Analyses and Interpretations of Structural Health Monitoring Data on Reinforced Concrete Buildings: A Critical Review

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Abstract: Existing reinforced concrete buildings have experienced different forms of failures due to limitations in analysing and interpreting the information derived from the study of their behaviour under loading. Structural Health Monitoring (SHM) which is the study of the way structures relate with different loading conditions using equipment and machine that can read data without affecting the existence of the structure has been analysed in times past using different methods and there is need to bring in probabilistic methods in terms of reliability-based paradigm, i.e., reliability theory to analyse and interpret SHM data. Reliability method expresses logical handling of structural design uncertainties in the assessment of the structures safety and serviceability; it provides a very powerful tool for SHM to add probabilistic structural evaluation function that current SHM applications and statistical analysis packages do not have. This review study looks into different ways SHM data have been analysed and the need to introduce probabilistic approach to SHM.

Key words: Structural health monitoring, non-destructive test, reliability theory, reinforced concrete building, limitations, statistical analysis

INTRODUCTION

Reinforced Concrete Buildings (RCB) undergoing construction to a greater extent can be assumed safe using the present day design requirements and assumptions, structural fitness is therefore guaranteed for this category but for existing buildings, there is need for timely monitoring methods to acquire data which will help to determine their state of fitness. Presently in the construction world, a great sensitization is occurring towards the usefulness of having systems in aerospace, civil and mechanical structures which can state the cause of damages. This damage prognosis system in a structure would give the user information on the structure’s health, accurate details of upcoming damage and the structure’s life span (Farrar and Worden, 2006). The assessment of existing buildings is of much importance and of great concern to the construction world, users also daily get involved in a new way of putting these structures to use and a standard is yet to be developed for the examination and retrofitting of existing RCB (Holicky et al., 2014; Rens et al., 1997). The structural health of existing buildings poses much treat to our environment due to inadequate methods of acquiring data on the structures responses to loads, environmental impacts and age. For an effective SHM process in terms of reliability-based paradigm, there is need to focus on the mode of testing structures both in real life and laboratory conditions/environment, equipment used, type of data to be taken, how they are analysed and used in reliability studies.

Literature review
Non-destructive testing: Recent innovations of codes (BSI., 1998) provide clear rules for assessing the safety and conduct of static strengthening on existing buildings. Inventors also have provided a way out in non-destructive methods or techniques to assess existing buildings. Non-Destructive Inspections (NDI) are ways of assessing a structure working with attached or embedded equipment which does not in any way affect the state of the structure (Elsener et al., 2000a, b, Chang et al., 2003). Non-Destructive Testing (NDT) is a maturing technology field that reveals, study and analyse defects in engineering structures using mostly physics-based techniques (Ibrahim, 2014, 2016). NDT has been defined has methods of examination without having an adverse
effect on the examined system. These methods are now top on the list in the area of reliability and effectiveness as it offers a better choice in testing in situ (Shaw and Xu, 1997). NDT techniques measures responses given by a structure to interferences induced using mechanical, chemical and electromagnetic energies. NDT techniques have gone through periods of revolution from unassisted visual and aural (acoustic) inspection (ACI Committee 228, 1998; Park et al., 2001; Estes and Frangopol, 2003; Gattulli and Chiaramonte, 2005; Alani et al., 2013, 2014) to advanced methods of lighting to aid visual inspections and tap-hammers to detect more subtle acoustic (and hence localised stiffness) changes (Ibrahim, 2014). Different researchers in different parts of the world have worked on numerous NDT methods which are visual inspection (Perenchio, 1989; Anonymous, 2001), chain drag (ASTM, 2003; Anonymous, 2009; Barnes and Trotter, 2000; Gueunski and NRC, 2013; ASTM, 1997; Barnes et al., 2008), coin tap test (McCann and Forde, 2001; Cawley, 1991; Wu and Siegel, 1999; Cawley and Adams, 1988), acoustic emission (Rens et al., 1997; Carlos et al., 2000; Holford and Lark, 2005; Holford et al., 2001), impact echo testing (Sansalone, 1997; Sansalone and Street, 1997; Lin and Sansalone, 1993, 1994, 1996; Cheng and Sansalone, 1993; Lin and Su, 1996; Azari et al., 2014), sonics (ACI Committee 228, 1998; McCann and Forde, 2001; Binda et al., 2001, 2003; Colla et al., 1997), ultrasonic NDT (ACI Committee 228, 1998; Azari et al., 2014; Afshari et al., 1996; Bogas et al., 2013; ASTM, 2009; Schickert, 2005; Shah et al., 2013; Shokouhi et al., 2013; Taffe and Wigenhauser, 2006), impulse response (ACI Committee 228, 1998; Davis, 2003; Turner, 1997), ground penetrating radar (ACI Committee 228, 1998; Barnes et al., 2008; Orlando et al., 2010; Alani et al., 2013; Yehia et al., 2014; Perez-Gracia et al., 2008; Diamantini et al., 2008; Solla et al., 2012; Hugenschmidt and Mastrangelo, 2006; Chang et al., 2009), conductivity (McCann and Forde, 2001; Colla et al., 1997; Garboczi et al., 1995; Whittington et al., 1981), coring (Gueunski and NRC, 2013; Suzuki et al., 2010; Scott et al., 2003; ASTM, 2003), electrical resistivity (Gueunski and NRC, 2013; Ryan et al., 2013; Layaste et al., 2003, 2013, Saleem et al., 1996; Polder, 2001), proof load test (Casas and Gomez, 2013; Faber et al., 2000; Saraf et al., 1996; Fu and Tang, 1995), infrared thermography (ACI Committee 228, 1998; Gueunski and NRC, 2013; McCann and Forde, 2001; Clark et al., 2009, Buyukozturk, 1998; Stanley and Balendran, 1994), half-cell potential (Elsener et al., 2003a, b; ACI Committee 228, 1998; ASTM, 1999; Elsener et al., 2003a, b; Elsener, 2001; Ohlts et al., 1997; Clemea et al., 1992), radiography (Ibrahim, 2014; Song and Saraswathy, 2007; Malhotra, 1976; Naik et al., 2004), dynamic/vibration testing (Bedon and Morassi, 2014; Cunha et al., 2013; Samman and Biswas, 1994; Hashim et al., 2013; Ismail et al., 2011; Gentile, 2006; Reynolds, 2008; Caetano et al., 2015; De Roeck et al., 2000; Salawu and Williams, 1995), Schmidt rebound hammer (Szlagyi et al., 2011; Breysse, 2012; Kim et al., 2009; Anonymous, 2001; Basu and Aycdin, 2004; Samman and Biswas, 1994). These NDT methods have limitations which are hindrances to their usage (Rehman et al., 2016) as iterated in Table 1.

<table>
<thead>
<tr>
<th>NDT methods</th>
<th>Limitations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Impact echo (Sansalone, 1997; Sadowski et al., 2016)</td>
<td>High temperature of asphalt concrete overlay not detectable</td>
</tr>
<tr>
<td>Low viscous material is difficult to detect</td>
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<tr>
<td>Signals are affected greatly by deck boundaries</td>
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<tr>
<td>Marking the boundaries of delimited area may not be possible without dense grids</td>
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<tr>
<td>Detection is only possible for loosely bonded overlay to the deck</td>
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<tr>
<td>Interference of boundary on signal is more prominent on limited dimensional elements like girders and piers</td>
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</tr>
<tr>
<td>Impulse response (Davis, 2003; Sadowski et al., 2016)</td>
<td>Selection of test points determines reliable data interpretation</td>
</tr>
<tr>
<td>Inability to detect small defects</td>
<td></td>
</tr>
<tr>
<td>Mautheuer et al., 2010)</td>
<td>Unavailability of automated apparatus</td>
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<tr>
<td>Acoustic emission (Holford and Lark, 2005; Suzuki et al., 2010; Behnia et al., 2014; Langenberg et al., 2010)</td>
<td>It works with a background noise</td>
</tr>
<tr>
<td>Its analysis application to real structure is difficult</td>
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<tr>
<td>Well defined procedure for all types of bridges is not available</td>
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<tr>
<td>Detection of shallow defects may not occur</td>
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<tr>
<td>Coupling of the sensor unit determines the quality of data in a great deal and there is difficulty in coupling on rough surfaces</td>
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<tr>
<td>Very close grid spacing is needed</td>
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<td>Lower frequencies may cause incomplete detection</td>
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</tbody>
</table>

The process of making use of non-destructive techniques and equipment to observe and study a structure within a time frame is known as SHM. Inspections in RCB is a periodic exercise, the transition from NDI to SHM is a transition from the traditional “time-based” to the emerging “condition-based” maintenance (Mandache et al., 2011).
<table>
<thead>
<tr>
<th>NDT methods</th>
<th>Limitations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground penetrating radar (Alani et al., 2013a, 2014; Barnes and Trotter, 2000)</td>
<td>Too costly to use</td>
</tr>
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<td></td>
<td>Difficulty to detect moisture completely frozen</td>
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<td></td>
<td>Strength, modulus and some mechanical properties estimation is almost impossible</td>
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<td></td>
<td>GPR data are affected by extreme cold conditions and acquired signal influenced</td>
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<tr>
<td></td>
<td>Effects like corrosion or位居 section loss are difficult to read</td>
</tr>
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<td></td>
<td>Isolating layers such as paint, coating and asphalt are difficult to read</td>
</tr>
<tr>
<td>Half-cell potential (Elesner et al., 2003; Elesner, 2001; Warkinde and Landgate, 2013)</td>
<td>Depth data is difficult to correct</td>
</tr>
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<td></td>
<td>Temperature higher than 2°C is required</td>
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<tr>
<td></td>
<td>Concrete cover depth influence unknown</td>
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<td></td>
<td>Method cannot be used for moisture or salt content calculation</td>
</tr>
<tr>
<td>Infrared thermography (Clark et al., 2009; Bayukozturk, 1998; Tortora et al., 2016)</td>
<td>Deep flaws difficult to detect</td>
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<td></td>
<td>Results are often influenced by conditions at the boundary, irregularities at the surface and atmospheric temperature</td>
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<td></td>
<td>Pre-wetting process must be carried out on the surface</td>
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<tr>
<td>Electrical resistivity (Latase et al., 2003; Polder, 2001; Torres-Luque et al., 2014)</td>
<td>Results are often confusing and difficult to analyse and interpret</td>
</tr>
<tr>
<td></td>
<td>Unavailability of read measurement system which are automated</td>
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<tr>
<td></td>
<td>Properties like salt content, porosity and moisture content have great influence on it</td>
</tr>
<tr>
<td>Chain drag and hammer sounding (Stanley and Balendra, 1994)</td>
<td>This cannot be used on vertical surfaces</td>
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<tr>
<td></td>
<td>Operator’s hearing skills are highly required</td>
</tr>
<tr>
<td></td>
<td>Initial delamination is not detected</td>
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<tr>
<td></td>
<td>Ineffective on bridge decks with overlays</td>
</tr>
</tbody>
</table>

**MATERIALS AND METHODS**

**Structural health monitoring:** Structural Health Monitoring (SHM) refers to the studying of a structural system for a period of time and taking records of its responses with the use of equipment like arrays of sensors, Damage-Sensitive Features (DSFs) extraction and statistical analysis to detect changes that may result from structural damages (Farahani, 2013). SHM can also be defined as the measurement of the operating and loading environment and the critical responses of a structure to track and evaluate the symptoms of operational incidents, anomalies and/or deterioration or damage indicators that may affect operation, serviceability or safety reliability (Aktan et al., 2000). It aims to give a diagnosis of the state of every element of a structure at every moment during the structure’s lifetime. SHM combines a variety of sensing technologies configured to capture, log and analyse real-time data, its systems are designed to accurately study and test the health and performance of structures such as buildings, stadia, bridges, dams, wind turbines, aircrafts, ships, etc. SHM emphasizes on monitoring structural responses to the environment in real time (Yun et al., 2003). The difference between NDT measurements and SHM is that NDT provides inspection into the structural geometry, response to load application, details of damage events, region of damage initiation and stress point while SHM involves the use of sensors which are fixed permanently for routing checks at intervals (Habel, 2010). The two philosophies are related and at times both use the same measurement physics. A major factor in SHM is the in-service positioning of sensors and systems to maintain calibration when exposed to the elements over many months or years. Several researchers have carried out various study on SHM, spanning from laboratory work to full scale tests (Ragland et al., 2011; Cheung et al., 2008; Fasel et al., 2002).

An early practice of SHM can be found in the aerospace industries which assessed the condition of materials and structural components by using Non-Destructive Evaluation (NDE) methods (Doebbling et al., 1998). Fasel et al. (2002) worked on a three story building simulation using an electro dynamic shaker attached to the base of the structure, it was reported that sensors position in any assessment is important and can determine the effectiveness of the work done. Ragland et al. (2011) used a different approach in finite element analysis of a five-girder bridge subjected to vertical vibration source and reported difference in sensitivities of the horizontal response of the bridge and the vertical response. Cheung et al. (2008) used the triaxial vibration data of the Z24 Bridge, Kramer et al. (1999) obtained under the ambient loading and reported similarities in the results obtained using horizontal and vertical vibration data. Lucena and Dos Santos (2016) proposed a new approach for SHM in structural damage detection using both Time Reversal Method (TRM) and Spectral Element Method (SEM). Their methodology uses numerical simulation evaluation (MATLAB environment) to bring together time reversal signal processing and wave-based spectral element model. It was established that healthy and cracked rod models simulations gave
same acceleration response result with the literature also damage status and position can be revealed with the method.

**Structural reliability theory:** Structural reliability analysis on the other hand is concerned with the logical management of uncertainties in the design of structures (Thoft-Christensen and Baker, 1982; Afolayan and Opeyemi, 2010a, b). Structural reliability in a most general sense is the ability of a structure to fulfill its design purpose for some specified time and in a narrow sense (or mathematically) is the probability that a structure will not attain each specified limit state (ultimate or serviceability) during a specified reference period (Thoft-Christensen and Baker, 1982). This ability of a structure to fulfill its design purpose is measured on a fundamental basis of probability; the reliability of a structure can be said to be the probability of the structure performing to the purpose of its design according to some performance functions with respect to excessive conditions within a time frame (Afolayan and Opeyemi, 2010a, b). Methods that have been proposed for assessment of structural reliability are First Order Second Moment (FOSM) method (Afolayan and Opeyemi, 2010a, b; Akindahunsi and Afolayan, 2009; Wen, 2001), Advanced Second Moment (ASM) method and computer based Monte Carlo Simulation (MCS) (Ayyub, 1997).

Numerous researches have been done on reliability theory and applications, Akindahunsi and Afolayan (2009) worked on developed reliability-based interaction curves for design of reinforced concrete columns, the criteria of British Standard Code of Practice (1997) was examined. For established safety level to be maintained in designs, FORTRAN computer language was developed using British Standards Institute (1997) design requirements and the First Order Reliability Method (FORM).

**RESULTS AND DISCUSSION**

**Previous analyses of SHM data:** Acquisition of SHM data requires effective analyses and evaluation, researches carried out on SHM in the past have been interpreted in different ways.

From Table 2, researches done on SHM have been analysed in times past using graphical representations, table, numerical analysis, 3D images, statistical analysis and finite element methods, very small number of the researches are in terms of reliability-based paradigm. Researches that have employed reliability theory to analyse SHM data are researches on bridges (Ye et al., 2018; Cebas et al., 2008). There is need for researches into reinforced concrete buildings which will use reliability theory to analyse full SHM data.

<table>
<thead>
<tr>
<th>Researchers</th>
<th>Analyzes Methods</th>
<th>Types of test</th>
<th>Equipment used</th>
<th>Data taken</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gamal et al. (2013)</td>
<td>Graphical representations and table forms</td>
<td>Laboratory test of a structural model</td>
<td>Microprocessors, wireless communication, transducer and cellular transmission</td>
<td>Structural strain data</td>
</tr>
<tr>
<td>Skolnik et al. (2008)</td>
<td>Finite element method, illustrations</td>
<td>Real structure test</td>
<td>Eccentric mass shakers, tri-axial accelerometers, linear variable differential transducer</td>
<td>Interstory drift/ displacement data</td>
</tr>
<tr>
<td>Roghaci and Zahibollah (2014)</td>
<td>Theoretical illustrations</td>
<td>Laboratory test of a structural model</td>
<td>Array of piezoelectric sensors</td>
<td>Deformation and stress data</td>
</tr>
<tr>
<td>Hajdusiewicz et al. (2015)</td>
<td>Graphical and tabular presentations</td>
<td>Real structure test</td>
<td>Vibrating Wire (VW) gauges, Electrical Resistance (ER) strain gauges, IP68 rated thermistor sensors, BMS and indoor sensors, weather monitoring sensors, etc</td>
<td>Temperature data</td>
</tr>
<tr>
<td>Hosseinieou and Mojtahedi (2016)</td>
<td>Empirical modelling</td>
<td>Laboratory test of a structural model</td>
<td>Electric sensors</td>
<td>Column and beam modal measurements</td>
</tr>
<tr>
<td>Karayannis et al. (2016)</td>
<td>Graphical presentations</td>
<td>Laboratory test of a structural model</td>
<td>Piezoelectric sensors, linear variable differential transducer</td>
<td>Flexural response and deflection</td>
</tr>
<tr>
<td>Loutas et al. (2015)</td>
<td>Numerical analysis</td>
<td>Laboratory test of a structural model</td>
<td>Fiber Optic Ribbon Tapes (FORTa)</td>
<td>Strain measurements</td>
</tr>
<tr>
<td>Comanducci et al. (2015)</td>
<td>Methods of multivariate statistical analysis</td>
<td>Laboratory test of a structural model</td>
<td>Multivariate statistical analysis tools</td>
<td>Wind speed and wind effect data</td>
</tr>
<tr>
<td>Lucena and Dos Santos (2016)</td>
<td>Numerical simulation</td>
<td>Computer based model</td>
<td>MATLAB, spectral element method</td>
<td>Frequency data</td>
</tr>
<tr>
<td>Lorenzoni et al. (2016)</td>
<td>Statistical models and algorithmic analysis</td>
<td>Real structure test</td>
<td>Traditional displacement transducers and optical camera</td>
<td>Crack data</td>
</tr>
</tbody>
</table>
CONCLUSION

For proper acknowledgement of SHM for assessment in structures there is a need for a reliability measure, similar to the probability of detection for NDI. Several questions must be answered for the actualization of SHM of structures such questions are:

• What are the economic and technical benefits?
• Is the approach validated?
• What is the false/positive call rate?
• What is the reliability of such a system?

Structural reliability approach has not been fully studied on reinforced concrete buildings using SHM data as the input. Most reliability methods make use of condition ratings based on visual inspections or theoretical/numerical models. There have been suggestions on supplementing reliability models with sensor data or non-destructive experimental results. A reliability approach using a complete SHM application needs to be further investigated. The integration of SHM and reliability analysis as a framework composed of a comprehensive structural health monitoring application for probabilistic analysis of buildings will foster efficient structural management and decision-making.

REFERENCES


