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Evaluation of distress mechanisms in bridges exposed to aggressive environments

Srikanth Venkatesan[1], Sujeeva Setunge[1], Tom Molyneaux[1] and John Fenwick[2]

[1] RMIT University, Melbourne, Australia, [2] Queensland Department of Main Roads, Brisbane, Australia

Bridges form one of the most important infrastructure facilities in many well developed nations. Most of these structures experience significant deterioration well before their expected useful life. The costs of maintenance and/or repairs associated with these structures require substantial commitment from annual budgets. Although the durability issues of concrete under normal environment conditions are well recognized, aggressive environments such as marine conditions and aggressive soil conditions can accelerate the deterioration process leading to early loss of serviceability and reduction in strength. Most of the life cycle models have focused on mechanisms responsible for steel reinforcement corrosion. However, structures confronted with aggressive environments evidence characteristic symptoms that are driven by other deterioration mechanisms. A simple easy-to-use guide in identifying the distress patterns and the responsible mechanisms is generally lacking.

In this paper, symptoms of bridge deterioration have been investigated to identify underlying distress mechanisms. Extensive investigation of the deterioration data on bridges in Australia has been undertaken in this connection. Systematic categorisation of the data in developing a rule based matrix that can clearly identify the causative distress mechanism has been proposed in this study. Significance of this approach in estimating the residual capacity of these structures has been highlighted.

Key words: Bridges, Distress mechanisms, Degradation process, Life cycle models, Residual life

1. INTRODUCTION

There are about 2500 bridges in Queensland, Australia. Majority of these structures require significant repairs around the halfway mark of their design life with probably 1% or less reaching a 100 year design life. (Carse, 2005). This is due to the fact that bridges constructed in aggressive environments such as the coastal regions experience accelerated deterioration. As a result, maintaining the service delivery of these assets has become one of the important issues for the Queensland Department of Main Roads (QDMR).

The option of knocking down a bridge and re-building seems to have practical implications. In many cases, approaches to the new bridges cannot be constructed. Furthermore, re-routing the traffic or closing down a service bridge might involve public dissatisfaction and political implications. QDMR has established some formal procedures for inspecting bridges, reporting and subsequent tasks (Bridge Inspection Manual, 2000, QDMR). Recently, electronic documentation of bridge inspections has also been undertaken. However, it is important to note, that the repair and / or rehabilitation strategies are dependent upon the assessment of the remaining useful service life.

The remaining useful service life of bridges is dependent upon the evaluation of the existing conditions. For this purpose an understanding of the possible mechanisms influencing bridge deterioration is essential. Carse, 2005, has listed the following mechanisms that are relevant in the present context:

- Carbonation induced corrosion distress
- External chloride ion attack of 20 to 32 MPa Grade concretes
- Aggressive ground conditions such as
    - Acid sulphate attack generated in coastal areas below 10 m Australian Height Datum (AHD) level
    - Sodic (dispersive) soils – sodium rich soils
- Alkali-Silica reaction (ASR) degradation in 40 to 50 MPa concrete due to reactive aggregates which then creates vulnerability in aggressive environments
- Fire damage due to bush fires and petrochemical fires
- Abrasion damage due to sand loads in rivers
- Impact loads due to vehicles or barges / ships

The above mechanisms induce defects such as cracking, spalling, honey combing of concrete, loss of cement paste, loss of reinforcement and many other such defects. The relationship between these symptoms and their causative mechanisms is required in evaluating the existing condition and estimating residual service life. For example, cracks may appear as a result of shrinkage in concrete or carbonation induced corrosion or due to structural defects. Unless the real mechanism is identified, a suitable repair strategy cannot be recommended. Even if repairs are undertaken without identifying the causative mechanism, it is only a matter of time before failure. Organisations like QDMR have substantial experience in maintaining and managing huge bridge stock. Capturing and documenting this expertise is beneficial to the Australian industry.

This paper describes the preliminary research undertaken leading to the evaluation of residual service life of bridges based on understanding the distress mechanisms and symptoms. Proposed methodology of research has been presented in Section 2. Section 3 presents some descriptions of case study bridges in Queensland. Section 4 presents an approach towards the development of a rule based matrix of relating distress mechanisms and causes. Section 5 presents conclusions and further research work to be undertaken.

2. RESEARCH METHODOLOGY

Proposed research methodology is shown in Figure 1. The frame work was developed by Nezamian, et.al (2005) focusing on four major tasks: Case studies of bridges exposed to aggressive environments, Relating the distress mechanisms and causes, evaluation of residual service life capacity, life cycle cost analysis for different proposed options.

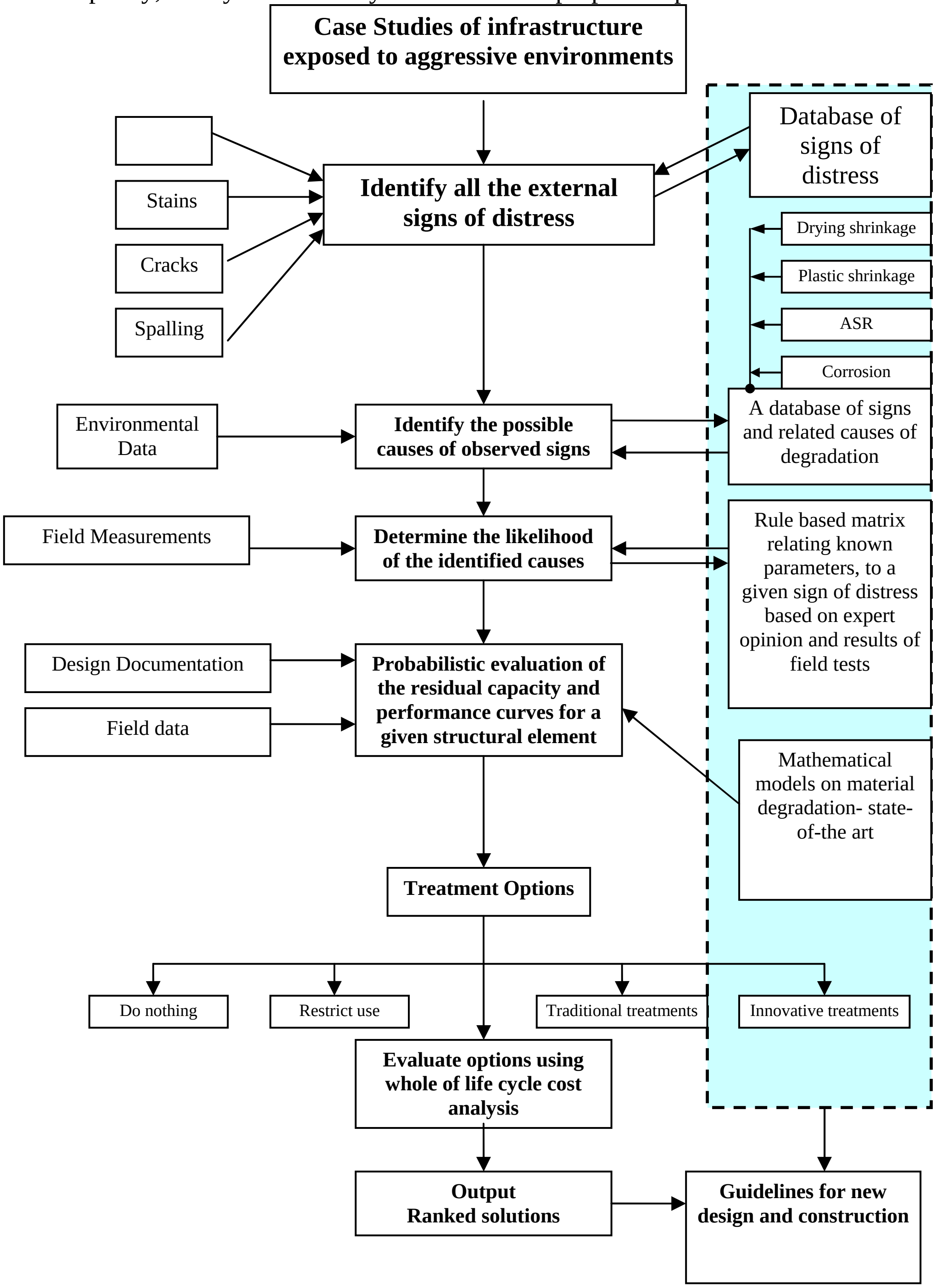

Figure 1. Proposed research methodology

The foremost task in the above methodology is in developing a rule-based matrix that can relate a given sign of distress to the most likely cause. Initially, a literature review was undertaken to establish the current body of knowledge. Some of the works by Bungey and Millard (1996), Dhir, (1993), Chan (1996), De Brito (1993), Gannon and Cady (1992), Teng, T.P., (2004) were reviewed and compiled into a research report (Venkatesan, *et.al.*, 2005). Published work mainly addresses research into specific mechanisms causing deterioration. They do not provide diagnostic information needed to identify a certain sign of distress to a related cause. In the second stage the research team examined case studies available through QDMR to identify common signs of distress and associated complexities in diagnosing the related cause. Two such case studies are reported in detail in the subsequent section. These information have been extracted from QDMR records.

3. DESCRIPTION OF CASE STUDY BRIDGES

3.1 Dawson River Bridge

Dawson River bridge is on the Dawson Highway enroute to Rolleston in Queensland, Australia. This particular bridge is a six span prestressed concrete (PSC) superstructure with a reinforced concrete substructure that was built in 1892. The first two spans comprise of 14 PSC deck units which are approximately 11 meters in length. The remaining 4 spans consist of 5 x 1.2 m deep PSC girders approximately 26 m in length. The end piers consist of a headstock on 550 mm octagonal PSC piles arrangement which directly support the superstructure. The mid piers are located in the deep water section and consist of blade piers each supported by 12 composite 550 mm octagonal piles. The design strength of concrete elements such as the Piers, Girders and Piles range from 25 MPa to 45 MPa, whilst the concrete cover to reinforcement ranges from 25 mm to 50 mm. Photo 1 presents a general view of the Dawson River Bridge.

Photo 1. General view of Dawson River Bridge, Queensland

The above bridge experienced significant deterioration leading to visual inspections by an expert and subsequent petrographic examinations of concrete cores in the year 2000. During the visual inspection, vertically propagating cracks were observed in the PSC piles. It was also noted that the spiral ligature intercepted by the coring bit did not appear to have undergone significant level of corrosion activity. The cores exhibited surface cracks that tapered back to zero in roughly perpendicular orientation to the surface and the cracks mostly propagated around the pieces of aggregate. At the broken of ends of the cores the presence of a significant amount of white reaction product (similar to the formation of air bubbles) was noted. This was particularly obvious at the aggregate / cement interface (Refer to Photo 2). Based on the above inspections, it was concluded that the major cause of distress in this case would be alkali-silica reactivity. As there were no signs of corrosion activity of the spiral ligatures, and due to the site location being considerably inland, it was interpreted that chloride ingress would not have played a significant role and consequently chloride ingress tests were not recommended. It has to be noted in here, that the white reaction product had appeared to be consistent with the symptoms of ASR, however petrographic examinations proved otherwise.

Photo 2. Concrete core sample from Dawson River Bridge (note the ettringite formations)

The petrographic examination of the sample core that has been presented in Photo 2 revealed that the coarse aggregates consisted of crushed, unweathered labile siltstone and related subordinate labile sandstone along with minor acid porphyry and micro diorite /andesite. The materials were closely representative of the materials from nearby quarries. The minor acid porphyry and micro diorite /andesite were observed to carry free silica, but on petrographic examination were predicted to be innocuous in relation to ASR. Further the petrographic examination observed "*Curiously, air bubbles are lined by an acicular, brightly birefringent mineral which appear to be of ettringite formations*". Without the petrographic examination, ettringite formations would have been considered to be the result of ASR. It was then concluded that the distress had been caused by tow mechanisms: ASR and delayed ettringite formation. In one of the studies reported by Nezamian, et.al., (2004), distress due to ASR resulted in the onset of corrosion. Therefore, correct diagnosis is imperative in developing preventative guidelines for new structures.

3.2 Nerang River Bridge

Photo 3 presents a general view of the Nerang bridge in Sundale, Queensland. This is a multi-span long PSC bridge. This bridge was built in 1960's and major inspections to quantify the distress were undertaken in the year 1998. The investigations showed that the concrete in the tidal zone had very high levels of chloride contamination from the sea water environment which had led to corrosion of the reinforcing steel and cracking of the concrete. Photo 4 presents the core samples taken from the tidal zone. Clearly the severity of cracking is apparent from the samples. Further to these tests, diving inspections were undertaken to determine the extent of cracking. The cracks in the central piers appeared to be the greatest around the tidal zone and reducing with the depth of concrete.

Photo 3. General view of Nerang River Bridge, Sundale, Queensland

During visual inspections extensive cracking, spalling and drummy areas of concrete were observed. Carbonation was considered to have less influence with chloride contents being identified to be far in excess of that required to instigate corrosion levels. However, chloride levels measured in girders and diaphragms were lower than that required to commence corrosion. Clear documentation of the width of cracks, location, and extent are available from the reports. Based on the extensive investigations, Impressed Current Cathodic Protection (ICCP) of reinforcements was recommended to ensure long term performance. Without the above repair option it was believed that the structure would survive only 5 or 10 years. It has to be noted that this estimation of residual service life is an assessment based on experience. The first author visited this bridge recently, to assess the performance of the repair work. No major cracks or other form of distress could be noted.

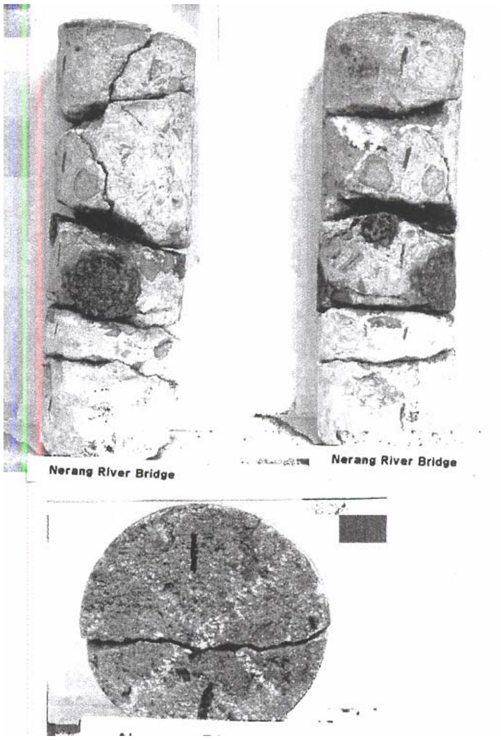

Photo 4. Concrete core sample from Nerang River Bridge (note the severity of cracking)

4. TOWARDS DEVELOPING A RULE-BASED MATRIX

Above case histories assisted the authors in mapping out the format of the diagnostic tool being developed. For example, chloride ingress is less significant for inland bridges and carbonation is less significant for bridge elements close to the tidal zone. This is because; the chloride ingress is caused by the splashing tides or air-borne chlorides with substantial influence of salts whilst carbonation is influenced by the presence of moisture. These information may be well known to experts in the field but are not genuinely known amongst practicing engineers. Specific to the aforementioned discussions, a probable framework for developing a rule-based matrix (based on logical questions) has been presented in Figure 2. The authors wish to compile similar information for the wide variety of case study bridges into a diagnostic tool to evaluate the residual service life of a given bridge structure and to recommend suitable remedial options based on life cycle cost. The important contribution of this research will be in identifying or segregating the synergic effect of the causative mechanisms. Classic example of this case is the Dawson River Bridge in which ettringite mechanism was observed but was not considered as the dominant cause.

QDMR has addressed the ASR problem by incorporating fly ash into all the structures built after 1989. Similar preventative measures can be advised during the design stage, through the research program being undertaken.

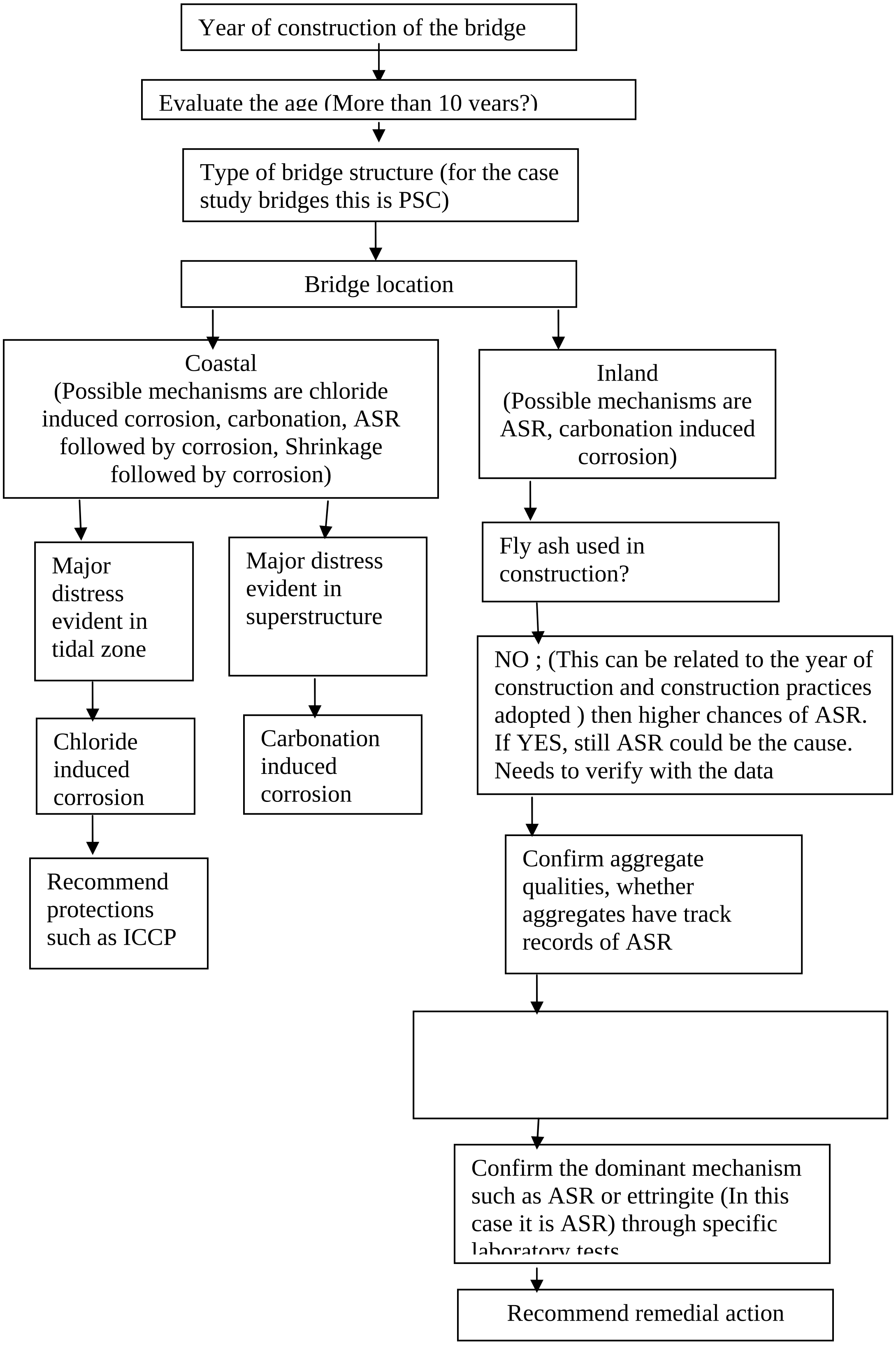

Figure 2. Typical format for diagnostic tool

The significant advantage of the above framework is the clear segregation of the expected mechanisms with respect to the location of the bridge. The authors have gone through the reports and have studied the possibility of including distress patterns and signs. At this point in time, considerable clarity could not be established in distress patterns because of the limited number of case studies considered. Authors are investigating bridges other than PSC, culverts and other structures. This will facilitate compiling of the missing information required to present a wholistic picture of understanding the distress mechanisms.

5. CONCLUSIONS AND FURTHER RESEARCH

Based on the research undertaken in this paper, the following conclusions may be arrived:

- Identifying the real mechanism influencing bridge deterioration is central to the recommendation of repair strategies, evaluation of residual service life and life cycle costs and developing preventative measures.
- Methods adopted in diagnosis of distress in concrete bridges exposed to aggressive environments are a combination of visual inspection considering environmental issues and conducting specific lab tests. Systematic documentation of the diagnostic process would improve the efficiency of the process and will assist in the development of guidelines for new construction.
- Development of a rule-based-matrix in relating the defects and distress mechanisms has the advantages of transparency, simplicity and wider applications by practicing engineers.

As noted earlier, this paper has considered only 2 case study bridges,,which has assisted in development of the format of the rule based matrix. Current research is focused on developing a data base of mechanisms of deterioration and related causes through investigation of similar case histories.

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