CARBON NANOTUBE DOPED SELF-SENSING CONCRETE BASED MULTI-FUNCTIONAL FRAMEWORK FOR STRUCTURAL HEALTH MONITORING AIDED BY MACHINE LEARNING

Abstract

Structural Health Monitoring (SHM) involves continuous or periodic data acquisition of structural responses and their interpretation, with the objective of detecting, localising, and characterising damage at the earliest possible stage. It refers to a systematic process of implementing sensing techniques, different acquisition techniques and advanced analytics to assess the condition of a structure during its service life. Conventional sensors, such as electric strain gauges (ESG) and vibrating wire strain gauges (VWSG), accelerometers, and smart material-based sensor such as optical fibres, piezo ceramic lead zirconate titanate (PZT) sensors are used for damage detection in structures but they are accompanied by several challenges, such as environmental degradation, operational performance, material incompatibility, and durability issues. For multipronged and robust solution of aforemen tioned problems, this doctoral research aims to develop, investigate and evaluate multiwall carbon nanotube (MWCNT) doped self-sensing concrete-based sensors (MWCNT-CS) un der different operational environments, encompassing both static and dynamic responses of the structure. This doctoral research begins with the development of MWCNT doped self-sensing block type concrete sensors, 50 × 50 × 50 mm in size, suitable for embedding in concrete struc tures, by doping four different dosages of 0.25%, 0.5%, 1%, and 2% (by weight of cement) of MWCNT, ensuring compatibility with the surrounding concrete. It is found that the 1% (w/w) MWCNT doping in cement mix shows best results in terms of sensitivity and strength. Furthermore, these standalone self-sensing concrete sensors are tested against static and dynamic loading conditions for calibration purposes. In case of static strain sens ing, these sensors are calibrated using ESGs to obtain individual gauge factor under static x xi loads. The sensitivity of the proposed sensors is found to be 200 to 500 times higher than that of ESGs. Similarly, for calibration of these sensors under dynamic loading conditions, a rectangular PZT sensor is used for validation. Responses recorded from proposed MWCNT and PZT sensors are found synchronous with each other. After fabrication and calibration, same MWCNT-CS sensors are used to study hydration monitoring of MWCNT doped con crete mix vis-à-vis ordinary concrete mix specimen (control specimen) for the duration of 28 days. Resin jacket piezo sensor (RJP) is incorporated in the hydration study of MWCNT doped concrete mix employing electro-mechanical impedance (EMI) technique using LCR meter. Extracted impedance based equivalent stiffness parameters (ESPs) from EMI signa tures display strength gain progression differently in MWCNT doped concrete mix vis-à-vis ordinary concrete mix. This study further aided with machine learning (ML) framework for automation and predictive analysis, it is found that decision tree (DT) and random forest (RF) models were best performed models for classification. In case of regression study, extreme gradient boosting (XGB) model outperforms other regression models in predicting various extracted impedance parameters showing value of the coefficient of determination i.e. R-square, ranged between 0.9 to 0.99. This study further extends to evaluate five numbers MWCNT-CS (embedded at the bottom surface) for their performance in large scale prototype reinforced concrete (RC) beam of span 3.12 m, 280 mm width, and 100 mm depth, in comparison with five numbers of concrete vibration sensors (CVS) (embedded on top surface) separated equally from the supports. Followed to this, efficacy of MWCNT-CS sensors is established for capacitance based hydration monitoring of surrounding concrete using LCR meter. It is found that capacitance of the proposed sensors is sensitive towards hydration progression of surrounding concrete. To candidate’s best knowledge, this is the first time LCR

measurement-based xii approach is used for strain sensing for MWCNT-CS sensors. Next part of the doctoral research begins with establishment of strain measurements as a credible alternative of deflection measurements for operational performance check (OPC) in real-life bridges. Furthermore, this doctoral thesis demonstrates OPC on prototype RC beam using MWCNT-CS based strain measurement under static loading condition using conventional and proposed MWCNT-CS sensors. A comprehensive experimental program is undertaken to demonstrate fractional change in resistance as measurement unit for strain experienced by MWCNT-CS. This study further extends the investigation of proposed MWCNT-CS sensor for dynamic analysis initiated with the identification of natural fre quency of the experimental RC beam followed by operational modal analysis (OMA) using surface bonded accelerometers and embedded concrete vibration sensors (CVS) to bench mark the study. The OMA, using first principle of obtaining vibrational mode, is performed through proposed MWCNT-CS sensors and validated against the results of embedded CVS. Dynamic excitations are produced by laboratory-based shaker, placed at middle section of the top surface of the beam. The outcome of this study establishes for the first time, the efficacy of MWCNT-CS as self–sufficient not only for static as well as dynamic response measurements, but also the modal analysis. In conclusion, the original contributions of this doctoral research consist, development of new AI-based hydration monitoring technology for concrete (plain, reinforced, doped) using the EMI technique, OPC using MWCNT-CS sensors under static loading conditions, and their extension to higher level dynamic evaluation such as determination of strain mode shapes that is based on principle of magnitude of deflection (peak to peak amplitude) under ambient vibrations. In addition to this a capacitance-based measurement approach is also proposed and validated for hydration monitoring of coventional concrete using MWCNT xiii CS. Hence, this doctoral thesis establishes self-sensing concrete sensors for the multipronged structural health monitoring addressing operational challenges associated with conventional sensors. Especially the same sensor can be utilized for the both static & dynamic evaluations, covering the full spectrum of SHM in reinforced concrete structures.