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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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.

CONTENTS

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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

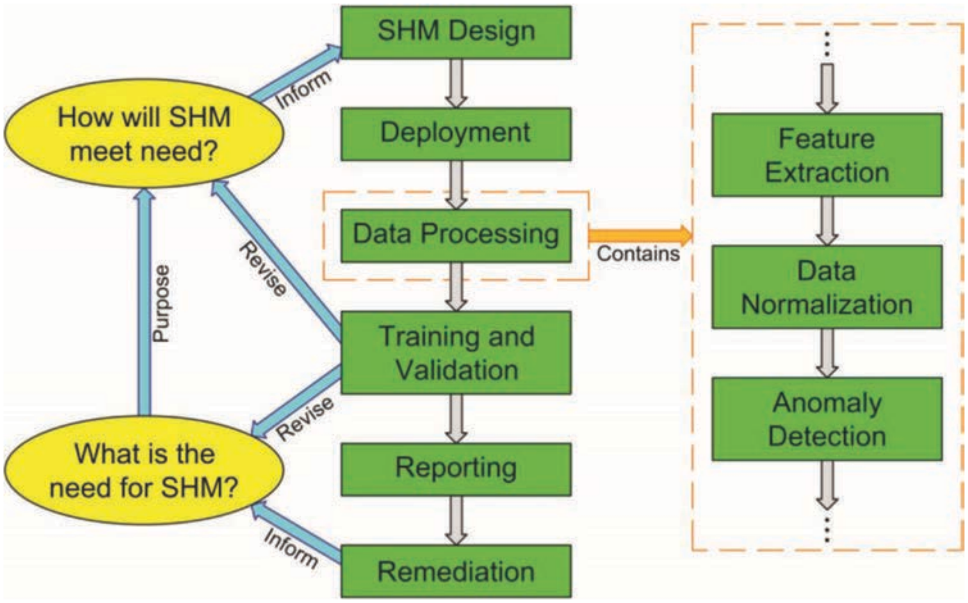

Fig. 3.1.2—Illustration of structural health monitoring process.

(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

Table 3.1.3—Sensor selection table with references to corresponding sections in Chapters 4 and 5

Measurement entity (in alphabetical order)	Alternative 1		Alternative 2		Alternative 3	
Acceleration	Accelerometer (structural vibration)	4.10	Acoustic emission sensor (stress wave propagation, acceleration-sensitive sensor)	4.1		
Acoustic emission	Acoustic emission sensor	4.1	Accelerometer	4.10		
Chloride content	Chloride sensor	5.1				
Crack motion	Potentiometer	4.4	Fiber optic sensor	4.5		
Cracking/fracture	Acoustic emission sensor	4.1	Conductive surface sensor	4.2	Fiber optic sensor	4.5
Corrosion	Corrosion sensor	5.2				
Displacement (contact)	LVDT	4.4	Potentiometer	4.4	Acoustic emission sensor (stress wave propagation, displacement-sensitive sensor)	4.1
Displacement (contactless)	RADAR	4.7	LIDAR	4.6	Digital image correlation	4.3
Force/load	Load cell	4.2.4	Weigh-in-motion sensor	4.2.8		
Humidity	Humidity sensor	5.3, 5.9				
pH value	pH sensor	5.5				
Precipitation	Rain sensor	5.9				
Pressure	Piezometer (water pressure)	5.6	Barometer (air pressure)	5.9		
Solar radiation	Pyranometer	5.9				
Strain (pointwise)	Strain gauge	4.8	Fiber optic sensor	4.5		
Strain (full field)	Digital image correlation	4.3	Conductive surface sensor	4.2		
Temperature	Temperature sensor	5.7				
Tilt/rotation	Tilt sensor	4.9	Digital image correlation	4.3		
Velocity	Laser Doppler vibrometer (structural vibration)	4.10	Geophone (structural vibration)	4.10		
Wind speed	Anemometer	5.9				

support utilities such as power and communications, and desire to periodically replace or update instrumentation

(c) Data processing plan, which requires extraction of the features of interest from the raw data, normalization with respect to known inputs or non-damage phenomena, and determination whether this measured response qualifies as normal or anomalous

(d) Plan for system validation and training to ensure that the data provide reliable, accurate, and necessary information for decision-making

(e) Reporting requirements, such as what, and how often (for example, alerts versus routine reporting), information is transmitted and to which stakeholders

(f) Plan of action

All these components are considered with respect to the expected structural service life and the expected lifetime of the monitoring system, both of which inform a long-term plan regarding how the above components may change with time.

Once an SHM system is deployed, validation and training provide the feedback used to assess and revise it. Validation refers to the assessment of whether the SHM system is achieving its intended objective. An invalid system may arise if insufficient or inappropriate instrumentation is used to monitor the behaviors of interest, if other unforeseen and unmeasured behaviors are found to better meet the monitoring objective, or if the objectives for SHM evolve over the service life of the structure. Training is used in the machine-learning sense—that is, adaptation of the monitoring system based on observed performance. Such adaptation is often necessary, for example, to establish thresholds for anomaly detection in variable environmental conditions, changing load demands on the structure, or changing structural condition.

3.1.3 *Selecting structural health monitoring technologies*—Selecting appropriate sensing technologies and instrumentation is critical for the successful implementation of an SHM system. Some general considerations apply to sensor selection in all cases, regardless of what is being measured:

(a) How must the sensor be installed? Must it be embedded into the concrete, tied to a reinforcing bar, or externally mounted?

(b) How many sensors are required to measure the behavior of interest?

(c) What range of response is the sensor capable of measuring? Does this encompass the entire expected range of structural behavior?

(d) What effects, if any, do temperature and humidity have on the sensor response?
(e) What other equipment is needed to measure the sensor response?
(f) How is the sensor and associated equipment powered?
(g) What are the accuracy and precision of the sensor?
(h) At what rate can the sensor measure the response? Is measurement desired every hour, minute, second, or less?
(i) Is the sensor robust enough to withstand the weather or being cast in concrete?
(j) What is the expected lifetime of the sensor? Is replacement expected, or is the sensor sacrificial?

It is important to note that no sensor technology directly detects damage or condition in a structure; most sensors measure a physical quantity (for example, voltage), which may be converted to an indirect measure of structural response and further interpreted as a state of the structural damage or condition (Worden et al. 2007). It should further be noted that currently no universally agreed-upon definitions for terms such as "damage," "condition," or "health" exist; these are typically defined on a project basis among the stakeholders of an SHM project. Therefore, sensor selection is largely constrained by the type of desired structural response. Table 3.1.3 summarizes the sensor technologies discussed in the report with respect to the entities that may be measured. Multiple alternatives are not meant to suggest a hierarchy of the listed sensors; this decision should be made on an individual basis considering the specific strengths, weaknesses, and measurement principles of each sensor, all of which can be found in the listed sections.

Chapter 6 discusses enabling system technologies, including energy harvesting technologies (Section 6.1), sensor platforms such as those based on micro-electrical mechanical systems (MEMS) (Section 6.2), and wireless sensor networks (WSNs) (Section 6.3).

3.2—Pertinent characteristics of concrete structures

3.2.1 *Introduction*—This chapter introduces those properties and response characteristics of concrete structures that must be known and accounted for when selecting sensor types, positioning sensors, and interpreting SHM data. As can be seen in Fig. 3.2.1, undamaged concrete is a macroscale composite material, normally composed of mineral aggregates of different size (light gray) bound by a cement matrix (gray) that incorporates both an interconnected pore structure and discrete (unconnected) entrapped and entrained air voids (black), which contains either pore fluid or air. Concrete is a quasi-brittle material and, as such, is relatively strong under compressive stresses but weak under tensile stresses. To overcome this weakness, designers add reinforcement in the tension zones of a structural member, typically in the form of steel reinforcing bars. Concrete and steel are compatible in that they exhibit similar thermal expansion characteristics, and the chemical nature of concrete protects the steel from atmospheric corrosion. Their responses to applied loads and other environmental conditions are, however, significantly different, which directly affect the response of structural

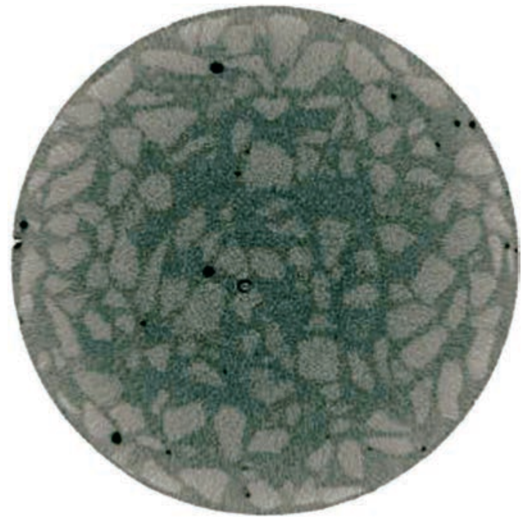

Fig. 3.2.1—Internal structure of undamaged concrete visualized using computed tomography (CT) scan (photo courtesy of University of Burgos, Spain). (Note: The diameter of the section is 100 mm [3.94 in.].)

concrete members. Unreinforced concrete structures are not discussed in this chapter.

3.2.2 *Material characteristics*—The constituents that comprise structural reinforced concrete are discussed in this section.

3.2.2.1 *Concrete*—This section discusses hydraulic cement concretes, which are primarily based on portland cement binders and a range of additives that modify the fresh and hardened properties of the material. The most important characteristics of concrete that have a direct influence on the SHM of concrete structures are the following:

(a) Early-age variations during the hydration process: Sensors embedded inside the concrete (either in direct contact with concrete or attached to a reinforcing bar) should be designed to withstand thermal variations and a basic chemical environment without damage.

Once the different components of concrete are mixed, compounds within the portland cement known as calcium silicates react with water to form calcium-silicate-hydrates (CSHs). The hydration reaction progressively provides stiffness and strength to the concrete, changing it from a malleable to solid material within hours. This causes a strong modification of the mechanical parameters over time (Bernard et al. 2003; Boulay et al. 2014; Granja et al. 2014; Azenha et al. 2010; Maia et al. 2011).

Hydration reactions are exothermic and result in significant heat evolution within the concrete at early age (Fig. 3.2.2.1a). Depending on the cement and admixture chemistry, boundary conditions, and concrete volume and geometry, an internal temperature up to 80°C (175°F) can be reached. The chemical reactions also create pore fluid within concrete that is highly basic (high pH) in nature.

The evolution of the hydration reaction changes during the first hours and days after mixing, where high heat evolution generally correlates with strength and stiffness development. The concrete remains in the malleable, fresh state

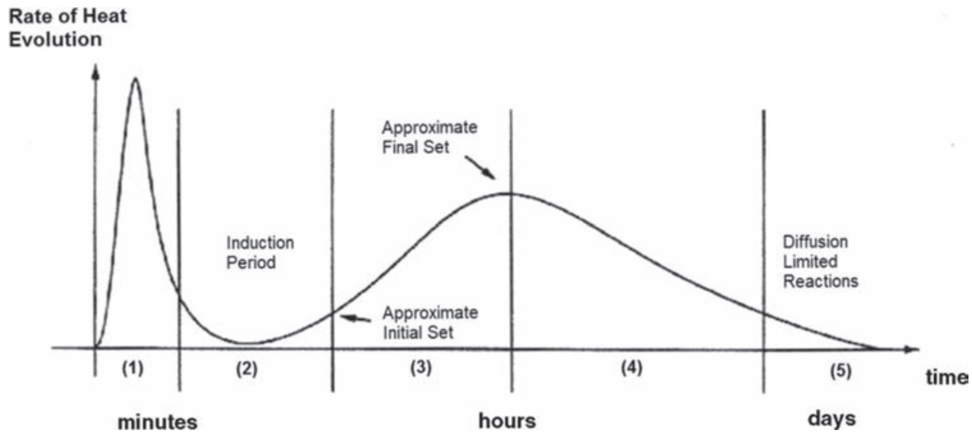

Fig. 3.2.2.1a—Heat evolution of concrete during the hydration of portland cement with different stages of the hydration reaction indicated by numerals (Nelson 1990).

through hydration Stages 1 and 2, and starts to stiffen and set at the beginning of Stage 3. During Stage 3, the compressive strength of concrete is low and its tensile strength is almost nonexistent. Consequently, surface cracking may occur that is induced by thermal or moisture gradients within the material (ACI 213R; Branco et al. 1992). Concrete continues to gain strength in Stages 4 and 5, but at a decreasing rate.

(b) Intrinsic heterogeneous mesostructure: Typically, theoretical analyses of concrete behavior are carried out assuming that concrete is a homogeneous material, and this is a reasonable assumption at the macroscale level where average values are used. For situations in which it is necessary to measure local response entities, such as strain, moisture, and pH, at a point, the heterogeneous nature of concrete cannot be ignored and may dictate sensor selection, data analysis methods, and data interpretation. At this local scale, the exact position of a sensor may have a relevant influence on the measured values, especially when the sensor exhibits a size similar to the aggregates.

Concrete is a composite material composed of coarse aggregates (with dimensions on the order of tens of millimeters) bound by a matrix composed of fine aggregates, cement, and water. The hydration process that gives rise to a solid material is described in Subsection (a). The mechanical properties of hardened concrete, from a macroscopic point of view, are a combination of the mechanical properties of the different components (Neville 1996) that directly affect the stress-strain relationship. In fact, the mechanical response (for example, stress-strain relationship of the concrete as a composite response) can be thought of as an intermediate between those of the coarse aggregate skeleton and that of the hardened cement paste (refer to Fig. 3.2.2.1b). However, the influence of voids and the interfacial transition zone between the paste matrix and individual aggregate particles, as well as other phenomena such as microcracks, cause the relationship to be more complex than a simple weighted average of constituent properties, as demonstrated by the nonlinearity of the concrete stress-strain curve.

(c) Modulus of elasticity and compressive strength: Deterioration processes, which typically result in a decrease

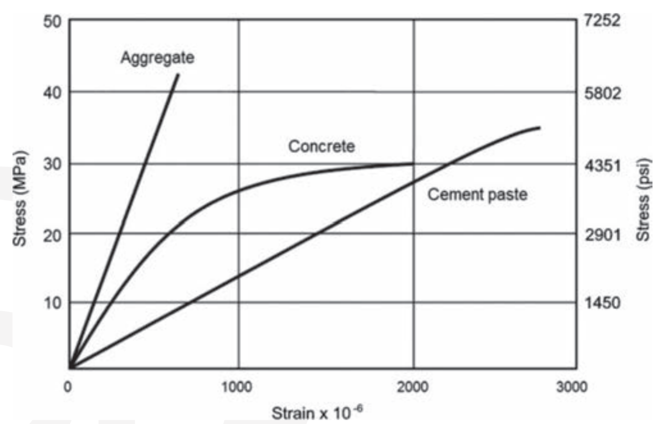

Fig. 3.2.2.1b—Stress-strain relations for cement paste, aggregate, and concrete (adapted from Neville [1996]).

in the macrolevel stiffness, may act to counteract the inherent increase in stiffness over time.

The modulus of elasticity (E_c) and compressive strength (f_c') of concrete continually increase over time as a function of the hydration process, although the rate at which they change may not be the same (ACI 209.2R). ACI 318 suggests the following relationship between E_c and specified 28-day compressive strength in response to applied mechanical strength f_c' for normalweight concrete

$$E_c = 4700\sqrt{f_c'}, \text{ where } E_c \text{ and } f_c' \text{ are in MPa} \tag{3.2.2.1}$$

$$E_c = 57{,}000\sqrt{f_c'}, \text{ where } E_c \text{ and } f_c' \text{ are in psi}$$

The time-dependency of f_c' impacts long-term monitoring applications where measurements of strain are to be related to stress or deformation and computed by using the modulus of elasticity (E_c).

(d) Nonlinear stress-strain behavior: The nonlinear stress-strain behavior of concrete is important from an SHM standpoint. For example, measurements of strain in concrete are usually used to calculate stress. In this case, the use of a stress-strain relationship is required. If it is necessary to correlate measured parameters of a concrete structure, such as vertical deflection, rotations, and natural frequency, with

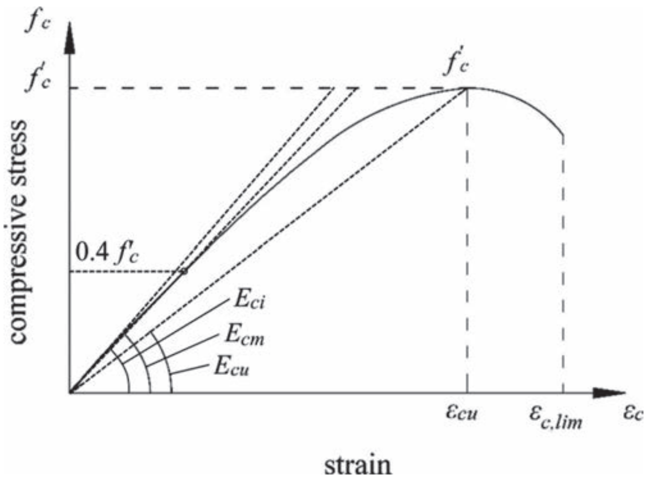

Fig. 3.2.2.1c—Schematic stress-strain relationship for quasi-static loading in uniaxial compression (adapted from fib *Model Code 2010).*

theoretical ones—for example, those obtained from finite element (FE) models—a well-defined stress-strain relationship is necessary.

Concrete shows significantly different mechanical response in compression compared to tension—that is, the tensile strength of concrete is typically on the order of 10 percent (or even less) of its uniaxial compressive strength. Thus, for strength calculations of reinforced concrete, the tensile strength of concrete is typically neglected. As will be discussed in Section 3.2.3, tensile forces are supported by the steel reinforcement in a reinforced concrete element. From a structural point of view, the behavior of concrete under compressive stress is more important. Recall that the stress-strain relationship of concrete under compression is nonlinear. fib *Bulletin 42* (*fib* 2008) provides theoretical parabolic stress-strain relationships for concrete in compression, which are valid for regular as well as high-performance concrete. Figure 3.2.2.1c illustrates a schematic stress-strain curve of concrete in compression.

ACI 318 does not define a theoretical stress-strain relationship; it only considers that, under service loads, the behavior of concrete is linear-elastic (and its modulus of elasticity is defined) and, under failure loads, a rectangular compression block may be considered in place of the more realistic parabolic curve shown in Fig. 3.2.2.1c. In the *fib* Model Code 2010, two different definitions for the modulus of elasticity (E_c) are given: the instantaneous modulus of elasticity (E_{ci}), defined as the tangent of the stress-strain curve at its origin; and the secant modulus of elasticity (E_{cu}), defined as the slope of the line connecting the origin with the peak of maximum compression (f_c'). Eurocode 2 defines a secant modulus of elasticity inside the elastic range of the concrete (where linear-elastic behavior is almost true) (E_{cm}), defined as the slope of the line connecting the origin with the point of the curve corresponding to a stress value of $0.4f_c'$ (shown in Fig. 3.2.2.1c). Both the *fib* Model Code 2010 as well as Eurocode 2 suggest that the following can be assumed: $E_{ci} = E_{cm}$. ASTM C469/C469M testing provides the modulus of elasticity from a compression test on concrete cylinders.

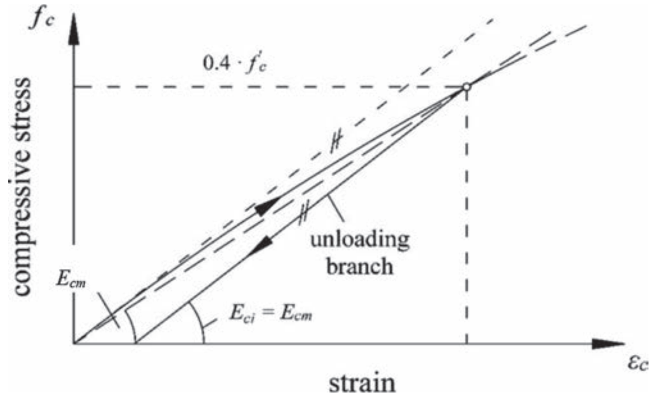

Fig. 3.2.2.1d—Illustration of stress-strain diagram for concrete showing loading and unloading branches (Model Code 2010).

The slope of the stress-strain curve is also different for loading and unloading. For the unloading branch, linear-elastic behavior of concrete is assumed, and the slope of this curve is E_{ci} (Fig. 3.2.2.1d). As can be observed, unloading from some stress level to zero stress leads to residual strain, which is largely attributed to microcracking. This residual strain is larger when unloading from a higher stress. The effect of cyclic loading is discussed in more detail in Subsection (f).

Finally, the stress-strain response of concrete is also strain-rate-dependent (Zhou and Chen 2013; Cadoni et al. 2009; Bischoff and Perry 1991, 1995; Fu et al. 1991; Dilger et al. 1984). Most of the international standards do not discuss this topic thoroughly. A relevant exception is Model Code 2010, which shows formulas to modify, among others, the modulus of elasticity as a function of the loading rate.

(e) Time-dependent volume changes—creep and shrinkage: Time-dependent volume changes have a strong influence on long-term SHM because they occur simultaneously with all other deformations. It is important to recognize that creep and shrinkage cause internal forces only in structures where deformations are restrained. Separating the deformations due to external loads and creep and shrinkage is difficult because there are no concrete stress-strain relationships that can reliably predict the complex nonlinear visco-elasto-plastic behavior of concrete. Not considering these time-dependent volume changes may lead to incorrect estimation of the stresses in the structure.

Concrete exhibits time-dependent volume changes caused by creep and shrinkage. Both phenomena have received significant attention since the 1970s. Figure 3.2.2.1e illustrates a simple example of the strain changes caused by creep and shrinkage with a sudden load applied at time x.

Today's consensus on the physical phenomenon behind shrinkage is that it is a result of progressive loss of water from the cement paste caused by evaporation and hydration of the cement. However, there is no consensus regarding causes of creep. This is evident in ACI 209.2R, where four different models are proposed to calculate creep in concrete. Creep has received significant attention over the last 50 years (Zienkiewicz and Watson 1966; Madsen and Bažant 1983; Bažant and Panula 1980; Neville et al. 1983; Vandewalle