Shifting qualitative approach in condition monitoring of bridge assets toward a quantitative approach

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Abstract

Many existing transportation infrastructure assets such as bridges, overpasses, underpasses, causeways and culverts in developed metropolises are aging and health monitoring data is now becoming a critical aspect when it comes to evidence based maintenance budgeting. Such infrastructure assets are owned and managed through different authorities representing local, regional, state and national levels of governance. Even in the current practice, especially at local and regional level, condition monitoring is predominantly qualitative and as such labour intensive and assessment is subjective. This raises some questions with regard to the decision making processes in budgetary allocations. This paper presents an insight to the current process of qualitative condition monitoring, based on Australian practices, and the quantitative approach covers through a literature review. Advanced methods of real time condition monitoring using remote sensing are also discussed although such modern techniques are currently being limited to large, recently constructed bridges which are relatively young bridges.

Keywords: Structural Health Monitoring, Bridge Assets, Condition monitoring of Bridges

1. Introduction

1.1 Condition monitoring of Road Structures

Condition monitoring of road infrastructures can be broadly categorised in to two sections. Namely, the condition monitoring of pavements and the condition monitoring of road structures such as bridge, culverts, underpasses, overpasses, causeways. This paper focuses on the road structures category. Majority of these road structures are aging continuously. In developed metropolitans evidence based decision making in maintenance budgeting is becoming a critical issue due to lack of quality condition data. Continuous usage of road structures in combination with increasing frequency of use and the magnitude of the imposed loading conditions as well as changes within the surrounding environment influence both visible and hidden degradation of a road structure during its life span. To maintain the integrity of these structures, a number of structural health monitoring (SHM) systems are currently being used with varying degree of sophistication by the road authorities.

Catbas et al. (2008) defines the structural health monitoring (SHM) as tracking the responses of a structure along with inputs, if possible, over a sufficiently long duration to determine anomalies, to detect deterioration and to identify damage for decision making. Therefore, all monitoring techniques and methods need to be regularly investigated, maintained and upgraded, due to everyday advancement in technology. This in combination with the higher expectations of the road users as well as the changing perception of public liability matters, pause a significant challenge to the road asset owners at present. After performing a thorough literature review on the subject, it can be concluded that quantitative SHM is in its infancy in road infrastructures, both, in developed and developing nations.

It is reasonable to note that the more structured and unified approach in handling this challenge is only beginning to realise. For instance in the state of Victoria, in Australia, the road structures inspection manual was published as recently as mid 2011, unifying the practice and providing a more structured pathway for the state's road asset owners. This paper objectively discusses the structure of the manual as well as some key out comes of the road structures inspection manual in Victoria. Paper also discusses, briefly, the widely adopted technologies involving in the quantitative condition monitoring of bridge assets including real time condition monitoring using remote sensing techniques

1.2 Current Practices

The current practice of Structural Health Monitoring of bridges, in general, can be discussed in three categories. Collation of qualitative generic data of bridge components gathered through on-site visual inspections which are conducted in a regular periodic manner. An inventory of such collected data of bridge assets is maintained by the asset owner. The second category is by obtaining condition data through detail engineering investigations involving none destructive on-site testing, theoretical structural evaluations and development of computer simulated behavioural models. Obviously this category seeks quantitative data which are more targeted and specific for a given situation and a bridge component. The other category of condition monitoring is more novel and relatively limited in practice which involves real-time condition data acquisition by remote sensing. Such advanced techniques are limited and can be justifiable only for major arterial bridges and quite often the instrumentation is incorporated into the bridge structure during design and construction phase. High maintenance cost of instrumentation, post processing and care taking of large volume of digital data, interpretation and incorporation of acquired condition data to support decision making processes are in development stage and, as mentioned, limited in general practice. Qualitative analysis, examination of a structure by just suspecting and looking, has been the conventional method of condition monitoring especially in bridge assets under local governance. This appears to be the initial trouble shooting phase through which most maintenance decisions are earmarked for quantitative assessment leading to a detail engineering investigation and diagnosis prior to intervention.

Real time condition monitoring through remote sensing assists decisions based on real time evidence, which are gathered by using variety of sensors and data acquisition systems. A number of quantitative data analysis techniques have been introduced recently but still they are not able to meet all the objectives. However, in relative terms, these techniques, instrumentation and software tend to become obsolete much faster than the aging of the road structure as time progresses and quite often involve extensive training personnel to keep-up with the scientific advancements. A brief introduction on available techniques and limitations has been provided in section 1.4.

1.3 Procedures of Condition Monitoring of Road Structures in Victoria, Australia

According to Wu (2003) the widely used inspection method to assess the structural condition of bridges is visual inspection on a regular basis and also as per VicRoads, one of the national road authorities in Australia, visual inspection is generally carried out at regular intervals of time to check the general serviceability of the structure, particularly for the safety of road users and to identify any emerging problems. It is mostly conducted with an objective of collecting all condition data to a component level required for the managements of road authorities (City of Casey, 2011).

Procedure of condition monitoring is quite straightforward and has been illustrated below, in accordance with City of Casey & Vic Roads (2011), regional level road authorities in state of Victoria, Australia.

Condition monitoring is generally carried out on three levels of inspection:

Qualitative

Level 1: Routine Maintenance Inspection

- A brief inspection of all structure components to assess any significant visible signs of damage, distress or unusual behaviour.
- Carried out on a twice yearly frequency with a maximum interval of 6 months.

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Level 2: Road Structure Condition Inspection

- Identifying current maintenance needs and assessing the effectiveness of past maintenance treatments.
- Forecasting future changes in condition and budget requirements.
- The structure condition inspection is to be a visual inspection.
- Carried out on a 2 to 5 year frequency, depending upon the condition of components.

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Quantitative

Level 3: Detailed Engineering Inspections and Analysis

- Detailed structural investigation of a structure.
- Provide improved knowledge of the condition, load carrying capacity, in-service performance and other characteristics which cannot be obtained from visual only, Level 1 and 2 inspections.
- Mostly initiated, when structures are initially reported in poor condition in a Level 2 Inspection and structures are showing evidence of accelerated deterioration.

Inspections are mainly conducted by a third party contractor and all inspectors must be personnel who have extensive practical experience in the inspection, construction, design, maintenance or repair of road structures. All road inspectors must be accredited by VicRoads. They shall have extensive practical experience, and be competent to judge the condition of structures and the importance of visual defects. Level 1 and 2 inspectors are need not be qualified professional bridge engineers, but, level 3 investigations shall be undertaken by appropriately experienced engineers.

At the site, the inspection shall proceed in a systematic manner, starting from the bottom and working through to the top of the structures. The inspector shall inspect and assess the condition of each structure component using the standard condition rating criteria (given below), assess the general condition of the structure and record the results of the assessment on the condition rating sheet (refer to Vic Road Bridge Inspection Manual).

- **Condition state 1:-** Component is in good condition with little or no deterioration.

- **Condition state 2:-** Components show deterioration of a minor nature with primary supporting material which is first signs of being affected. Intervention points for maintenance are generally as follows: Minor spalls or cracking of real concern.

- **Condition state 3:-** Components show advancing deterioration and loss of protection to the supporting material which is showing deterioration and minor loss of section. Intervention points for maintenance are generally as follows: large spalls, medium cracking and defects should be programmed for repair works.

- **Condition state 4:-** Component shows advanced deterioration, loss of effective section to the primary supporting material, is acting differently to design or is showing signs of overstress.

Level 1 and 2 inspections involve examination of every accessible parts of the bridges and culverts, above ground and water level, (for further details may refer to Vic roads bridge inspection manual). Accessible parts include decking, stringers, abutments, piers, crossheads and handrails. Whereas, level 3 investigation incorporates the inspection of such areas of the structures that are beyond the scope of level 1 and 2 inspections, including, investigations requiring specialised access equipment and/or personnel such as cherry pickers, scaffolding, barges, diving gear, or similar and for investigations on railway property, within confined spaces, requiring protective clothing or similar, underwater inspection of piles and other components.

In addition, Level 3 investigations aim to quantify the visual observations from obtaining other data which is not visually evident. These investigations generally include on-site non-destructive testing and sampling of materials for laboratory testing. Non-destructive testing involves dye penetration testing of steel members to identify the size and extent of the fatigue cracks, cover meter measurement of reinforcement cover and sizes to determine approximate loss of section and compare depth of reinforcement against depth of chloride ingress and carbonation. Examples of sampling testing for condition data assessment include concrete cores to obtain concrete strength, depth of carbonation and chloride ingress profiles.

All information obtained from the site inspections shall be recorded on the corresponding level inspection data sheets (refer to Vic Roads Inspection Manual). For example, data sheet for level 2 inspections include, structure inventory and photographic record sheet, condition rating sheet, structure defect sheet, structure information sheet and also information describing the structure, such as, its location, region, road name, road number, general location description for roadside structures, structure identification number and much more.

1.4 Techniques of real time condition monitoring

As mentioned before, real time condition monitoring through remote sensing, appears the most advanced quantitative approach. However such technology can not be afforded by most road asset owners. In order to increase the service life of a road structure, the early detection of the signals emitting from structural decay, not conceivable to the human eye, are paramount. Especially, decaying of structural materials and elements is a Markov process. Markov process is one that the future condition depends on the present condition but not the past or original condition. As such, the availability of real time condition data, especially not accountable to visual inspection, can be of menace value in prolonging quality of road structures. The type of information may include localised decay which adversely impacts the stress and strain distribution within the components which triggers a Markov chain. A brief description of such latest advancements in technology and measuring devises currently in operation is provided below.

To maintain and inhibit deterioration, optical fibres have extensively been used in the developing quantitative health monitoring methods. Brillouin Optical Time Domain Deflectometry (BOTDR) is one of the sensing techniques which are used to measure strain and crack monitoring of reinforced structures. BOTDR is based on the propagation of a train of incident pulses and Brillouin scattering that occurs when ever light is transmitted through an optical fibre (Wu, 2003). It can determine strain distribution of a full structure constantly. An experiential investigation has been conducted by Wu (2003) which shows the relationship of detected strain with optic fibre sensors and gauge lengths of optic fibres, in which the BOTDR with 1 m spatial resolution is used. Specimens were collected from plain/reinforced concrete beams and columns bonded with optic fibres, as shown in Figure 1, the outline of the RC beam model. Several kinds of installation methods, one round loop, one round superposition loop, and two round superposition loops were proposed and shown in Figure 1 (Wu, 2003). Later the results were measured by the displacement transducer. BOTDR has been applied for strain distribution measurement and crack and bond/deboning monitoring for a 17m PC girder strengthened by prestressed PBO sheets (Wu, 2003).

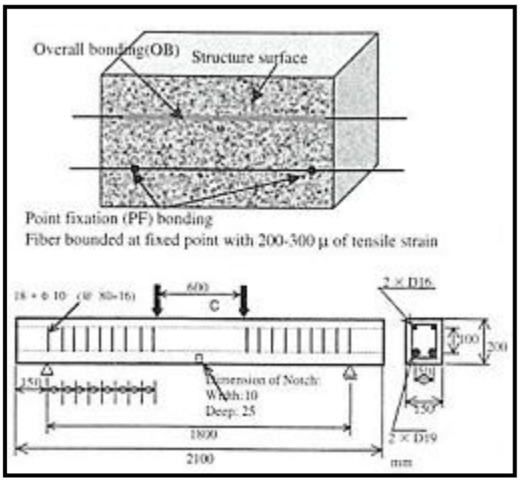

Figure 1: Bonding Methods of optic fiber and RC beam model (Wu, 2003)

Acoustic Emission (AE) is another new technique which is attracting attention of engineers and researchers all over the world. It is mostly used to determine the source location of damage and source identification. Acoustic emission is a non destructive testing technique. AE waves are elastic stress waves that arise from the rapid release of energy from localized sources within a material (Kaphle et al., 2009). AE techniques involve recording these stress waves by means of sensors placed on the surface and analysing the signals to extract information about the nature of the source (Kaphle et al., 2009). Growth of cracks, impacts, failures of bonds, impacts, fibre failure, sudden joint failure and traffic noises are few common sources of AE signals. Mostly, piezoelectric type sensors are used to convert mechanical vibrations into electric signals. AE is considered well suited technique to determine the damage location in bridges as it is capable of regular in-situ monitoring and able to identify extensive range of damage mechanisms in real time (Kaphle et al., 2009).

Electrical time-domain reflectometry (ETDR) is a remote sensing based technology based on the propagation of electromagnetic waves in a electrical cable or transmission line, which functions both as a signal carrier and a sensor (Belarbi et al., 2003). This technology is designed to detect the location and magnitude of the cracks. A sampling instrument is used to unleash a series of low-amplitude and fast-rising step pulses onto the transmission line and sequentially samples the reflected signal when a pulse encounters an electrical property change along the cable (Belarbi et al., 2003). Reflected signal contains arrival time, distance between the points of monitoring and change in electrical property. The amplitude of the reflected signal is directly related to how much the cross sectional area or the structure of the outer conductor of a cable has been disturbed (Belarbi et al., 2003). In this way, ETDR embedded in concrete can identify both the location and magnitude of a crack.

Every novel invention related to quantitative health monitoring was stated vital, rational and most relevant by the corresponding writers. In addition, Dyke and Koh (2007), suggested among the variety of damage detection methods, modal based techniques have the most widely investigated due to the global nature and simplicity.

2. Limitations of current condition monitoring practices

2.1 Reliability of Visual Inspection Processes

It has been identified that visual inspection is the most widely used inspection technique to access the structural condition of bridges and which conducted periodically. The scope and frequency of inspection vary with the type and condition of the structures. Inspection types have been categorised in *NBIS (National Bridge Inspection Standards, US Department of Transportation)* as regular, interim, special, in-depth, essential completion, construction supervision / quality control, maintenance, underwater (diving) inspections and extreme event / emergency. The numerous inspection types listed above seek to match several causes and forms of the bridge distress. As such the frequency of inspection determines the reliability of the condition data and, more importantly, the reliability of decisions made on such data.

As visual inspections take place at regular intervals with a specific scope and objective, they are designed to meet the structural integrity standards and maintenance decision making. However, increase in traffic demand than forecasted, which impact on loading magnitude and recurrence interval, during to then life span of the road structure is quite difficult to mange and capture through visual inspections. This is because the material degradation related surface cracks alone do not express the full extent of structural integrity. Even though non destructive investigations can identify most of the localised decay, such as corrosion, deboning and stiffness degradations using specialized instrumentation the outcomes are somewhat limited in predicting when is the right time to intervene. Periodic visual inspection strategies seem uneconomical when a bridge is young and in good condition and could miss the damage occurrence between two inspections (Wu, 2003). For example, inspection of bolted and welded connections of a bridge calls for knowledge of their construction specifications but inspector does not necessarily have the access to such information. Speed of inspection, imposed on the inspectors, through contract managers can have negative impacts where meeting the target means drop in quality of reporting. There is precedence where either inspection quality was inadequate or intervention decision making was too late which leads to catastrophic failures of road infrastructure. Cohen and Stambaugh, (2007) indicated that in 2007 the I-35 W Bridge spans the Mississippi River in Minneapolis, Minnesota, collapsed and killed 13 people under similar circumstances.

Visual inspection outcomes are, obviously, qualitative and subjective. Most of the bridge asset owners make decisions based on the submitted reports where the condition of each inspected element is stated in words, such as, for a damage “minor”, “serious”, or “advanced”, for condition “good” or “bad” and for recommendations, “repair required” and “need further inspection”. Sometimes, an inspector does not have clear access to get underneath the bridge or site due to high water level, extra weed grown underneath or around the bridge deck; valley is too deep, unavailability of appropriate machinery, such as, long boom cranes or bucket truck. As a result, inspector makes comments by just looking at the structural element, far from the actual position and occasionally without even been able to look at the structural element. Continuous rotation of inspectors at inspection sites also brings dissimilar condition ratings.

However, based on above mentioned vague parameters, this method has been found unreliable, time consuming and sometimes costly to use in critical damage detection and intervention decisions.

2.2 Limitations of Real Time Sensing Techniques

It is believed that most of the structural health monitoring techniques and methods has been borrowed from aerospace and mechanical engineering. The majority of these methodologies have been refined to meet the challenges offered by civil structures. Even after the refinement in technology and quantitative health monitoring methods, system maintenance, data acquisition and recognition of spurious noise in data acquired are major troubles which are still faced by the concerned road authorities. A lot depend on the post processing of data and ability to filter spurious noise to retain quality data.

As new strategies are emerging each day, the application of wireless sensors for bridge monitoring is still considered in technology stage. So the question arises, can this wireless sensors technique be applied such as optical fibre sensors and will it be able to provide necessary information and how much would it cost to maintain such instrumentation over a longer period of time in prime condition?

According to Wu (2003) in system identification the robustness as well as the convergence and stability must be considered. It is necessary to develop methods, which are highly tolerant of incompleteness of measured data, measurement noise, modelling error and structural uncertainty and are applicable for large-scale bridge structures for vibration-based damage identification.

3. Research areas of significance

Based on literature and the current body of knowledge three areas have been identified needing attention. It is envisaged that any individual or research team involved in condition monitoring requires to see the condition monitoring of road structures as an integrated decision making process by which the data acquisition, post processing and decision making evolve together and that a feed back loop to ensure that the desired outcome being reached. This requires close collaboration between the asset owners, researchers and field practitioners.

One key area of interest would be to develop predictive time series functions, for structural materials widely used in road structures, to predict material decay of structural materials over a long period of exposure to environmental and imposed conditions of loading. Such functions also need to have some statistical backing to ensure reliability of the prediction which can then be used in informed decision making processes.

Such time series functions should then strengthen the hand of analytical and simulation tools which can simulate and predict the overall behaviour of a structural component or the entire structure leading to damage modelling and the evaluation of residual capacity of the structural components as a time series function. Such would enable the practitioners to assemble complete picture of the behaviour at various stages of the life cycle.

Finally it requires support informed decision making process where by maintenance budgeting become factual rather than political or speculative.

Probabilistic approach should underpin the technical data and decision making. It was reported that probabilistic approach allows optimum maintenance strategies and will help in designing more crucial repair and retrofit applications (Catbas et al., 2008). Finally, decision makers should be able to quantify the risk they take and the consequences through a probabilistic and statistical approach.

4. Discussion

- The current practice of Structural Health Monitoring of bridges, in general, can be discussed in three categories. Collation of qualitative generic data of bridge components, obtaining condition data through detail engineering investigations involving none destructive on-site testing and real-time condition data acquisition by remote sensing. A brief description of such latest advancements in technology and measuring devises currently in operation has also been discussed.

- In order to increase the service life of a road structure, the early detection of the signals emitting from structural decay, not conceivable to the human eye, are paramount. Especially, decaying of structural materials and elements is a Markov process.

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- Decision makers should be able to quantify the risk they take and the consequences through a probabilistic and statistical approach.

- Agreeing an unified procedure for condition monitoring, both qualitative and quantitative, among different stake holders is fundamental in maintaining healthy road assets.

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