with unreinforced, reinforced, and prestressed concrete structures in the selection of sensors and the implementation of SHM systems. The various SHM technologies are discussed in Chapters 4 through 6. Each chapter documents the working principle, necessary equipment, method of deployment, strengths and limitations, readiness for field application, and applicable codes and standards for a single technology or systems of related technologies. Chapter 4 presents technologies that measure the structural response, including acceleration, displacement, strain, or rotation. Chapter 5 presents technologies that measure inputs or stimuli that result in or affect a structural response such as load, environmental conditions such as temperature or humidity, or chemical activity. Emerging technologies, including conductive surface sensors and fiber-optic sensors, as well as related SHM systems such as energy harvesting, micro-electromechanical, and wireless sensor network systems are discussed in Chapter 6.

CHAPTER 2—DEFINITIONS

Please refer to the latest version of ACI Concrete Terminology for a comprehensive list of definitions. Definitions provided herein complement that resource.

acceleration—the rate of change of velocity with respect to time of a vibrating structural member.

accelerometer—sensor that may be mounted on a structure to measure acceleration at a point.

acoustic emission—stress wave resulting from a sudden, irreversible, and not repeatable release of strain from internal sources such as fracture due to externally-applied or thermally-induced loading.

acoustic emission event—single occurrence of an acoustic emission source, which must be recorded by multiple sensors for it to be associated with a specific source.

acoustic emission hit—count of the acoustic emissions exceeding a specified threshold, as recorded on an individual sensor.

aperture, radar—effective area or receiving cross section, as a measure of how effective an antenna is at receiving the power of electromagnetic radiation (such as radio waves).

aperture, ultrasonic transducer—diameter of sensing element; determines focusing angle of transducer.

autonomous enforcement—enforcing legal weight limits for illegal overweight trucks by issuing autonomous citations based on an advanced weigh-in-motion (WIM) system with a specified accuracy of gross vehicle weight.

***b*-value analysis**—data analysis based on the slope of the cumulative-frequency (log-scale) versus acoustic emission amplitude plot.

bending plate, weigh-in-motion—high-strength steel plate instrumented with high-precision strain gauges at its bottom and secured in a foundation frame within a pavement to weigh trucks at highway speed.

broadband—property of a sensor that is sensitive over a broad range of frequencies.

carbon nanotube—cylindrical nanoscale particle used in material science to modify mechanical and electrical properties of another material.

convolution—mathematical operation describing how one function operates on another function to produce a third function, used to describe how an input (for example, surface vibration) is changed by a system (for example, transducer) to produce an output (transducer output voltage).

data acquisition system—electronic system used to sample (or digitize) and store data gathered from a sensor.

Doppler shift—apparent change in frequency and wavelength of a wave observed by a receiver that is moving in relation to the wave source.

electrical resistance—opposition to the flow of electrons; inverse of electrical conductance.

fiber optic—glass fibers used to transmit light.

frequency response function—system impulse response function in the frequency domain fully describing the properties of a system such as a transducer, filter, amplifier, or data acquisition system.

geophone—passive sensor that may be mounted to the ground or a structure to measure movement (velocity) at a point; most commonly used for stress wave and seismic applications.

Green's function—transfer function describing relationship between unit impulse force at a particular location on a solid and the resulting response at another location.

high fidelity—of high quality, without distortion or bias.

inductive loop—setup that measures the fluctuations of current passed through a conductive loop or coil to detect the presence of ferromagnetic objects that disturb the resulting electromagnetic field.

interferogram—two-dimensional map representation of differences in phase values.

interferometry—the superimposing of two waves (for example, light or electromagnetic waves) to obtain additional information about the similarities and differences between the waves, which are typically measured from two adjacent, closely-spaced positions.

laser Doppler vibrometer—device that measures contactless measurements of the vibrations of a surface.

lead zirconate titanate—piezoelectric material typically used in transducer element to capture minute motions.

modal properties—natural vibration frequencies and mode shapes of a structural member or system.

moment tensor analysis—quantitative approach used to characterize the nature of an acoustic emission source, developed in the field of geophysics.

neural networks—algorithms loosely modeled after the human brain designed to detect patterns in data.

nondestructive testing—operator-controlled process of measuring structural and material properties of a system that causes no structurally significant damage to the concrete.

pattern recognition—automated recognition of patterns, see **neural networks**.

pencil lead break—standardized source to produce an acoustic emission having a quasi-step function.

piezoresistivity—change of the electrical resistivity of a material in response to applied mechanical strain.

potentiometer—displacement sensor based on the principal of voltage division.

radar—radio detection and ranging; a technique that employs transmission of radio waves of known frequency and time of transmission and detection of their reflections to detect and infer movement of remote objects over time.

scatterer—physical object from which radar or acoustic energy is reflected or refracted, typically at boundaries between media having different dielectric properties or acoustic impedance, respectively.

sensor—device, subset of transducer having the ability to sense (but not transmit).

structural health monitoring (SHM)—methodology entailing the use of instruments and sensors to identify changes of structural and material responses, environmental conditions, and loads.

transducer—device that can both sense and transmit a physical process.

vibrations (structural)—dynamic motion of a structure caused by live loading, wind, seismic activity, or various construction tasks; differentiated from vibrations used to consolidate fresh concrete.

visual inspection—examination of the visible surfaces of a structure with the objective to recognize and classify different types of damage and identify the probable cause of the observed distress.

weigh-in-motion (WIM)—process that uses devices to capture and record the axle and gross vehicle weights when vehicles drive over them at highway speed.

CHAPTER 3—CONSIDERATIONS FOR IMPLEMENTATION OF SHM SYSTEMS

3.1—Purpose of structural health monitoring (SHM)

3.1.1 *Introduction*—Structural health monitoring (SHM) entails the use of instruments and sensors to gather structural performance data from a structure over a period of time. The principal purpose of SHM is to monitor changes in the structure's response, which could be related to the occurrence or progression of damage, and, ultimately, to establish a measure of structural condition or health. The resulting information is used by owners and asset managers to make decisions regarding maintenance and repair of the structure. In this report, a wide range of approaches and technologies are considered as part of SHM, such as:

(a) Short-term monitoring (days to weeks) during load testing, where measurements are usually repeated every year or so for comparison

(b) Long-term monitoring (months to years) to capture response changes caused by aging and deterioration

(c) Monitoring with fixed installed or embedded sensors with the options of both wired and wireless technologies

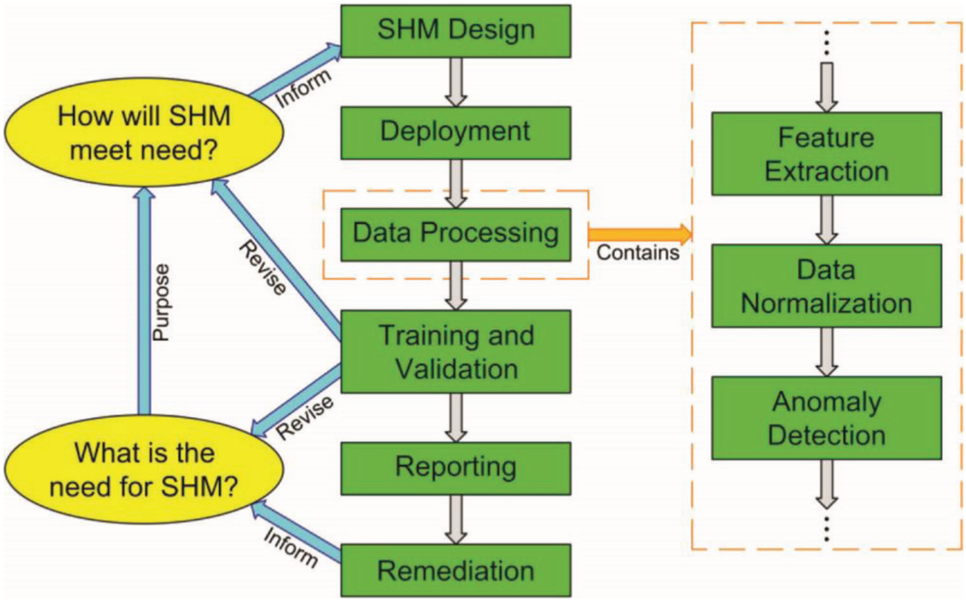

Fig. 3.1.2—Illustration of structural health monitoring process.

(d) Contactless monitoring using remote sensing technologies

(e) Global monitoring to capture changes in modal properties—that is, natural vibration frequencies and mode shapes

(f) Local monitoring to capture changes in material properties caused by fracture, corrosion, or material degradation processes

In this document, SHM is defined to be distinct from nondestructive testing (NDT) primarily in terms of scope and convention. NDT refers to periodic or specially scheduled nondestructive/non-invasive measurements to examine a specific characteristic of a structure that is normally confined to a specific local area. SHM more broadly employs data collection over time, not necessarily on-demand but possibly continuous or real-time, to establish the structural condition over time. Another distinction is that SHM is typically passive—that is, the response due to often unknown or uncontrolled stimuli is monitored—whereas NDT is usually active—that is, the response caused by a known stimulus is measured and analyzed. However, these definitions are not strict and universally observed, so there is some uncertainty and disagreement about them. For example, unaided visual inspection is often considered to be NDT, while contactless/vision-sensing applications, such as digital image correlation, are often classified as SHM. In practice, SHM may augment information determined by routine inspections and NDT or may inform the owner when some specific on-demand method should be employed. A recent application of SHM is their use for digital twins where data collected from in-service structures are used to update the properties of their numerical counterparts, which typically is a finite element (FE) model. Digital twins enable:

(a) Operational assessment (for example, routine updating for material property changes due to cyclic loading)

(b) Post-event assessment (for example, after a major load event has occurred)

(c) Prediction of damage or failure (for example, when threshold values for certain structural properties are reached)

Regardless of the definitions above, this document does not discuss technologies already addressed by ACI Committee 228 and its documents (ACI 228.1R, ACI 228.2R).

3.1.2 *Basic considerations to implement a structural health monitoring system*—Implementation of an SHM system requires the collaboration of multiple stakeholders (for example, owner, engineer, contractor, data analyst) to meet a need for structural maintenance and safety. SHM systems are engineered systems designed according to a process, an illustration of which is shown in Fig. 3.1.2, starting with identification of the goals of the system and ending in stakeholder action. While the focus of this report is specifically on sensor technologies for SHM design, the process is briefly discussed in this section, as the monitoring process may inform which sensors are selected.

Prior to its design, the need for the SHM system must be established ("What is the need for SHM?"). Objectives of the SHM system may include: 1) validate or assure that the structural system behaves according to design assumptions; 2) track the change in condition or response of a known critical structural element (for example, a bridge beam); or 3) inform scheduling for maintenance and remediation actions throughout the service life of the structure. The specific objective will often be determined by the owner's needs and expectations for a return on investment. A set of measured structural responses are then proposed to meet the specific objective ("How will SHM meet need?"). SHM design then considers the following components:

(a) Physical infrastructure, such as sensor types and positions to best measure desired response, but also including computing and data management resources

(b) Plan for installation and deployment, which may depend on accessibility of the structure, availability of