Structural Health Monitoring in Nigeria: Bridging the Gap Between Literature and Practical Application

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Abstract-Structures are designed to withstand several environmental loading conditions and to ensure the safe transfer of these loads to the foundation within specified periods. However, loss of lives and adverse economic effects are potential problems caused by the collapse of structures. Operational and structural health monitoring (SHM) for buildings can be used to mitigate building failure in Nigeria. Damage detection with the use of camera-based techniques, ground penetration radar (GPR), fibre optic sensors (FOS), and piezoelectric films are considered in this study. These techniques were analysed from available literature to evaluate their application and validate their effectiveness concerning availability, practical application, operational evaluation, data acquisition, and processing. This study characterizes the performance of SHM systems, how they can be used, and their availability in Nigeria. Consequently, proposing BHM as a tool for building failure mitigation in Nigeria.

Keywords- Building health monitoring (BHM), Ground penetration radar (GPR), Fibre optic sensors (FOS), Piezoelectric films, Building failure in Nigeria, Vision-based technique.

1 INTRODUCTION

Buildings are designed to carry and transfer both dead and live loads to their foundations safely and without excessive deformation, however certain circumstances including bad design, poor construction methods, little or no supervision, foundation failure, excess loading, not adhering to design, and a combination of these or other causes may lead to building failure and collapse. Ede (2016) defined building collapse as any failure that occurs in a building due to its inability to serve the aim for which it was constructed.

The collapse of structures cannot only be considered as the failure of a structure, when a part or whole of the structure becomes unsafe for use to support loads it was designed to bear, this scenario can also be termed the failure of the structure. According to Awoyera et al (2021) any of these three scenarios can be considered a failure.

a. Serviceability limit state failure: this occurs when it becomes unserviceable by undergoing excessive deflection and cracking
b. Ultimate limit state failure: occurs when the structure fails by overturning, ultimate collapse, or buckling of the vertical supports.
c. Durability failure: involves the deterioration of the components beyond repair.

According to Mohammed (2017), the failure of buildings globally had been attributed to two circumstances: natural and man-made. Natural incidents include earthquakes, flood, tsunami, soil liquefaction etc. and when these occur, they are regarded as natural disasters while man's negligence in areas of soil type testing, structural design inclusion of factors of safety, poor quality of materials, incompetent professionals and inadequate monitoring of workmanship account for the man-made aspect.

The archaic materials used for construction in past centuries made buckling not a major structural problem along with the fact that high-rise buildings were not common in those times. Many important roman structures survive till the present because materials were used generously to ensure these structures do not fail (Taiwo and Afolami, 2011). Examples of these structures include the Colosseum in Italy, Imperial Baths of trier in Germany, Pont du Gard and Roman Theatre of Orange both in France, etc. In contrast, there are improved procedures, durable materials, improved construction machinery, and better-advanced ideas on construction in the modern world. Sadly, even with such advances in modern-day construction, cases of collapsed structures still exist and are even more prevalent in developing countries such as Nigeria.

Collapse in the developed countries is majorly due to natural causes or man-made causes like bombings or war. However, collapse in developing countries is usually due to the use of substandard materials, inadequate or no supervision, no adhering to necessary regulations, bad understanding of the job to be done, quackery, lack of geotechnical analysis, wrong construction procedure, wrong demolition process, lack of maintenance and numerous others (Odeyemi et al, 2019; Micheal and Oyewale, 2018 Oyegbile et al, 2016; Ajufoh et al, 2014; Windapo et al, 2012).

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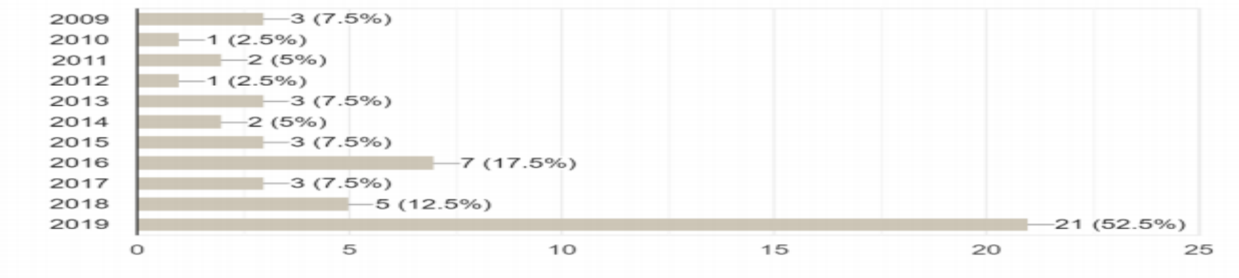

Fig. 1: The most amount of building failure in Nigeria each year over the last ten years (Awoyera et al, 2021)

According to Awoyera et al (2021), over the last decade, the major cause of building collapse in Nigeria is man-made as this account for 87.5% whereas natural conditions contribute least as regards building collapse in Nigeria. However, the rising number of cases serves both as a warning and a wakeup call to all stakeholders in the construction industry. The most amount of building collapse in Nigeria per year over the past decade as depicted by Awoyera et al (2021) is shown herein as Figure 1.

Consequent to the rate of building failure or collapse, regular building health monitoring to determine any potential risk on the integrity of the building structure becomes necessary. Structural health monitoring (SHM) systems provide information about any significant change or damage occurring in a structure to identify the type, location, reason, degree, and type of damage. This helps to ascertain the damage severity and consequently predict what is left of the structure's service life. Structural deficiencies which cause complete failure or collapse may result from internal factors including corrosion, fatigue, and aging, and external factors, including earthquakes, wind loads, and impact loads. The damage caused by these internal and external factors progresses very slowly and may become visible when the damage becomes severe. Hence, the detection of structural damage is a necessity in ensuring structural safety across a structure's lifetime. It is however important to monitor the occurrence of deterioration, its location, and extent, from both safety and performance perspectives. (Sivasuriyan et al, 2021).

Ongbali et al (2020) stressed that Building health monitoring has drawn the attention of researchers over the past decades because of its necessity to building collapse mitigation. Consequently, different methods of structural health monitoring have been put forward by different researchers and they are available in literature. However, according to Cawley (2018), this extensive research endeavour on structural health monitoring has resulted in only little industrial application. Consequently, the aim of this review is to bridge the gap between select methods of SHM put forward by researchers and is available in literature, review their practical application to determine their effectiveness, discuss their availability while recommending them for the mitigation of building collapse in Nigeria.

2 Mechanism of SHM

Nuhu et al (2021) defined SHM as a process of detecting damages to engineering structures. They noted that the goal of SHM is to improve both the safety and dependability of infrastructures. In addition, Tudor (2012) noted that building health monitoring is aimed at understanding the loading and response mechanisms of earthquakes, wind loads, and other natural sources, he also noted that SHM screens the ability of a structure to perform its function as it is aging even presence of damages arising from operational environment and unexpected situations to determine necessary information about the building. However, Jun et al (2017) defined building structural health monitoring as a program to determine if structures are fit for use under conditions occasioned by load and response mechanisms of the structures while Yoshiro and Akira (2004) described building health monitoring as a procedure for damage detection of a structure. Cawley (2018) in describing the mechanism of SHM noted that SHM involves transducers that are attached permanently to structures and are usually integrated with instrumentation which enables regular measurements while functioning. He noted that signals obtained from these transducers can be read by comparing them with previously obtained measurements, this process is called baseline subtraction.

Structural health monitoring involves health observation of structures, operation evaluation of these structures, data extraction, and development of statistical models to describe the condition of these structures. Operation evaluation sets the limits on what to be monitored and how to go about it, how the damage of the system being investigated can be defined, under what conditions the system to be monitored functions and limitations on the acquisition of data. Extraction of data involves selecting the excitation methods if any, types and amount of sensors or transducers, locations, and storage of data obtained while statistical model development deals with the implementation of algorithms that operate on obtained data to ascertain the extent of damage. Steps involved in SHM are expressed in Figure 2.

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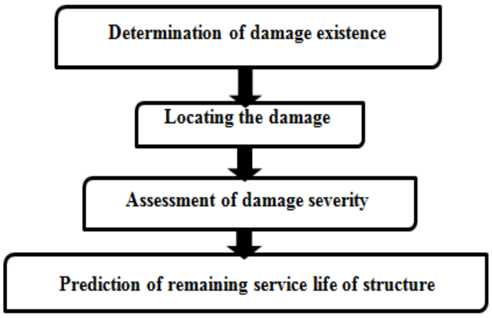

Fig. 2: Steps involved in SHM

The first step involves damage identification. The interest of structural health monitoring is to detect damage at its earliest stage and a good damage detection system will be able to indicate damage at an early stage. Damage in buildings can be defined as an unexpected response or changes in the properties (usually dynamic) of a building that may hinder the building from serving its purpose. After damage have been detected, the next step involves identifying the location of the damage then it further tries to quantify the extent of the damage which may also include prediction of the rate of increment. From the data obtained, the remaining service life of the structure can be predicted and appropriate recommendations can also be made.

3 Techniques Used in Structural Health Monitoring (SHM) and the Nigerian Environment

Parameters used for SHM applications include the detection and quantification of strain, cracks displacement, impact, pH-level, moisture, and vibration signatures, (Kuang et al, 2009; Cawley P., 2018). The SHM methods proposed in this review for use in Nigeria are discussed in the following subsections.

3.1 Visual Inspection

Structures can be monitored by visual inspection (Mao, 2015), this is one of the traditional and conventional methods of structural health monitoring which is dependent on human visual examination. Benefits of visual inspection include simplicity and low cost. However, since this assessment is usually visual, they are subjective (Grabeal et al, 2002). Visual inspection is subject to exposed surfaces only and cannot exactly describe or reflect the extent of damage; hence, it doesn't directly relate to the structural performance. (Rens et al, 1997; Thoft-Christensen, 1999; Feng and Feng, 2018). The degree of deterioration is not exactly apparent from only surface examination, especially when the damage does not occur at or close to the surface.

GB 50982:2014 divides SHM into monitoring during construction and during operation. Monitoring during construction is usually done by visual inspection and may require the measurement of strain and cracking (Cawley, 2018). Visual inspection is one most widely used structural health monitoring technique in Nigeria. Although visual inspection is necessary and a prerequisite for non-destructive examination of buildings, (Ibrahim et al, 2020; IAEA, 2014; Mahadik and Jaiswal, 2014) it cannot act as an ultimate tool. Visual inspection has been used in Nigeria to ascertain the current conditions of buildings and hence the nature or degree of testing required for SHM (Ibrahim et al, 2020; Osuji et al, 2020; Thomas and Ede, 2019).

Recently, concurrent with recent evolution in technology, visual inspection has been replaced by computer-camera-based techniques. The application of computer-aided vision techniques has increased recently in SHM (Tobiaz et al, 2019). This system aims to monitor any displacement that may occur in a structure. Processing software is used in measuring displacement accompanied with its time history and the results can be displayed on screens and automatically saved (Kot et al, 2021). Khuc and Catbas (2016) developed a contactless SHM system employing the use of computer-aided vision methods and regular cameras. Their method relied on the basic camera principle as expressed in Figure 3. This system was deployed to obtain displacement and vibration responses for the assessment of structures. Key-points were used as virtual targets and pixel-based displacements of monitored structural location were determined using an improved detection and match key-points algorithm. These pixel-based displacements were converted to engineering units by a practical calibration method they developed. The efficacy of this system was verified on a stadium during football games, results obtained converged with data from sensors. Their proposed technique is contactless and hence, an inexpensive and practical alternative for the structural assessment of structures.

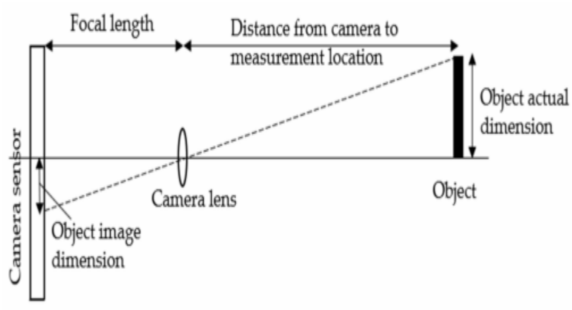

Fig. 3: Basic camera principle (Khuc and Catbas, 2016)

Xu et al (2018) applied an identification framework using a restricted Boltzmann machine (RBM) which was used for the identification of cracks and removal from images having cracks and complex background within steel box girders of bridges using consumer grade cameras. They used a deep learning model or network consisting of multiple processing RBM layers to learn the abstract features to match the input image elements with corresponding state representation vectors. They employed a three-layer RBM and a divergence learning algorithm to determine the optimal parameters. The computer-camera based methods can be used to monitor displacements in buildings in Nigeria. Already predefined targets can be captured using digital cameras and digital images obtained can be processed with a

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pattern-matching algorithm (Ye et al, 2016; Catbas et al, 2016). Consequently, the already defined targets are assessed and structural displacements at these points can be determined. A single camera can be used to obtain displacements in two-dimensional coordinate directions while two digital cameras are used simultaneously to obtain three-dimensional coordinate displacements (Ye et al, 2016).

Advantages of camera-based methods include contactless measurements, ability to collect data from long distances and low cost. However, challenges encountered in the use of camera-based technique include distortion errors that may be encountered due to wind or vibration, optical turbulence effect when taking measurements over long distances, self-heating of camera and lens distortion. Consequently, the need for continuous research to overcome these challenges cannot be overemphasized.

3.2 Ground Penetrating Radar

Ground-penetrating radar (GPR) is an equipment that is used for the non-destructive investigation of the properties and characteristics of substructures. It is a real-time technique that provides data within a short time. GPR can be used in evaluating the stability, maintenance, and health of concrete structures. This technique can also be used to investigate asphalt pavements in order to detect voids, damages, or other defects (Capozzoli and Rizzo, 2017; Maierhofer, 2003) to ascertain the presence and investigate the geometry of steel bars in reinforced concrete members (Barrile and Pucinotti, 2005; Shaw et al, 2005; Miramini et al, 2018), location of voids and cracks in concrete members and foundation (Muldoon et al, 2007; Perez-Garcia et al, 2008) depth of concrete cover (Wiwatrojanagul et al, 2017) diameter of reinforcement bars (Wu et al, 2003; Che et al, 2009) and corrosion of reinforcement bars (Mechbal and Khamlichi, 2017).

The GPR utilizes the microwave aspect of the electromagnetic spectrum that comprises of a transmitter and a receiver to send and retrieve the reflected wave as expressed in Figure 4. Based on the measurement required, different frequencies can be employed against the depth of penetration. To obtain accurate results from the GPR systems, they have to be calibrated with a core sample of the material that is analysed (McCann and Forde, 2001). The measured signal is processed and analysed based on an altered signal.

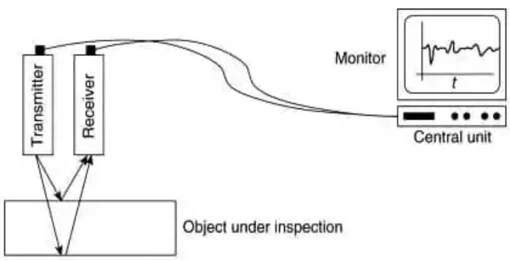

Fig. 4: GPR working principle

Merits of the GPR technique include its safety of operation, ability to cover a large area, low cost of operation and its ability to detect voids, irregularities, metals and non-metals. However, one of the necessities and hence limitation of the GPR technique is that it requires a specialist that is highly skilled to analyse and decipher the data obtained from the system. Consequently, researchers have recommended varying methods to overcome this challenge including artificial intelligence techniques to analyse the data obtained.

Khudoyarov et al (2020) proposed a three-dimensional convolutional neural architecture to analyse the GPR data to help classify underground objects. Morris et al (2019) proposed the attribute analysis technique for characterization of materials, where the data obtained was analysed using a core set of filters which focused on maintaining the amplitude of the data instead of the absolute amplitude as the absolute amplitude is modified by electromagnetic characteristics of the material, roughness of the material surface, and other external factors. Other disadvantages of the GPR technique include the requirement of a flat terrain for optimum radar penetration, distortion in penetration due to obstructions and time delay in the collection of data in clay soils.

3.2.1 Collection of Data Concrete Structures

The GPR can be conducted in simple line scans (Evinemi et al, 2016) to ascertain the thickness of concrete. To determine a required point within the concrete, the scan can be performed in grid formats and results are obtained in form of images for the different sections of the concrete under observation. These images are combined to get a final 3D plan of the picture.

3.2.2 Availability and Cost of GPR in Nigeria

Different studies have been carried out using GPR in Nigeria. Oladunjoye et al (2020) used the Mala RAMAC/GPR 250MHz bi-static shielded antenna GPR purchased from India to investigate foundation failure at Medina Estate Lagos. However, both Olakunle and Adekunle (2012) and Evinemi et al (2016) used the USA manufactured GSSI SIR System-300 equipment to perform survey analysis for their research in Nigeria.

According to the USRADAR Inc. subsurface imaging systems, the cost of a GPR manufactured in the USA usually starts around $14,000 (equivalent to five million, seven hundred and sixty-three thousand, one hundred Naira) for a single frequency GPR system and around 12 lakh Indian Rupee (equivalent to six million, six hundred and thirty-three thousand, eight hundred- and sixty-one-naira, sixteen Kobo) in India according to MALA ground-penetrating survey services in India.

3.3 Sensors

Various types of both wired and wireless sensors have been proposed for structural health monitoring. However, a very important and critical aspect of sensors is determining the appropriate type of sensor to efficiently obtain the required results. Sensors can be used to obtain data for stress, strain, vibration, inclination, humidity, and temperature. Monitoring of a structure using Sensors can either be local or global. The local approach is focusing on a specific material behaviour

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while the global approach deals with the whole structural performance. Sensors have varied performance in the SHM field. Sensors usually used in SHM include Fibre-Optic sensors (Leung et al, 2015; Barrias et al, 2016; Soto and Thevenaz, 2013; Rajeev et al, 2013; Masoudi et al, 2013; Garcia et al, 2015; Hong et al, 2016; Takeda et al, 2012; Mihailov, 2012; Kinet et al, 2014; Wang et al, 2015; Lai et al, 2016; Tan et al, 2016; Hong et al, 2017) and piezoelectric element (Liu and Giurgiutiu, 2007; Zou et al, 2013; Baid et al,2017). These sensors however have certain limitations and disadvantages

3.3.1 Fibre Optic Sensors

Fibre optic sensors utilize optical fibres as a sensing element and can be used to measure strain, temperature, pressure, and other parameters with the advantage that no electrical power is needed at the remote location and their small-sized nature which means they can be inserted in buildings during construction or on the body of existing buildings. This gives fibre optic sensors an edge over the conventional electrical sensor in SHM. Culshaw and Dakins (1996) classified fibre optic sensors as local (Fabry-Perot FOS or long gauge FOS etc.), quasi-distributed (fibre Bragg grating), and distributed sensors (Brillouin-scattering-based distributed FOS) depending on the sensing range.

A typical optical fibre sensor consists of a receiver, light transmitting element, the optical fibre, a modulator and a processing unit as expressed in Fig 5. The optical fibre is the core part of the sensor and it can be made from silica or polymer materials. The optical fibre acts as a sensing element and transfers the light from the source to the modulator.

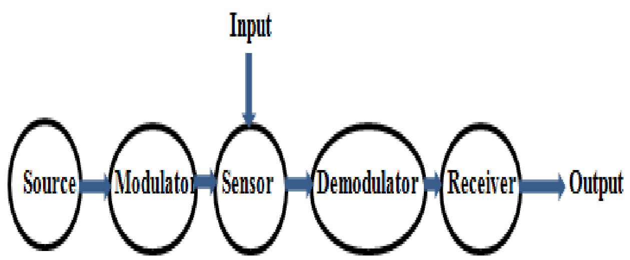

Fig.5: A fibre optic sensor system

Detecting corrosion, chloride content, and pH depends on colour change or modulation of the sensor while strain or temperature depends on expansion or contraction of the fibre leading to loss or change of optical transmission. This change is modulated and transmitted back as an optical signal to the processing unit for deriving the concerned parameter of the structure. Advantages of fibre optic sensors include the stability of measurements, durability of fibres for a long period, and ability to carry out local and global measurements. Limitations of the fibre optic sensors include complexity of detection systems, limited dynamic range and its relatively high cost.

3.3.2 Piezoelectric Sensors

Piezoelectric films are thin strips of ceramics that are embedded within or placed on the surface of the structure. Consequently, when multiple layers of piezoelectric layers of alternating polarity are piled, piezoelectric stacks or wafers are obtained (Benjeddou, 2007).

Piezoelectric materials indicate a simultaneous (actuator/sensor) behaviour considering electrical to mechanical variation. Piezoelectric materials range from ceramic, polymer, and composites. The capability of piezoelectric materials to create an electric field under the influence of mechanical stress is termed the direct piezoelectric effect. Consequently, this property can be used in generating electrical energy; the inverse of this process where mechanical strain is developed due to electric field is the inverse piezoelectric effect. However, the crystal orientation greatly affects these phenomena (Dineva et al, 2014; Holterman and Groen, 2013; Chee et al, 1998; De Jong and Chen, 2015)

A detailed model of the piezoelectric sensor includes the effects of the sensor's mechanical and electrical construction (Carazo, 2000). An electric model of the sensor is expressed in Figure 6, where Lm is the inductance, C_e is inversely proportionate to the mechanical elasticity of the sensor, C_0 represents the static capacitance of the transducer and R_i is the insulation leakage resistance of the transducer element. If the sensor is however coupled to a load resistance, the load resistance acts in parallel with the insulation leakage resistance, thereby the high pass cut-off frequency is increased. The voltage at the source is directly proportionate to the induced force, strain, or pressure if the piezoelectric sensor is modelled as a proportional voltage source and filter system. The signal then obtained at the output is associated with the mechanically induced force as if it has passed through the circuit.

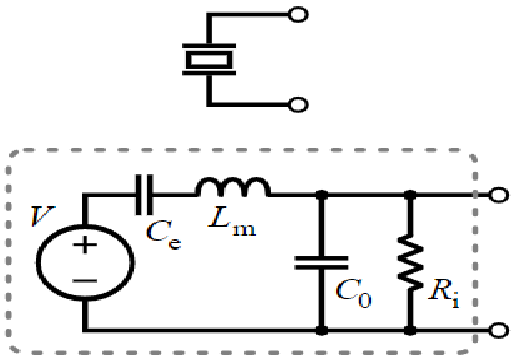

Fig.6: Schematic symbol and electronic model of a piezoelectric sensor (Carazo, 2000)

Peizoelectic sensors have numerous advantages including its small size, excellent frequency response, light weight, simple orientation, ability to withstand high temperatures and high surface pressure. Requirements of moisture proofing and poor output response from its DC which requires high impedance are some of its limitations.

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Table 1. Piezoelectric and FOS manufacturing companies

Company name	Location	mail	Phone/fax
The Roditi International Corporation Ltd	156-158 Buckingham Palace Road, London SW1W 9TR, England	sales@roditi.com	+44 20 7819 8080 +44 20 7730 4131
CSRayzer Optical Technology	2F, 3rd Bldg., 88, Youke Yuan Rd. Hongshan District. Wuhan, Hubei 430074, China.	INTL@csrayzer.com	+86 2787697602
Evanescent Optics Inc	3325 North Service Rd. Unit 109 Burlington, ON L7N 3G2, Canada	sales@evanescentoptics.com	+1 905-336-2626 +1 905-336-5620
OZ Optics Limited	219 Westbrook Rd. Ottawa, ON K0A 1L0, Canada.	sales@ozoptics.com	+1 613-831-0981 +1 613-836-5089

3.3.3 Availability of sensors in Nigeria

Efforts by a researcher have been made to promote the use of sensors for building health monitoring in Nigeria. Boyinbode et al (2020) developed an Internet of things (IoT) system, comprising of two microcontrollers, dsPIC33EP128MC502 and ATMEGA328p, one for reading the signals from sensors while the other was for data processing. Piezoelectric transducers were used as sensors while an identification module was used for data transmission. The resulting IoT system was proposed for use as a building health monitoring system in Nigeria, where the signals from the system could notify subscribers if any structural damage is noticed. Although the system was not validated on real-time building, they proposed a system implementation.

Although Fibre optic sensors and Piezoelectric films are not manufactured in Nigeria, custom-made type sensors to suit applications where necessary can be ordered from manufacturing companies and delivered to Nigeria. Some verified manufacturing companies are shown in Table 1.

4 Implications for Building Health Monitoring in Nigeria

The increasing cases of building collapse leading to loss of lives and adverse economic effects serves both as a warning and a wake-up call to all actors and stakeholders in the construction industry. With the use of Building health monitoring techniques in Nigeria, structural failure in worst case scenarios accompanied with its economic consequences is not going to lead to loss of lives. These techniques will eliminate catastrophic failure and consequent liabilities associated with it. In addition, huge cost incurred during contactless BHM is majorly once during the installation stage of the system as compared to other Non-destructive tests (NDT) techniques, where the cost is usually recurrent for periodic inspection. This presents a cost-effective way forward for Nigeria.

The industrial application of Building health monitoring in Nigeria can be attributed to the unavailability of the necessary systems/equipment and lack of the requisite technical knowledge about these systems. However, with continuous conscious efforts towards bridging the gap between what's available in literature and its practical application, progress will be made to extricate the construction industry in already ailing economy.

BHM can be used to lengthen the economic life of a structure, enable new maintenance concepts, develop repair planning, and monitor the real-time health situation of a building frequently. Once installed, BHM can be employed to monitor areas that might be inaccessible or expensive using other NDT techniques. While contactless BHM can be performed anytime, it is more rigorous for other techniques.

5 Conclusion

The emergence of improved technology not only considers function and convenience but also technical improvement. Several monitoring techniques have been put forward by researchers, while some were validated on real-time structures, others are evaluated under laboratory conditions. This review discusses the literature on some available building health monitoring techniques, their availability, and how they can be used practically in Nigeria. The following conclusions are drawn:

i. Although visual inspection of buildings alone is widely used in building health monitoring in Nigeria, it is not a dependable method as it cannot predict damage severity and does not effectively reflect the degree of damage.
ii. Industrial deployment of building health monitoring systems in Nigeria can be used to mitigate building collapse as damages are noticed early.
iii. The techniques discussed in this study present a practical and economical means that can be used to implement buildings health monitoring in Nigeria.
iv. The practice of Building health monitoring should be encouraged amongst stakeholders and actors in the construction industry.
v. The static and dynamic behaviour of buildings can be used to predict damage at a premature stage by adopting BHM techniques.
vi. Damage location and severity can be monitored using piezoelectric films and Fibre optic sensors.
vii. The remaining service life of a building can be estimated in Building health monitoring.
viii. BHM can be used to provide feedback to improve the future design when new construction methods are used.

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