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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. Inventions 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*., 2003a, 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

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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 has 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, 2009; Barnes and Trottier, 2000; Gucunski and NRC, 2013; ASTMD, 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 Wiggenhauser, 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; Diamanti *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 (Gucunski and NRC., 2013; Suzuki *et al*., 2010; Scott *et al*., 2003; ASTM., 2003), electrical resistivity (Gucunski and NRC., 2013; Ryan *et al*., 2013; Lataste *et al*., 2003; 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; Gucunski 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; Ohtsu *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 (Szilagyi *et al*., 2011; Breysse, 2012; Kim *et al*., 2009; Anonymous, 2001; Basu and Aydin, 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.

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 1: Limitations of non destructive methods

NDT methods	Limitations
Impact echo (Sansalone, 1997;	High temperature of asphalt concrete overlay not detectable
Azari *et al*., 2014;	Low viscous material is difficult to detect
Sadowski *et al*., 2016)	Signals are affected greatly by deck boundaries
	Marking the boundaries of delimited area m7ay not be possible without dense grids
	Detection is only possible for loosely bonded overlay to the deck
	Interference of boundary on signal is more prominent on limited dimensional elements like girders and piers
Impulse response (Davis, 2003;	Selection of test points determines reliable data interpretation
Sadowski *et al*., 2016;	Inability to detect small defects
Maierhofer *et al*., 2010)	Unavailability of automated apparatus
Acoustic emission (Holford and Lark,	It works with a background noise
2005; Suzuki *et al*., 2010; Behnia *et al*.,	Its analysis application to real structure is difficult
2014; Langenberg *et al*., 2010)	Well defined procedure for all types of bridges is not available
Ultrasonic pulse velocity (Bogas *et al*.,	This method is time consuming
2013; Breysse, 2012; Jain *et al*., 2013)	Detection of shallow defects may not occur
	Coupling of the sensor unit determines the quality of data in a great deal and there is difficulty in coupling on rough surfaces
	Very close grid spacing is needed
	Lower frequencies may cause incomplete detection

Table 1: Continue

NDT methods	Limitations
Ground penetrating radar (Alani *et al*., 2013a, 2014; Barnes and Trottier, 2000)	Too costly to use Difficult to detect moisture completely frozen Strength, modulus and some mechanical properties estimation is almost impossible GPR data are affected by extreme cold conditions and acquired signal influenced. Effects like corrosion or rebar section loss are difficult to read
Half-cell potential (Elsener *et al*., 2003; Elsener, 2001; Wankhade and Landage, 2013)	Isolating layers such as paint, coating and asphalt are difficult to read Depth data is difficult to correct Temperature higher than 2°C is required Concrete cover depth influence unknown Method can't be used for moisture or salt content calculation
Infrared thermography (Clark *et al*., 2009; Buyukozturk, 1998; Tortora *et al*., 2016)	Deep flaws difficult to detect Depth of crack data are not provided Results are often influenced by conditions at the boundary, irregularities at the surface and atmospheric temperature
Electrical resistivity (Lataste *et al*., 2003; Polder, 2001; Torres-Luque *et al*., 2014)	Results are often confusing and difficult to analyse and interprete Pre-wetting process must be carried out on the surface Unavailability of road measurement system which are automated. Properties like salt content, porosity and moisture content have great influence on it
Chain drag and hammer sounding (Stanley and Balendran, 1994)	This can't be used on vertical surfaces Operator's hearing skills is highly required Initial delamination is not detected Ineffective on bridge decks with overlays

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, regions 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 uses 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 (Doebling *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 fulfil 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 fulfil 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 has 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; Catbas *et al*., 2008). There is need for researches into reinforced concrete buildings which will use reliability theory to analyse full SHM data.

Table 2: Different methods of analyses of SHM researches

Researchers	Analyses Methods	Types of test	Equipment used	Data taken
Gamal *et al*. (2013)	Graphical representations and table forms	Laboratory test of a structural model	Microprocessors, wireless communication, transducer and cellular transmission	Structural strain data
Skolnik *et al*. (2008)	Finite element method, illustrations	Real structure test	Eccentric mass shakers, tri-axial accelerometers, linear variable differential transducer	Interstory drift/ displacement data
Belostotsky and Akimov (2016)	Finite element method, illustrations	Computational assessment of load-bearing finite element model	Computer based	Stress-strain state and load- bearing capacity of structures
Roghaei and Zabihollah (2014)	Theoretical illustrations	Laboratory test of a structural model	Array of piezoelectric sensors	deformation and stress data
Hajdukiewicz *et al*. (2015)	Graphical and tabular presentations	Real structure test	Vibrating Wire (VW) gauges, Electrical Resistance (ER) strain gauges, IP68 rated thermistor sensors, BMS and indoor sensors, weather monitoring sensors, etc	Temperature data
Hosseinlou and Mojtahedi (2016)	Empirical modelling	Laboratory test of a structural model	Electric sensors	Column and beam modal measurements
Karayannis *et al*. (2016)	Graphical presentations	Laboratory test of a structural model	Piezoelectric sensors, linear variable differential transducer	Flexural response and deflection
Loutas *et al*. (2015)	Numerical analysis	Laboratory test	Fiber Optic Ribbon Tapes (FORTs)	Strain measurements
Comanducci *et al*. (2015)	Methods of multivariate statistical analysis	Laboratory test of a structural model	Multivariate statistical analysis tools	Wind speed and wind effect data
Lucena and Dos Santos (2016)	Numerical simulation	Computer based mdel	MATLAB, spectral element method	Frequency data
Lorenzoni *et al*. (2016)	Statistical models and algorithmic analysis	Real structure test	Traditional displacement transducers and optical camera	Crack data

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.

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