Life cycle analysis of aging structures based on reliability approach

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ABSTRACT: Bridge management plays an important role to ensure the sustainability of bridge infrastructure. Life cycle analysis [LCCA] of such ageing bridge structures has to be based on dynamic, robust, and real-time information. The performance of the ageing bridge structure under live loading needs to be monitored. Performance data will need to be used for triggering interventions. GABM enables deterioration model based on dynamic, real-time monitoring data under live load conditions. Monitoring is periodic and for short time durations. Monitoring results in time series data revealing the possible decrements in the performance of the bridge structure. Decrements in performance are linked to increments in distress occurring in the bridge. Deterioration models based on such evaluated increments in distress results in more realistic prediction about the future behaviour of the bridge. Sustainability yields maximize the Economic, Social, and Environment benefits.

1. INTRODUCTION

Bridges are a significant part of infrastructure development. The performance of in-service bridges is of great concern to asset owners and civil engineers in this era with rapid growth in public awareness of infrastructure safety.[11] The structures start to deteriorate from the time of completion of construction and continue as time passes, prominently due to environmental and physical factors such as corrosion, carbonation, impact, fatigue, etc. According to Irina Stipanovic, structural infrastructure failures are happening because of catastrophic events and these events are a result of climate change. However, only this factor is not responsible for failure.[12] A large number of infrastructures all over the world are over 50 years old and suffer from extensive deterioration that affects their serviceability. The high costs associated with preserving the ageing structures in conjunction with the limited funds allocated for their maintenance pose significant technical and financial challenges, which require systematic approaches for risk-informed condition assessment.

This scenario calls for decision-making to be based on reliable accurate information regarding the progression of distress which is the basis of the deterioration process. Most Bridge Management protocols are dependent upon the judgement of engineers inspecting the bridge [13]. The data collected by the engineering staff will need to be supplemented with factual data related to the performance of bridge elements showing distress. [5] It is an established fact that an increment in distress results in decrement in performance. 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 changes 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. Structural Health Monitoring of distressed bridges elements over short durations will yield the required factual information about the elements. Periodic records of such short term monitoring will result in creating time series of data.[5]

The challenge is to correlate this decrement in performance to increments of distress. The correlation will allow changing the Cause matrix to Performance-based cause matrix. Cause matrix enables formation of Deterioration model which forms the basis for risk estimates and further optimization of fund allocations. 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 solution wherein the Cause matrix is modified by actual observation of performance of the bridge and its elements. Integration of SHM within the analytics of GABM [Global Analytics for Bridge Management] steers the decision-making process away from person dependent judgement to factual observation and performance based decision-making procedure.

Life Cycle Cost Analysis (LCCA) is a useful tool for selecting the most reasonable scheme from an economic standpoint. The challenge is to use the LCCA within Bridge Management. SHM integration helps to get a more realistic view of LCCA. The paper presents a methodology of using LCCA within Bridge Management. LCCA, is used to choose the best economic design for both structural integrity and durability. Comparison of alternative design approaches, strategies, identification of cost-effective improvement, Project's budget, cum economic viability assessment, and long-term financial planning all are possible within LCCA. LCCA is a process of evaluating the total costs over the life of a bridge. Total costs include initial costs and project future costs such as maintenance, repair, rehabilitation, and reconstruction (discounted to today's money value). LCCA and total cost incurred from construction to the end of service life evaluation are the basis for decision-making for project selection among various alternatives. LCCA is also used to evaluate different design features of a bridge for selecting the best option among alternatives.

2. STRUCTURAL HEALTH MONITORING INTEGRATION IN GABM

Structural Health Monitoring [SHM] have been in use for investigating the behaviour of the structures since decades. What initially started with steel structures soon encompassed the concrete structures also. SHM is today possible either by close contact or remotely. Various techniques are available to analyse the data generated by SHM. This analysis makes it possible to identify the performance of the structure. [5, 11]

This performance to be used in Bridge Management needs to be converted to known parameters for which data has been collected over the past many years. SHM historically was never linked to identifying the various causes that lead to the deterioration of structures. Again, past research in this has provided various techniques that make it possible to identify the location, extent, and severity of distress. [5]

The challenge was to correlate this performance or identified distress to the three cause processes of deterioration. Such correlation could make it possible to generate the Cause matrix. The cause matrix is the starting point of any further applications of analytics in Bridge management. The three principal processes identified by EN1504 are the Physical process, the Mechanical process, and the Chemical process.[18] Further, these principal processes are subdivided into 11 sub-processes. The rating assigned to these 11 sub-processes forms the Cause matrix. Three main reasons are identified and listed out for the need to identify the location of the damage is critical to the structural evaluation and the deterioration process. [5,13]

Different modes of failure are location dependant and assume criticality based on their location along the length of the element. The strength of the element as evaluated using the deteriorated cross section affects the load capacity of the member along the length of the element. None of the existing BMS including GABM can provide accurate digitized data relating to the location of the damage or distress. [5, 10, 13] GABM allows for using the cause matrix as the base for the evaluation of the deterioration process.

These shortcomings within BMS are required to be overcome by using all available new innovative technologies. Integration of technologies, which can provide data regarding the correct geospatial location of distress would be the first phase in the refinement. Moreover, the next phase is to be identifying the critically distressed elements and evaluate the performance of such severe distress elements under live loading using Structural health monitoring [SHM] for short durations only. Using this data as base data, we shall need to repeat SHM observations over time to create a time series data that is used to compare with base data collected initially.

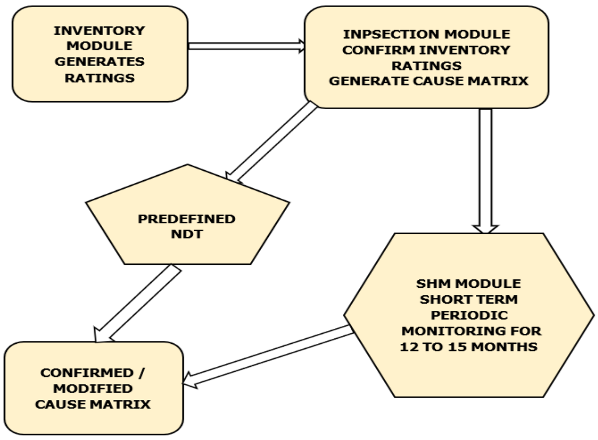

Figure 1. Process of data utilization within GABM

The solution of partial Integration of SHM with GABM provides to utilize the performance to evaluate the deterioration process in bridges or any other infrastructure [5,14]. This solution is able to develop a deterioration model based on performance monitoring. The results should yield sufficient information regarding the present status and types of distress and severity of distress resulting from causes. SHM will provide confirmation of the type of distress, its extent and its severity. Based on this SHM, will confirm the prognosis and resultant cause matrix is updated to be used for all further analytics within GABM

Presently this is done by Non-Destructive testing. SHM will replace NDT. SHM conducted on distressing elements for the periodic short term will yield time series data relating to changes in the performance of the bridge element on which SHM is conducted. This change in performance can assist in the application of modification to the cause matrix. A modified cause matrix will result in more realistic and factual deterioration modelling.

2.1 Application of Deterioration models to LCCA:

Because of the rising interest in predicting the future condition of infrastructure assets. The focus is mainly on the importance of safety, construction materials used and structural functionality. The deterioration model is a link between a structural condition that assesses the extent and severity of damages, and the factors affecting structural deterioration such as age, material properties, environmental conditions, etc. The deterioration model is intended to describe the process and mechanisms by which assets deteriorate and even fail through their service life.

Based on the assigned ratings primary cause of distress can be identified. All other contributory causes are called secondary causes. These observations conclude the inspection process. Moreover, it involves confirmation of the prognosis. To date, this confirmation was done by Non-destructive testing techniques. The confirmed Cause Matrix is used as the first of the important data. The system starts with the help of data collated during the Bridge Information System [BIS] namely Inventory, Inspection and Testing process helps to confirm the prognosis of the Deterioration process.

Small-duration SHM monitoring under live loads will result in the identification of such changes over time. The first such monitoring should be implemented based on identified distress and cause matrix-generated post-Inspection. In GABM, to ensure the optimization of funds, the assignment of available budgetary allocations for rehabilitation intervention is allotted to bridges which qualify for such allocation. Other bridges are stored in the list of Bridges under Observation and Monitoring [BUOM] Bridges in this BUOM are subjected to short-term SHM over 12 to 15 months.

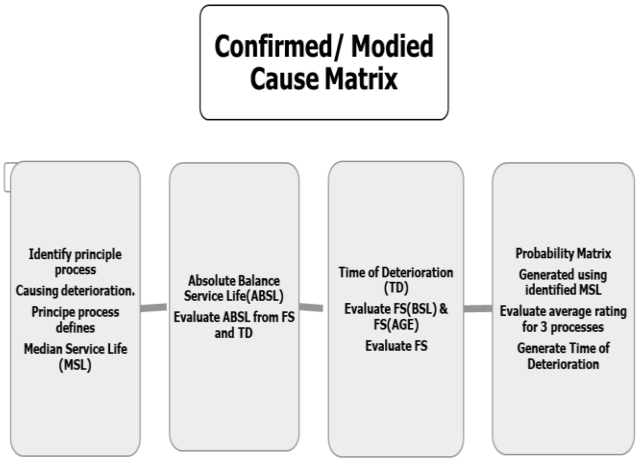

Figure 2: Analytics flow chart Cause matrix to Deterioration model

After this initial monitoring, repetitive short-duration monitoring is applied. The time lapse between two sets of monitoring can be defined by the severity of distress observed in the first set of the Inspection cycle. Such time series data will yield a decrement in performance, which is related to increments in distress zone and severity.

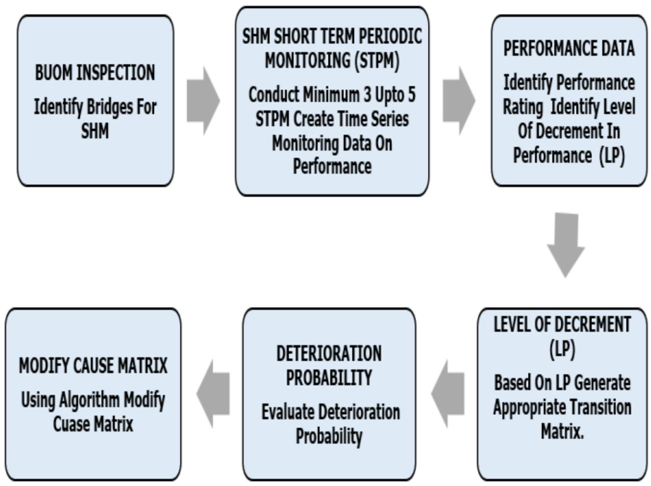

Figure 3: Flow chart of Partial Integration of SHM and GABM

2.2 Two types of SHM to achieve the objective are as follows [5]:

Remote or No contact SHM: System wherein the parameters essential like Vibration, acceleration, frequency, strain, and displacement is captured by technology without being in contact with the bridge or bridge elements.

Close Contact SHM: System wherein major strain, stress, linear displacement, inclination, vibration, frequency, acceleration, and corrosion potential is 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/ elements of bridges.

Both the “No contact” and “Close Contact” systems will yield results that identify typical changes in performance parameters to determine the correlation between the decrease in performance parameters and an increase in distress zone and severity.

Research in the application of computing algorithms to SHM to evaluate the performance of the structure under live loads has resulted in over 15 known and tested techniques to evaluate performance and link it to the extent and severity of distress. SHM-based parameter observes the performance between Initial Scenario and Operational Scenario which shows the "Presence of Distress situation" of structure.

GABM provides a solution for partial integration of SHM with Bridge management analytics. The resultant deterioration model prepared is more realistic and based on factual performance data. Further analytics applications will yield more reliable results.

3. LIFE CYCLE COST ANALYSIS (LCCA) FOR USING RESULTS DERIVED FROM SHM

Structural Health Monitoring (SHM) provides operational performance, early warning data, future prediction, and analysis. It is widely used in many bridge infrastructures, which helps the behaviour of the structure and access the real-time monitoring of the structure using different technologies and sensors. The idea to utilize the results from various SHM elements of the bridge structure will help to better analyse the results that are generated from the LCCA to determine and calculate the economic design from various alternatives prepared to maintain the structural integrity, and restore the durability of the structure.

3.1 Necessity of LCCA for bridges:

LCCA is a cost-centric approach for determining the most cost-effective alternative. The lifespan of various bridge components is determined by their rate of deterioration. The pier and foundation are more vulnerable to deterioration because of environmental or collision impacts. The environmental exposure of steel components influences quickly the steel corrodes. A bridge is a long-term, multi-year investment, and the cost to an agency for a bridge is never a one-time expense. Bridge components require preservation and maintenance actions to counter the effects of deterioration throughout their Service Life. Each design alternative must first show it reliably achieves project requirements such as service life, structural stability, and desired level of maintenance.[1]

Conventional LCCA results in an evaluation of Internal Rate of Return [IRR] which is mostly dependant on direct costs and benefits. Bridge structure connects two area which otherwise are not connected. Such unconnected areas could be residential, commercial or island zones. This connection adds value and intangible benefits to the area which it connects. This results in generation of employment opportunity for population of the residential area. Such increased employment potential results in a general increase of turnover of the organizations operating in the commercial zones. Island zones get better availability of consumer goods at cheaper cost resulting in saving due to the connections that the bridge provides. The Bridge also results in increased emmission of gases and degradation of forest cover due to increase in traffic in the area brought under influence of the bridge. This is intangible cost arising due to bridge in the area. Evaluation of all such intangible or indirect costs and benefits yield the realistic IRR. Such IRR can be termed as the IRR including Intangible impact. Application of LCCA to evaluate both tangible and intangible impact of the bridge on the area is applied within GABM.

Evaluation of the best-suited bridge to be allocated funds for rehabilitation interventions can now be altered based on the Sustainability Index [SI] evaluated from the LCCA which calculated IRR including Intangible impact. Every bridge on the list of BOUM is subjected to LCCA which yields SI for the bridge. Every bridge on the list of BOUM is subjected to LCCA which yields SI for the bridge.

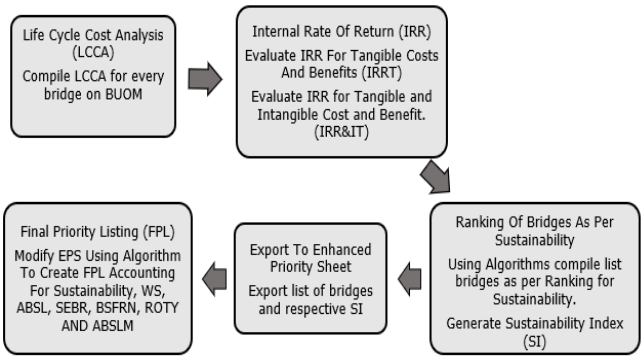

Figure 4: Flow chart of LCCA in GABM

This SI matrix is then exported to Economic Priority sheet [EPS]. Application of algorithm results in Final Priority Listing [FPL] which is accounts for Sustainability, Sum of Critical weightage and Influence weightage, type of road, Absolute Balance service life [ABSL] of the bridge, Structural, Functional and Socio-Economic ratings of the bridge.

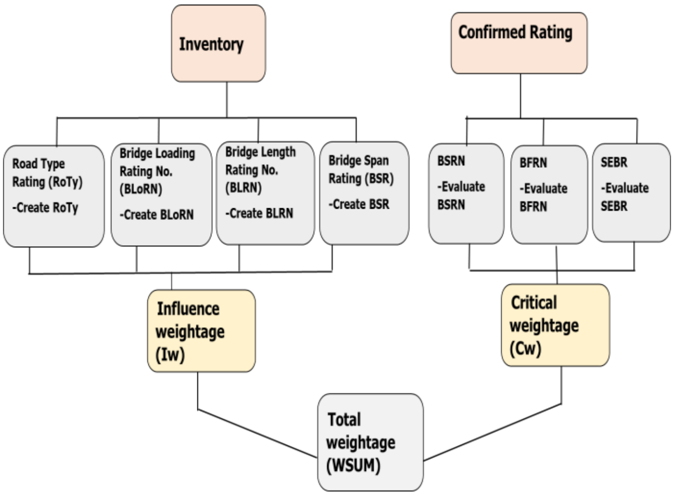

Figure 5: Flow chart of GABM Priority and Ranking

Bridges selected for rehabilitation interventions based on FPL ensure that the optimization of fund allocation not only follows technical and commercial principles of allocation but also ensure that rehabilitated bridges will enhance the Sustainability of the network.

4. RESULTANT SUSTAINABILITY

Sustainability is defined as the preservation of the present environmental, economic and social structure of the society for the present generation and also ensuring that the same is maintained for the future generation [6]. The decision-making within any Bridge Management system should ensure Sustainability [14]. GABM empowers the application of Sustainability within the management of the life cycle of the bridge.

LCCA is a decision-making tool particularly useful from the conceptualization of the bridge to its decommissioning. It ensures to evaluation rate of return for the design of Bridges as it predicts lifetime expenses and supports the inspections management and the maintenance activities. Bridges or any other infrastructure should be seen as a key part of the economic activity and well-being of a given community [15].

Currently, the use of sustainable materials in the construction of bridges is increasing ensuring a positive impact on the environment, economic and social parameters [16] LCCA which ensure this can be applied as a tool for calculating and comparing the life cycle cost of a projects [17].

While a structure is designed from economic, technical and safety perspectives, the environmental performance was often not considered in the decision-making process. GABM enables maintenance, strengthening, repair, and rehabilitation of bridges if interventions are applied timely. This ensures maximizing the life span of bridges without the need for replacement. Such interventions ensure to reduce the cost of the life cycle and reduce the impact on the environment by reducing the usage of raw materials. These interventions enhance the environmental and economic management in the entire life cycle by maximizing the benefits for the given costs. The timely provision of interventions ensures economic benefits by managing the cost-effectiveness in the design of such interventions, by ensuring to reduce the detour travel time, congestions, and traffic jams delay resulting in avoidance of productivity loss and its impact on the reduction of GDP of the area of influence of the bridge. Such intervention also ensures to enhance a social benefit by reduction or avoidance of failure/ collapse and increased reliability of network which impacts the safety during travel, life loss, timely delivery of goods and raw materials which are crucial to maintaining the productivity which ensures stable GDP. Environmental goals of minimizing the carbon emissions are ensured by avoidance of traffic jams, and longer journey time due to detours in case of closure of the bridge for a longer period when collapse occurs.

Sustainability ensures to delivery of the optimal level of service safely to existing and future bridge users in the most cost-effective way. LCCA enables us to prioritize investments on the assets that need it most. This optimization is ensured by a risk-based analysis to identify cost-effective investments during conceptualization, designing, construction, and during the entire operational life of the bridge.

5 CONCLUSIONS

Several infrastructure networks are currently facing issues, such as increasing annual maintenance costs, ageing infrastructure, as well as climate change impacts. The main purpose of the reliability-based life cycle analysis of the ageing structures model presented is to satisfy the required performance. This needs to also consider and ensure the economic, social, and environmental impacts of different maintenance and safety strategies.

Management needs reliable data, which is collated during Inventory and Inspection process. In the inspection process, the inspectors record certain information regarding distress structure and based on observations, the inspector comes to conclusion. The accuracy of the result depends on the experience and judgement of the engineer. Most of the infrastructure management systems rely on this judgement. Mostly majority of the networks are faced with ageing problems. Bridge structures constructed before or during the last five decades face aging scenario. This necessitates the need to have realistic management systems. Within GABM the functionalities of deterioration modelling, risk analysis and fund allocation were till date based on theoretical evaluation and observation of increments of distress in the bridge. GABM system has evolved over time to provide solutions to users. GABM management procedures include the impact of Sustainability of infrastructure, Life Cycle Cost Analysis (LCCA), and Structural Health Monitoring (SHM). The main forte of the approach is to identify the cause of distress structure and then apply short duration real-time monitoring to determine the changes in behaviour of the ageing bridge under live loads. This helps engineers to record performance and the changes. Application of developed algorithms corelates current deterioration of the structures to the decision-making process. This approach enhances the observation and judgement based conclusions of engineers to realistic performance based approach.

The Bridge Management Analytics include the use of accurate and realistic data for the generation of deterioration models, the inclusion of socio-economic parameters to assess the benefits [direct and indirect] that accrue to the area of influence under the bridge. Finally, LCCA tool is utilized to assess the life cycle costs impacts that are used in the decision-making during the entire life cycle. Data from various several Socio-Economic parameters collated under GABM protocol enables to ensure that the evaluation of intangible advantages or costs that result from a bridge structure are applied to access the economic impact. Using enhanced LCCA technique, ensures the decision-making process is based on realistic approach. Through this approach, sustainability goals are also guaranteed, ensuring that a structure fulfils present requirements without endangering the ability of future generations to satisfy their own. A sustainable course of action should preserve the harmony of the three key factors of social, economic, and environmental issues. Sustainable bridges support the environmental, social, and economic systems that we depend on. Life cycle analysis of ageing structures based on reliability approach ensures Sustainability and Economic growth.

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