TOWARDS PERFORMANCE BASED DYNAMIC & REAL TIME BRIDGE MANAGEMENT

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Abstract:
Structural health monitoring (SHM) only provides a perspective for online analysis, prediction, and early warning. Integration with Bridge management enhances this capability. SHM has been widely used in many bridge structures, and a lot of bridge SHM data have also been collected. Structural Health Monitoring (SHM) can now be used to assess a real-time behaviour of structures using different kinds of sensors to measure the performance of structures. Performance is now linked to modification of deterioration model. Deterioration models are the key to initiation of bridge management system. The idea to utilize the performance of various elements of the bridge structure for generating the deterioration model was born out of the need to have a more robust, realistic, and reliable deterioration model. The drawback to this were the intense mathematical operations essential to determine the presence of distress based on raw data generated from Structural Health monitoring of those elements under live loading. Emergence of computing tools made this possible. Research to apply computing algorithms to SHM data resulted in enhanced solutions to the 3D model, this resulted in a real time, robust and efficient Bridge Management.

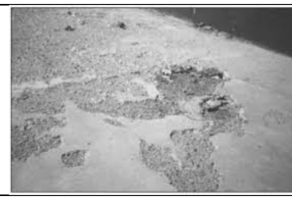
INTRODUCTION

Ever increasing number of bridges are one of the main components of any transportation infrastructure network.[15]. Deterioration impacts may occur due to natural disasters, the increase in traffic volumes, weather conditions and/or material strength degradation (i.e., corrosion, soil scour and others), which may have significant reduction on its structural capacity or may urgently require action. By using Structural health monitoring (SHM), it is possible to monitor the bridge periodically. It is possible to monitor the response of the bridge structure which reveals modifications to the material and geometric properties. SHM is important for maintenance planning to find a cost-effective solution to reduce costs and extend the life of critical assets like bridges. SHM for bridge structures is generally referred to, for the damage detection or characterization strategy for real-time assessment of structural condition. It is important to thoroughly assess periodically the safety, serviceability, and sustainability of bridges during their service life, and hence SHM systems are being actively developed to fulfil the task. SHM is considered as a key solution to provide information about the operational performance of the structures under examination. Predominantly, there are two types of SHM systems, that can be used in assessing the structure performance under different loading conditions [15]. SHM has been widely used in bridge structures the world over. This has resulted in lot of bridge SHM data being available for analysis.

Structural Health monitoring – Real time analysis of the structure under live load.

Bridge management requires details of bridge structure and its condition. The process of collection of this essential data begins with Inventory and Inspection of Bridges on the network.

During Inspection of bridge structure, it is mandatory for the bridge inspection engineer to collect and collate data related to the various types of distress observed, its locational details, extend and degree of severity. The bridge elements show varying degree of distress. Observation of distress originates with emergence of cracks in the bridge profile. Cracks propagation is most of the time the starting point of all distress seen visibly. Correlating the cracks with the Cause is one important step to integrating the Performance with Bridge Management.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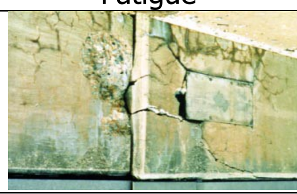
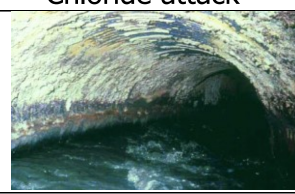
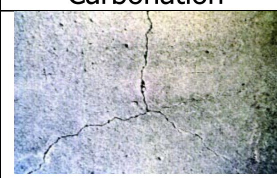
			
Sulphate attack	Alkali silica reaction	Acid attack	Plastic shirnkage

It is elements that show very severe distress that fail first and creates a situation for cascading effect of progression of such failure to other elements and finally to the whole bridge. Locational details, degree of severity and extent of distress hence are very important from bridge maintenance point of view. Having identified the geospatial locational details along with the extent and severity of the distress in the element, the Bridge inspector can then focus on identification of the most severe distressed elements. Identification of elements which exhibit severe distress is critical for further implementation. Once the degree of distress, extent and location are identified by the bridge inspection engineer, the elements showing severe distress are subjected to short term SHM. SHM applied on the bridge for the first time will yield performance index for a known degree of distress, known extent of distress and known location of distress on an element which is subjected to SHM. Application of all subsequent SHM is done to monitor the variation in the performance of such distressed elements under live loads.

Various techniques and types of sensors can be used for such short-term monitoring. The type of sensors to be used and the techniques and parameters to be monitored shall be dictated by Cause of distress. Three principal processes define the Cause of distress. These three principal's processes are further subdivided into 11 sub processes [1].

Two types of SHM are envisaged to achieve the objective.

1. Remote or No contact SHM: System where the parameters essential like Vibration signature, amplitude, acceleration, frequency, strain are all captured by technology that does not require any physical contact with the bridge.
2. Contact SHM: System wherein major strain, stress, linear displacement equations, inclination, vibration, frequency, acceleration, corrosion potential are all measured by sensors (Strain Gauges, Linear Variable Differential Transformer (LVDT), Tilt Meter, Inclinometer Sensors, Acoustic Emission Sensors (AE), Fibre Optic Sensors, Corrosion Sensors, Accelerometer) in close contact with various desired components of bridges.

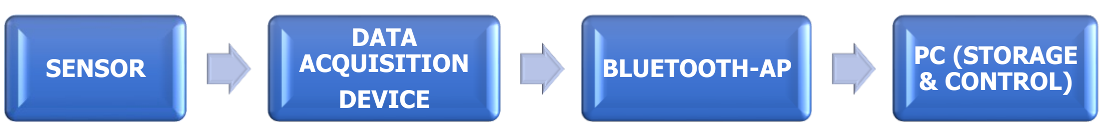
A brief indicative list of sensors that can be used and their limitations are enumerated below. The limitations could be overcome and are indicative. The list is totally indicative and many other types of sensors can be used for short term SHM.

Both the No contact and Close Contact systems will yield results that identify typical changes in performance parameters. Such changes in performance will imply changes in distress also. It is a known fact that increments in distress extent, severity will lead to decrease in performance of

Sr.No.	Sensors	Uses	Limitations
1.	Strain Gauges	To measure strain, to measure resultant stress.	1.Require the application surface to be finished and clean. 2. Sensitive to overload
2.	Accelerometer	For measuring acceleration force, vibration of the bridge.	1. Does not measure constant velocity.
3.	Temperature Sensors	To measures temperature of its environment.	1. Difficult to verify. 2. Non-linear. 3.Recalibration is difficult.
4.	VIDUR & VEDA	Used for Photonic System for vibration and condition monitoring of Structures.	-----

the bridge element. It is this fact that is used when SHM is used within BMS.

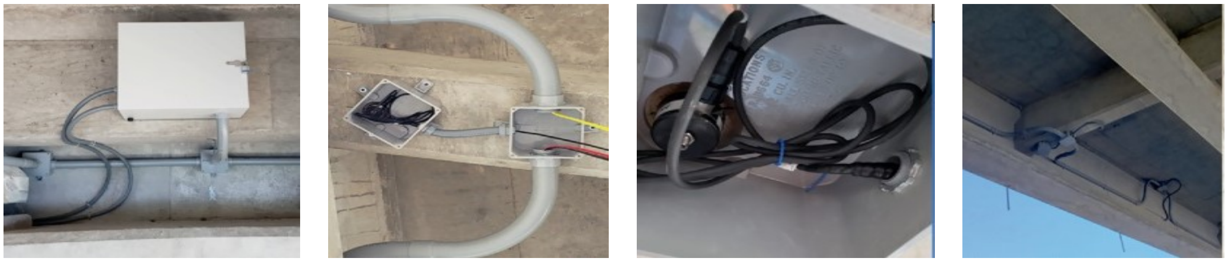
Sensors are connected to a data acquisition device by wire or remotely. Measured data are digitized in AD converter and delivered through Bluetooth module and Access Point (AP) by wireless. The collected data are stored in Storage Device (SD) memory or on hard drive of a computer. A data acquisition device is time synchronized by signal sendr from Computer. Computer (PC) stores data in real time and controls the sensor nodes (data acquisition devices) makes this a real time system



Application of computing algorithms to SHM to evaluate performance of bridge under live loads.

Changes in Performance parameter can be identified by SHM based on the time series observations of Performance between base scenario which exhibits 'No Distress Situation" or "Initial Scenario" and with operational scenario which shows "Presence of Distress situation" or "Enhanced distress Situation". Further, Performance monitoring should be able to correlate decrease in Performance level with increments in the extent, severity of Distress.

Techniques available and know for correlating performance of structure to presence of distress are many. Few of techniques are elaborated herein under as:



A. **Optical matrix updating methods:** All-optical method performing the operation of matrix multiplication on the base of the matrix of waveguide ring micro resonators. Information is processed immediately when it passes through the optical system, which performs the computation procedures, and with supply of the input data in parallel. The speed of such optical matrix processor is multiple times high [17].

B. **Sensitivity based updating methods:** Sensitivity-based finite element model updating (FEMU) is to create a well-established framework for updating the inherent structural properties of FE models prepared under noisy modal data. When noise contaminates the measured modal parameters, another challenging issue stems from the ill-positioned of the FEMU inverse problem [14]. FEMU updates such FE models to correct No noise situations.

C. **Wavelet techniques:** Wavelet techniques is a mathematical technique which can decompose a signal into multiple lower resolution levels by controlling the scaling and shifting factors of a single wavelet function [17].

D. **Frequency response function:** A frequency response function (FRF) is a function used to quantify the response of a system to an excitation, normalized by the magnitude of this excitation, in the frequency domain [13].

E. **Artificial Neural networks (MLP: Multi-Layer Perception and RBF: Radial Basis Function):** Artificial neural network is an attempt to simulate the network of neurons that make up a human brain so that the computer will be able to learn things and make decisions in a humanlike manner. ANNs are created by programming regular computers to behave as though they are interconnected brain cells [14]. Such network can provide the network to compute very complex algorithm.

F. **Hybrid ANN namely Imperial Competitive Algorithm [ICA] and Genetic Algorithms [GA]:** ICA is one of the most recent evolutionary algorithms. This population-based approach is based on humans' socio-political evolution, and it has been successfully applied in several optimization problems. GA, another meta-heuristic algorithm which has been also used in many optimization problems. Both evolutionary algorithms work with random populations to find the solution [14].

G. **Principal Component Analysis (PCA):** A method of analysis which involves finding the linear combination of a set of variables that has maximum variance and removing its effect, repeating this successively [13].

H. **Reliability Analysis:** Reliability analysis allows you to study the properties of measurement scales and the items that compose the scales. The reliability analysis procedure calculates several commonly used measures of scale reliability and provides information about the relationships between individual items in the scale [15].

I. Symmetry Index Analysis: The linear regression is used to estimate a simple novel symmetry index (SI) of bridges. The slope of the regression model of both sides' performances of the bridge is used to calculate SI as follows [15]

$$SI = |S1|/|S2|$$

Typical application of techniques to yield analytical results:

From the numerous techniques available (9 of which are listed above), we can combine and use with advantage the techniques to yield the desired results which provide information about decrements in performance of bridge structure. Typical analysis procedure is evolved with one of the above techniques or a combination of few. Few of the known researched combinations are illustrated below:

1. V.V. Nguyen and Ulrike DACKERMANN et.al had studied that the application using (Operational modal analysis) OMA, frequency response functions (FRF), Principal Component Analysis (PCA), Artificial Neural Network (ANN): Operational modal analysis (OMA) which can be Cepstrum based. They applied the same for the regeneration of frequency response functions (FRFs). This application yielded detection of distress zones. Distress / damage features can be identified in the regenerated FRF data. Response measurements comprise effects due to excitation and transmission. Their separation is essential before relevant transfer functions can be determined. The employed technique achieved source-path separation using Cepstrum technique which can deal with 'frequential smooth' inputs. After separation, the transfer function is obtained by curve-fitting the transfer path Cepstrum, from which the desired FRFs are generated. Principal Component Analysis (PCA) techniques can be used to reduce their size and to provide input data for ANN training. ANN training yielded Artificial Intelligence application to forecast the probability of distress propagation. [12] [13].
2. Meisam Gordan et.al had recommended that the application using ANN, frequency response functions (FRF), Imperial Competitive Algorithm (ICA), CFE: The methodology of this study is divided into two categories, comprising operating techniques (inverse analysis) and diagnosis techniques (ANN/hybrid models) for input data. The test structure (1:10) was formed and various scenarios were imposed on the structure. Whenever, FRFs are generated they are stored in NVGATE and ICATS was utilized to extract the structural dynamic parameters from measured vibration data and compute the FRFs by means of curve-fitting extraction process. this extracted output will be the input for ANN or hybrid ANN [14].
3. The Mosbeh R. Kaloop et.al considered Sangsu bridge as their case study. Application uses Frequency Domain Decomposition (FDD), Markov Chain Monte Carlo (MCMC), SI (Symmetric Index) for behaviour assessment of bridges for vibration-based NDT (Non-Destructive Testing) of short period structural health monitoring systems. Strain, displacement, and acceleration measurements for a Bridge are adapted and applied as a metric for fault diagnosis of the bridge. Symmetry index is conducted using static behaviour test of the bridge and dynamic factor, frequency modes and reliability are assessed using dynamic tests. The Frequency Domain Decomposition (FDD) and Markov Chain Monte Carlo (MCMC) are applied to estimate the frequency models and reliability, respectively [15].
4. Qiwen Jin studied urban CFST Truss Girder Bridge in his case study and advised that the application using Distribution Frequency Function (DFF), Time Series Analysis (TSA): Essential dynamic problems in bridge SHM and the characteristics of bridge SHM data are pointed out, and then three targeted analysis methods are proposed. Three data mining methods (distribution function, association analysis, and time-series analysis) are employed for predictive analytics of structural response and deterioration extent [16].
5. Muntazir Abbas et.al had studied that the ultrasonic guided waves potentially offer a smart alternative solution to conventional approach towards Non-Destructive Evaluation (NDE) and Structural Health Monitoring (SHM). It aimed to determine the signal variations in excited Lamb waves (short tone burst) with the surface cracks in several shapes and orientations. It seems quite possible to sense the projected changes in an output signal

upon interaction with these aspects of structural discontinuities. The defects may be investigated at various angles with respect to the position of transducers. Upon successful identification of defect geometries, an empirical model can be designed to predict the defect features and quantification [17].

In the process of Bridge Management, it is critical to identify the Cause of distress. This is primarily done by the Bridge inspection engineer during his long-drawn procedure to record and collate all the information for each element of the bridge from hand touch distance. This leads to the establishment of a prognosis which defines the Cause of distress. Being a prognosis, it is based on judgement of the inspection engineer and his / her team. Prognosis based on judgement leads to a scenario wherein such prognosis has to be validated and confirmed by independent set of procedures and team. Till date this was done by Non-Destructive tests procedure performed at preselected locations by a bridge testing team which is different from the bridge inspection team.

Option of using SHM provides us with a better alternative to accept the prognosis based on actual observation of the performance of the bridge under live loading. The performance being recorded by short duration SHM for a bridge element which shows the most severe distress. Such short duration SHM performance records collected over a period of time provides us with a time series data about the possible decrements in performance. Correlating this performance decrement with distress increment allows us to establish a logic to define deterioration model.

Cause matrix in UBMS is based on identification of the reason of distress and co-relation with one of the three principal processes namely Mechanical, Physical or Chemical [1, 11]. Typical different cracks patterns are below (Typical and indicative only) [1]

SHM of critical element provides us with time series data for that element showing very severe distress. The Starting severity of distress is known by physical observations. Once the SHM time series data is analysed, we are able to establish the progression of distress in that critical element. Such progression is established by an algorithm which correlates the performance decrement with the distress increment (extent and severity). This correlation is the key to integrate SHM with the analytics in UBMS. SHM enables us to generate a Probability matrix. This is then used to modify the prognosis-based cause matrix. Such modified cause matrix is now performance-based.

Typical probability matrix generated for a bridge is as under

Ratings	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**0**
9	0.29	0.21	0.50	0	0	0	0	0	0	0
8	0	0.21	0.16	0.63	0	0	0	0	0	0
7	0	0	0.16	0.13	0.71	0	0	0	0	0
6	0	0	0	0.13	0.11	0.76	0	0	0	0
5	0	0	0	0	0.11	0.09	0.80	0	0	0
4	0	0	0	0	0	0.09	0.08	0.82	0	0
3	0	0	0	0	0	0	0.08	0.07	0.84	0
2	0	0	0	0	0	0	0	0.07	0.07	0.86
1	0	0	0	0	0	0	0	0	0.07	0.93
0	0	0	0	0	0	0	0	0	0.0	1.00

Increment in distress generates a scenario where in we can modify the Cause matrix generated by the prognosis of the bridge inspection engineer/ team. From acceptance of judgmental prognosis, we have a situation wherein the Cause matrix is modified by actual observation of performance of the bridge and its elements. Integration of SHM within the analytics of UBMS steers us away from person dependant judgement to actual observation and performance based decision-making procedure.

CONCLUSION:

Bridge Management has undergone transformation since the day it was established in early Seventies in USA. 2014 witnessed a fully digitalized IBMS being launched as the new Bridge Management system. Bridge Management starts with the definition of Deterioration model. This model is the first steppingstone to other tools of the management system. The deterioration model is used to defines the risk involved if the remedial intervention is not provided to a particular bridge. This deterioration models evaluate the balance life and its boundaries. This model also helps determine the type of remedial intervention to be designed for that bridge. Finally, the model enables us to provide appropriate information to the ranking and priority process. This makes deterioration model very critical in Bridge Management system. However, it was based on the judgment of a bridge inspection engineer to define the symptom and the process of deterioration. It emphasizes the search for a robust, non-biased approach to defining the deterioration model. Early deterioration model was based on observed symptoms of distress. As knowledge base improved, Modern Bridge Management moved to Cause based system. This shift from symptom-based system to a Cause based system happened due to identification of 3 principal processes that cause distress in concrete. Even the Bridge Management system reliant on Cause definition of distress is based on the same judgment of the bridge inspection engineer. The dependence of the entire decision-making process on the judgement of a single person heavily influenced the need for a process independent of judgment. Performance monitoring of bridges using Structural health monitoring systems provide the much-needed freedom from judgement-oriented procedures.

Various obstacles prevented use of this technology till date. Advent of computer-based algorithms to solve these problems resulted in the solution. Varied algorithms are now available for identification of degree of distress based on SHM raw data. This definition of degree of distress, its extent and severity enabled our using the same to modify the Cause matrix. The fact that decrement in performance implies increments of distress helped to identify the modifications algorithm for Cause matrix. This makes the Deterioration model dynamic, robust and totally non-judgmental. It is a real time model which now defines the decision-making process. It results in cost saving over the entire life span.

Our further research is directed to integration of technologies relating to providing us Geospatial information of distress and capability to establish the 3D model for the critical elements which show sever distress. Much work on this front is nearly complete and soon we shall publish the results of the same.

With this done, our focus now shifts to ensuring that Life Cycle Cost Analysis are incorporated into our Analytics to ensure sustainability of the bridge during its life cycle. Major breakthrough has been established in this front and we shall be able to bring in enhanced cost effectiveness and increased efficiency in reaching a conclusion as to which of the bridge showing distress shall need to be provided with remedial interventions. This decision-making will ensure that all three important aspects (economy, environment and social) of sustainability are enhanced and protected. Importance of timely routine maintenance cannot be more significant.

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