Building structural health monitoring: a tool for building collapse mitigation

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Abstract. Building collapse occurs recurrently worldwide on account of a myriad of variables associated with man or nature whose consequences are loss of life and properties that are sometimes incalculable. This paper aims to appraise the current advances in the topic area to identify and provide a holistic document on building structural health monitoring approaches that are fragmented in the literature to enable practitioners, stakeholders, and inspectors gain insight into the modern and cost-effective methods of building structural health monitoring to alleviate the incessant problem. It appeared that most of the approaches are interwoven and dependent on one another to obtain reliable information on building structural integrity. Apart from the traditional methods of visual inspection and non-destructive assessment of building health monitoring, it appeared the predominant and recent approaches to building health monitoring are analytics or statistics-based, statistics-sensor based, fiber optic framework, fiber optic-sensor network, and sensor-based. Arguments in the literature suggest that the analytics or statistics approach may not provide accurate information on account of the outlier and data corruption. The fiber optic approach is expensive and time consuming compared with the fiber-sensor network method. Finally, the sensor-based building health monitoring is less expensive over other approaches and provides reliable and accurate information on building integrity. Hence, we suggest future research direction should focus on the development and integration of fiber optic-sensor network and sensor-based methods of building health monitoring to improve the accuracy of the methods

Keywords: Building, structure, collapse, health monitoring, mitigation

1. Introduction
Building collapse occurs frequently worldwide on account of a myriad of variables associated with man or nature whose consequences are loss of life and properties that are sometimes incalculable depending on the response time. Hence, there is a necessity for periodical building health monitoring to determine and remedy any potential risk on the integrity of the building. Building structural health monitoring involves regular evaluation of structures to detect any damage for maintenance to sustain the build against collapse. Existing building structures deteriorate with time on account of many variables such as environmental hazards, excessive loading, and manmade problems among others. Building damage detections are normally based on changes in dynamic response to load and environmental conditions of the structure. However, if the responses are not monitored, the building may degrade and eventually collapse. The
traditional building health monitoring frameworks that rely on visual inspection and non-destructive assessment to evaluate and provide information on the integrity and functionality of the structure is inadequate. Building health monitoring identifies variations in the properties of a building concerning its functionality over some time. The health monitoring procedure includes checking the structure over a while through sampled response measurement via sensors, retrieval of damage-sensitive features from the measurements followed by analysis of the features to ascertain the status of the building and the result of the process can be occasionally updated concerning the capability of the building to perform its intended function regardless of aging and operational environment degradation.

Building health monitoring is thematic and has gained the attention of researchers over the past decades because of its relevance to building collapse mitigation. Researchers have proposed diverse methods for building structural health monitoring that are fragmented in literature. Consequently, this paper seeks to evaluate the current efforts to identify and provide a holistic document on building structural health monitoring approaches to enable practitioners, stakeholders, and policymakers gain insight into the modern and cost-effective methods of building health monitoring schemes to alleviate the incessant problem of building collapse to save lives and properties. According to [1], condition assessment (CA) is one of the many approaches for building health monitoring systems and stressed that building health monitoring is aimed at enhancing the understanding of loading and response mechanisms of earthquakes, wind loads, and other natural sources.

[1] noted that a building health monitoring scheme time-to-time screen building’s ability to perform its function as it is aging in the presence of damages arising from operational environment and unexpected situations like earthquake and blast loading to provide information about the integrity of the building [2] defined building structural health monitoring as a scheme applied to structures to determine their fitness for use under changes occasioned by load and response mechanism of the structures such as the dam, cable-supported bridges, and offshore production platforms among other forms of structures. [3] Described building health monitoring as a procedure for implementing a damage detection system for a structure. Similarly, [3] defined building health monitoring as a combination of sensing and intelligence system that records changes in structure, analyzed, localized, and predict the integrity of the building in conjunction with the nondestructive testing approach. [4] Stated that building health monitoring as a scheme deployed to identify damage in buildings. The damage detection system is capable of indicating (i) the presence of damage, (ii) position of damage, (iii) severity of the damage. Additionally, [5] stressed that building health monitoring is to show the existence of damages in building based on the measured dynamic or static response of the building. [6] argued that aging buildings deteriorate further on account of incessant loading and tough environmental condition and noted that the health monitoring frameworks consist of sensors such as accelerometers, temperature sensors, and displacement transducers which are mounted in building to obtain response measurements data caused by environmental or internal factors that are further analyzed to ascertain the state of a structure. Also, [7] claimed that structural health monitoring assesses the level of deterioration and residual service life of a civil infrastructure. [8] Argued that infrastructure health monitoring entails detecting the position and severity of impairment in a building, dam, or bridge using measured parameters as they occur. The core purpose of building structural health monitoring is to detect and identify the onset of structural deterioration and damage to protect lives and properties. The monitoring scheme is used to track the characteristics of building during mandatory vibration investigation or natural excitation [9] asserted. Similarly, [10] argued that building health monitoring provides information on ‘fitness for use’ of the structures under changes in their state occasioned by load and response mechanisms.

Besides, [11] described building health monitoring as the key components of building safety. Usually, early warning systems comprising of sensors networks, signal processing devices, and communication amenities are deployed to provide real-time information that are used for planning maintenance and repair
works on buildings to minimize the impact of building degradation [12] asserted. The system combines a wide range of sensors and evaluation methods to provide accurate forecasting and enables users to improve the level of emergency preparedness. Usually, the traditional approach to building health monitoring is based on visual inspection for damage propagation. Buildings are expected to meet standard safety requirements, maintainability, and sustainability during their operational life cycle [13] argued. The professionals in the building and construction industry therefore must ensure that these properties are incorporated in building design from the onset. [14] claimed that using fiber optic as a sensing device in the building provides a more precise and dependable results than other sensors such as strain gauge. Advances in the building health monitoring schemes aid researchers in building characteristic identification, exposure of harms to the building, model improvement, security, and sustainability evaluation by using observed response data obtained from the building health monitoring system. Notwithstanding the advances in building health monitoring systems [15] stressed that there are still challenges in to be addressed such as accuracy of sensory devices, frequency and exact data sampling, and data mining among others for decision making on maintenance and management of buildings. [16] Asserted that proper management of civil infrastructure requires condition, serviceability, and reliability assessment for which SHM provides information on the present status of the building by measuring the vibration responses and other physical disorders.

Section one provides background to building structural health monitoring, section two itemizes approaches for building structural health monitoring and section three present conclusions to the appraisal.

2. Methods for building health monitoring (BHM)
Diverse approaches for building health monitoring have been proposed by researchers over the years. For example, [17] presented a vibration monitoring system and identification method of building structural health monitoring aimed at increasing the security and consistency of buildings by identifying impairment in buildings before it reaches a dangerous stage. [18] Projected ARMA-eigenvalue analysis for detecting building damages under wind loads. Similarly, [19] proposed a local information analysis method for online building health monitoring via wireless sensor frameworks where each sensor estimates the coefficient of damage statistically by measured acceleration data for every monitoring exercise. Subsequently, a nonlinear programming analytic was used to identify the existence of impairment, the local impairment location, and quantify the impairment severity from the damage-sensitive coefficients in the integrated sensing module.

Figure 1 Statistics-sensor-based scheme for building health monitoring

Figure 1 illustrates the statistics-sensor-based approach of building health monitoring where the characteristics response measurement data of a structure is obtained by the sensor device. Subsequently, the data containing damage-sensitive features are retrieved and statistically analyzed to ascertain the integrity and state of the building.

[20] Proposed statistical process control for building health monitoring contextualized in pattern recognition using statistical control chart to diagnose and identify building impairment by vibrational method. Also, [20] stressed that autoregressive coefficients of the models fitted thereafter to a new set of
data were supervised relative to the control chat and the statistically noteworthy numbers of characteristics outside the control limits suggest that the building is in transition from a healthy status to a damaged status. Likewise, [21] projected the ARMA model for building health monitoring with the ARMA coefficient been fed to a classifier capable of learning and establishing new classes when the building response show variations conforming to diverse structural status. Also, [21] employed a statistical pattern recognition approach in building health monitoring. Similarly, [22] presented a Bayesian probabilistic method for building health monitoring.

[23] Advocated wireless sensor networks as an emerging substitute for traditional structural health monitoring device whose benefits include no wiring cost between sensors and the data retrieval systems on like the traditional approach. Besides, they argued that wireless sensors play a vital role in processing structural dynamic response data used to screen data for symptoms of structural damage. However, [23] further argued that wireless sensors have limitations that need innovative designs and manners of operation. Furthermore, [23] stressed that bridges, dams, pipelines, aircraft, ships, and buildings are complex and multifaceted engineering structures that enhance the economic prosperity of a nation. However, these structures are usually endangered with excessive loading and harsh operational environment. Consequently, there is a justification for the health monitoring of structural performances to achieve the desired goal of constructing the structure in the first instance.

Also, [24] emphasized that it is mandatory for some buildings located within the region of high seismic activities to incorporate structural health monitoring devices as a requirement that is responsible for acquiring measurement and storing outputs from sensors with data center repository, an operation that can be expensive and labor-intensive, unlike the wireless. The size of a structural health monitoring system is determined by the overall number of sensors which in turn determine the cost. Hence, the cost associated with installing and maintaining wires is always high. For instance, the cost of 350 sensing channels on the Tsing Ma bridge exceeds US$8million [24] with similar cases reported in monitoring systems installed within aircraft, ships, and other structural systems.

Figure 2 Distributed sensor frameworks for instrumented building health monitoring system

Figure 2 depicts sensor networks for a building health monitoring scheme where the sensors obtain the building dynamic response measurement data, retrieves and analyze the data, and subsequently detects damage therein for actionable plan by the operator. According to [24] building damage detection approaches are usually grouped into local-base or global-based. The local-based approach identifies building impairment by screening buildings at their component or subparts and non-destructive evaluation (NDE) methods such as ultrasonic inspection to detect cracks and yielding of the steel moments frame connections used by experts, an expensive approach. The global-based impairment identification approach involves statistical methods that take into account global vibration behavior such as the natural frequencies of the building to detect building impairment. [25] Asserted that wireless sensors networks are capable of autonomous operation such as the collection, storage, analysis of data, and decides what to transmit to other sensors within the network with the aid of the embedded software in the network. Also, [25] Presented impedance-based structural health monitoring by applying excitations via the surface-bonded piezoelectric transducers that records the impedance of building by checking the current and voltage applied to the transducers. Furthermore, [25] noted that variations in impedance show variations in the structure that indicate that damage has occurred in the building.
[24] and [25] pointed out that building damage detection approaches include damage identification and it is conducted in conjunction with five related areas that include (i) SHM, (ii) Condition monitoring (CM), (iii) Non-destructive evaluation (NDE), (iv) Statistical process control (SPC), and (v) Damage prognosis (DP). However, SHM is associated with online–global damage detection in structures. [26] Argued that modern building monitoring systems should be able to identify and determine impairments, locate impairment, the severity of the impairment, consequences of impairment, and self-diagnose to restore the damage. In building a health monitoring system the sensors do not measure damages rather it requires extraction of features via signal processing and statistical identifier to convert the sensor data into damage information for actionable plan. [28] Noted that structures are designed to operate within specified limits of the environment that they are intended to be used and that is why it is justifiable to ensure continuous health monitoring to detect the onset of damages. Structure loading is approximated during design and required materials are specified, however, engineers depend on modeling techniques to gain knowledge of the behavior of the structure in the operating environment based on approximations and assumptions. Modern structural health monitoring schemes employs and implement sensors networks typically optical fibers, electrical resistance strain gauge or acoustic systems to monitors the behavior of the structure online.

Table 1 Reference of building structural health monitoring techniques

| No | Building Structural Health Monitoring Technique | Ref. | No | Building Structural Health Monitoring Technique | Ref. |
|----|-------------------------------------------------|------|----|-------------------------------------------------|------|
| 1  | ARMA-eigenvalue analysis | [1,10] | 13 | Vibration-based monitoring | [1,4,7,19] |
| 2  | Ultrasonic testing | [1] | 14 | Fiber optic-sensor networks | [1,2,22,24] |
| 3  | Eddy current testing | [1] | 15 | Optical inspection | [1,7] |
| 4  | Magnetic particle inspection | [1] | 16 | Optoelectronic scanning | [1] |
| 5  | Liquid penetrant testing | [1] | 17 | Laser scanning systems | [1] |
| 6  | Visual inspection | [1] | 18 | IoT-based system | [1] |
| 7  | Early warning systems | [1,6] | 19 | Stiffness reduction system | [2,7] |
| 8  | Multivariate ARMA model | [7] | 20 | Inter-story drift measurement | [2] |
| 9  | Signal processing method | [5] | 21 | Modal-based algorithm | [3] |
| 10 | Impedance-based method | [6] | 22 | Bayesian probabilistic | [8] |
| 11 | Statistical process control | [7] | 23 | Piezoelectric transducers | [7,9,12,17,24,28] |
| 12 | Statistical pattern recognition | [7] | 24 | Wireless sensor networks | [2,3,7,8,13,14,18,20,21,27] |

Table 1 depicts various approaches used for building health monitoring to detect the onset of deterioration and damage. The methods appeared to be interwoven and dependent on one another.

A vibration-based method in conjunction with signal processing for beams can be used in building health monitoring. Also, smart sensors, with onboard computational and communication capabilities, offer new opportunities for building health monitoring without the need for power, communication cables, and installation cost. Thus, smart sensors can aid in building monitoring with an array of sensors economically. Similarly, a piezoresistive strain sensor from carbon nanotube-polymer material for building structural health monitoring that is used to detect large strains, cracks, and reduces the number of data acquisition required for health monitoring and claimed that it is cost-effective, lightweight and easy to install. Similarly, dynamic response measurements have been used over the years in which outliers may exist in the measurements that lead to unreliable results. Hence, an outlier-resistant extended Kalman filter was proposed to detect outlier in an online structural parameter identification using dynamic response data that may be corrupted.

[29] Presented damage prognosis that forecasts building performance by measuring the existing damage, assessing the future environmental loading, and predicting the remaining useful life of the
building by simulation and experience. However, the capability of the approach requires the design and integration of technology that include measurement, processing, telemetry hardware couple with deterministic and probabilistic modeling capacities to quantify the uncertainties therein the predictions. The application of piezoelectronic transducer patches is used in health monitoring of civil infrastructure by attaching the patches to the surface of the structure that is electrically excited, and the electrical conductance part was extracted as a function of frequency. Subsequently, an impedance analyzer was used to scan the patches over some frequency to obtain the signature and was discovered that the deviation from the obtained record for a healthy state is an indication of the new state of the health of the structure.

[30] Emphasized that building structural health monitoring (BSHM) involves four basic steps including, (i) acquisition of data, (ii) validation of data, (iii) analysis of data, and (iv) prognosis and management. Hence, structural health monitoring (SHM) scheme integrally comprise five features namely (i) sensors and sensing technology, (ii) diagnostic signal generation, (iii) signal transmission and processing, (iv) event identification and interpretation, and (v) integration into an actionable plan for management of the structure. Furthermore, [30] stressed that though some non-destructive evaluation (NDE) methods are integrated into SHM techniques, there is a clear difference between SHM and NDE. While NDE measures specific characteristics and assesses the state of a single point without determining the level of deterioration, the SHM scheme entails diagnosis, prognosis of damages, and the order of damages based on the parameters and as well determines the residual service-life of the structure.

3. Conclusion
The various approaches presently available for building health monitoring converges in the materials reviewed and thus, bring the appraisal to a compendium as outlined below. The two categories of solutions to building structural health monitoring are local and global solutions. The non-destructive evaluation (NDE) presents local solutions while the structural health monitoring (SHM) approach offers a global solution. The NDE measures specific characteristics and assesses the state of a single point in a structure without determining the level of deterioration whereas, the SHM scheme entails diagnosis, the prognosis of damages and the order of the damages based on the parameters as well as the determination of the residual service-life of the structure.

It is evident from the foregoing that the approaches used in building structural health monitoring are interwoven and dependent on one another to obtain real-time reliable information on building structural integrity. The common methods include wireless sensors networks, fiber optic networks, fiber optic-sensor networks, and statistics or analytics methods. It appeared that the sensor network is increasingly gaining attention than any other method of building a structural health monitoring scheme. Apart from the cost-effectiveness of the approach, it is easy to install, easy to operate, and provides real-time and reliable information than other methods presently available it is capable of obtaining and analyzing data autonomously for actionable plan unlike the statistic or analytic methods that generate data with the possibility of outliers and likelihood that the data may be corrupted before analysis thereby resulting in providing wrong information.

4. Recommendation
Despite the advances in building structural health monitoring, there are still challenges to be addressed such as accuracy of the sensory devices, frequency, and exact data sampling among other issues for decision making on maintenance and management of buildings. However, we recommend that the future research direction should explore more of the sensor network and sensor-fiber optic networks techniques because of the potential therein particularly the generation of real-time and reliable information about the status and integrity of a building as well as determining the remaining service life of a structure.
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