Venkatesan, S., Setunge, S., Molyneaux, T.C.K and Gravina, R.J. *Towards a rule-based matrix for evaluating distress mechanisms in bridges.* November, 2006, Brisbane.

Towards a Rule-based matrix for evaluating distress mechanisms in bridges

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ABSTRACT: The effective management of bridge stock involves making decisions as to when to repair, remedy, or do nothing, taking into account the financial and service life implications. Such decisions require a reliable diagnosis as to the cause of distress and an understanding of the likely future degradation. Such diagnoses are based on a combination of visual inspections, laboratory tests on samples and expert opinions. In addition, the choice of appropriate laboratory tests requires an understanding of the degradation mechanisms involved. Under these circumstances, the use of expert systems or evaluation tools developed from "real-time" case studies provides a promising solution in the absence of expert knowledge. This paper addresses the issues in bridge infrastructure management in Queensland, Australia. Bridges affected by alkali silica reaction and chloride induced corrosion have been investigated and the results presented using a mind mapping tool. The analysis highights that several levels of rules are required to assess the mechanism causing distress. The systematic development of a rule based approach is presented. An example of this application to a case study bridge has been used to demonstrate that preliminary results are satisfactory.

1 INTRODUCTION

Approximately 100 of the 2800 bridges in Queensland, Australia, are concrete structures of which many are exposed to aggressive environmental conditions such as saline water or aggressive soils (sodic soils). These environmental conditions have contributed significantly to many of the bridge structures requiring significant repairs within the first 50 years with 1% or less reaching a 100 year design life. (Carse, 2005). As a result, maintaining the service delivery of these assets has become a major issue facing the Queensland Department of Main Roads (QDMR). (Venkatesan, et.al., 2006).

The current QDMR bridge management practice is based on three levels of inspection, namely:

1 Routine maintenance inspections,
2 Bridge condition inspections and
3 Detailed engineering inspection.

During these inspections it is necessary to quantify the structural defects, identify a suitable repair strategy and estimate the residual service capacity of the affected elements or the bridge. While structural defects are normally quite evident in the form of cracking, delaminations, rusting, staining and spalling, determination of the underlying causative mechanism(s) usually requires further investigation. Thus an understanding of the symptoms and the causative distress mechanisms is essential in the condition assessment of bridge structures. Expert opinions and acquired knowledge from similar case histories are invaluable under the above circumstances. Recent bridge management practices have adopted the use of expert systems to alleviate the lack of expert knowledge in other areas. This research reported here has been undertaken at RMIT University funded by the CRC CI (Cooperative Research Centre for Construction Innovation). Preliminary results obtained during the investigation of several case studies are presented. Main broader objective of the research project is to develop a software tool that assists the bridge asset owners in the decision making process.

The bridges studied have been affected by alkali silica reaction (ASR) and chloride induced corrosion (CIC). These bridges are classified as exposed to aggressive environmental conditions as they are situated in coastal areas. Detailed inspection reports and the associated laboratory test results have been analysed and the findings presented in the form of a mind map. The analysis reveals a structured rationale comprising several levels of rules that can be used to evaluate such distress mechanisms. Thus the analysis has a scientific basis, since the rules developed are derived based on the evidence of laboratory test results. Results from mind map analyses and the development of a schematic rule-based matrix is presented below.

2 DISTRESS OBSERVED IN CASE STUDY BRIDGES

This study has involved case studies of bridge structures exhibiting a range of distress symptoms. One particular representative case study, involving a bridge that has been affected by chloride induced corrosion, which is described below.

2.1 Case study

The bridge is a seven span structure consisting of 15 m long prestressed concrete (PSC) deck units supported by reinforced concrete cast-in-situ piers and driven PSC piles. Each pier comprises a head stock supported by two cylindrical columns, which in turn is supported by a pilecap. The headstocks, columns and pilecaps are all cast insitu concrete. Below each pier pilecap are ten 450 mm driven precast concrete piles. The outermost piles are raked outward (i.e. lateral to chainage) at a gradient of 1:5. The remainder of the piles are raked longitudinally in alternating directions at a gradient of 1:5. This bridge was constructed in approximately 1978 and is located at a critical position in the road network – the bridge is vital for the needs of tourists, council and the community. Photograph 1 shows a clear view of this bridge.

Photograph 1. General view of Bridge

In 2001, severe cracking was noted within the top 300 mm of each pilecap during an inspection undertaken by means of boat access. Cracks were noted on the top faces, extending down to approximately mid-depth of each pilecap. Tapping with a hammer revealed that much of the cover concrete in these areas was delaminated. In Photographs 2 – 4, distress observed on the pilecaps is evident.

Photo 2. Cracking observed on pilecap sides

Photograph 3. Cracking and Spalling at the corners due to "Double diffusion".

Photograph 4. Cracking and Spalling of concrete cover on sides of pilecap

The delamination observed in the cover concrete was believed to be the effect of expansive corrosion of the reinforcement. The sizes of cracks and the extent of delamination varied from location to location and pier to pier. This was attributed to changes in the degree of concrete compaction, differences in concrete batching and variability in the depth of concrete cover. Thus construction issues were considered as "possible" causes. The type of cracking observed especially within the tidal zone (this refers to the height up to which the waves splash on the structure from normal water level) has been attributed to the ingress of chlorides due to the saline water environment. Particularly the cracks taper with respect to the height within the tidal zone. In addition the similarity of cracking observed at the corners is attributed to the ingress of chlorides from both directions - known as “double diffusion”. (Refer to Photograph 3). Based on the above observations and hypotheses, ten concrete samples were extracted and analysed for chloride profiles, petrographic analysis, strength test and density tests. In particular, the chloride profile analysis (Figure 1) revealed that chloride contents in the concrete samples exceeded the “threshold” levels by a factor of 2 on an average. Threshold levels are determined based on the mix design and concrete content during the time of construction. Thus the mechanism affecting the pilecaps was confirmed to be chloride induced corrosion.

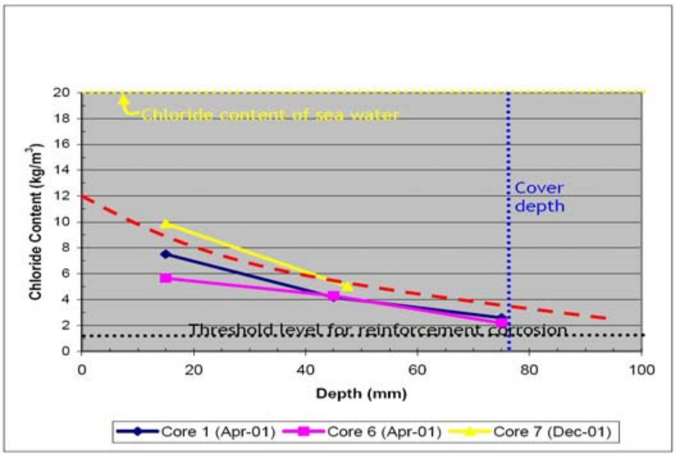


Figure 1. Chloride profile analysis on concrete samples

3 ANALYSIS OF INFORMATION

In this section, salient details of the mind map analysis are presented. A complete analysis in the form of a pictorial representation cannot be provided within the space limitations of this paper. Information was segregated under different headings:

- Type of element,
- Type of construction,
- Structural details,
- Age of the structure,
- Width, length, pattern of cracks,
- Associated distress signs such as emission of corrosion products,
- Spalling, rusting, and staining.

The above information was collated from six bridge case studies (the bridge described above is one of the case studies). Similarities of the patterns of information were sought. In particular, the examination of the data revealed that the elements affected in the tidal zone exhibited similar crack patterns and similar levels of chloride ingress (in terms of threshold levels). It was observed that the grades of concrete adopted during construction were less than 30 MPa. In addition it was observed that particular types of construction (hollow spun piles for example) exhibited similar distress symptoms. Although construction issues were noted as possible influences, the degree of certainty as to cause was not clear in all cases. The influences were analysed under three levels of confidence: high, medium and low. A schematic representation of part of the mind map is presented in Figure 2.

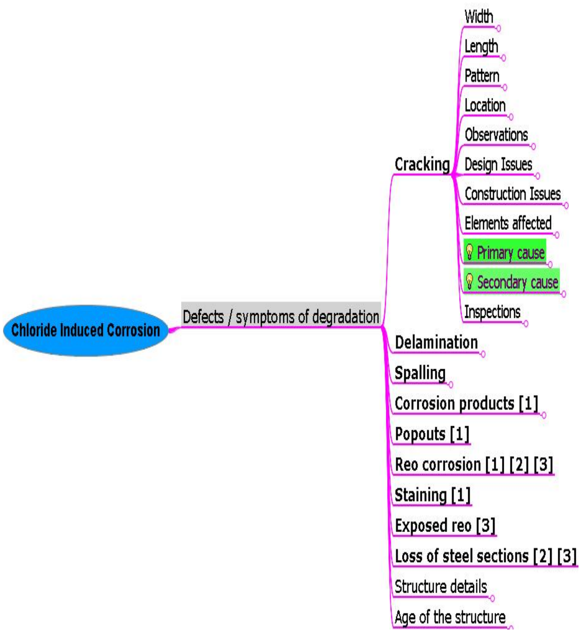


Figure 2. Schematic representation of mind map

Note: Numbers in brackets denote case study bridge number – the case study presented here is number 1.

4 SCHEMATIC DEVELOPMENT OF A RULE BASED MATRIX

Based on the mind map analysis, three levels of probable rules were identified: high, medium and low - corresponding to the degree of confidence judged during the mind map analysis. For example, the rules which have a higher (“high”) degree of occurrence in typical chloride induced corrosion are:

- Low grade of in-situ concrete (30 Mpa as designed - measurements taken during inspection may be as high as 40 Mpa).
- Element in tidal zone.
- Cracks tapering with height in tidal zone.
- Similarity of crack patterns at element corners.
- Chloride profiles exceeding threshold levels in concrete samples.
- Inadequate concrete cover for a given element (based on the code of practice prevalent at the time of construction and the current code of practice for the given element).

Examples of “Medium” level rules are:

- Early exposure of concrete to aggressive environment.
- Age of the structure (typically bridge elements could be affected by chloride ingress after 15 years).
- Construction issues such as curing, mixing.
- Element away from tidal zone but could be influenced by tidal actions.
- Evidence of spalling, staining, corrosion products.
- Type of element (Such as hollow spun [driven] piles and are therefore vulnerable to early exposure of chlorides).

Typical examples of “Low” level rules are:

- Width of cracks.
- Length of cracks.
- Repeat patterns amongst similar members.

Further analysis of these rules revealed that classifying the rules as they were presented would be inadequate in evaluating the distress. For example, the “inadequate cover” rule would have to be broken down (expanded) to a sub-set of rules in order to categorize a given element. Furthermore all of the specified rules may not apply to a given structure. Thus the reasoning based on rules has to encompass a further level of input. For this purpose, a literature study was undertaken. [Chiang, et.al, 2000, Chan, P.P.F, 1996, de Brito, et.al., 1993, Dhir, R.K., 1993, Kushioda, et.al., 1997]. Based on this review, the following reasoning scheme was developed. (Refer to Figure 3)

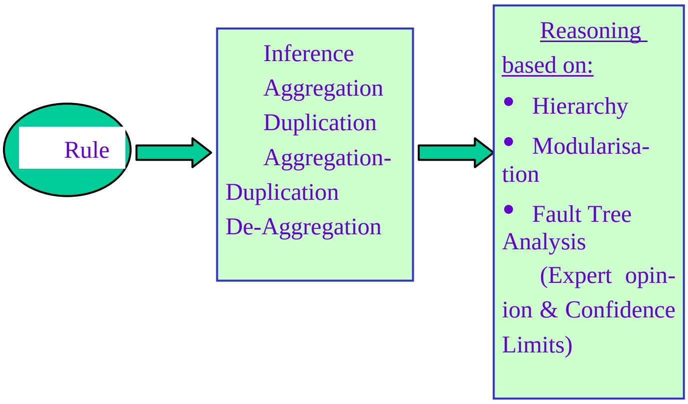


Figure 3. Reasoning based on developed rules

In the above figure, inference is a direct evidence of the rule relating to a known fact. Aggregation is the process of several rules leading to a conclusion. Duplication is the re-occurrence of known information that does not enhance the present level of conclusion. Aggregation-Duplication is a combination of the above two, that can be used to link to a common variable. De-Aggregation is a process of acquiring more information, to augment the inadequate information supplied. For example, the High probable rule of “Inadequate concrete cover” would need extra information on the size of aggregate; mix design; exposure class of the given element or it would need to be related to a codified provision at the time of construction.

To overcome the complexity arising out of a large set of rules or the combinations thereof, the rules were characterised as:

(i) A hierarchy (Typically - rules corresponding to an element in a tidal zone would be categorised differently to elements that were permanently submerged under water)

(ii) A modularised rule-base. (Typically this involved an if-then-else situation. For example, if the grade of concrete is less than a given strength and the cover is less than a given limit, then the grades of concrete and concrete cover are genuine contributors of the observed distress)

(iii) A Fault-tree analyses (in which the probabilities are higher for “inference” type rule bases than the “aggregation” type rule bases)

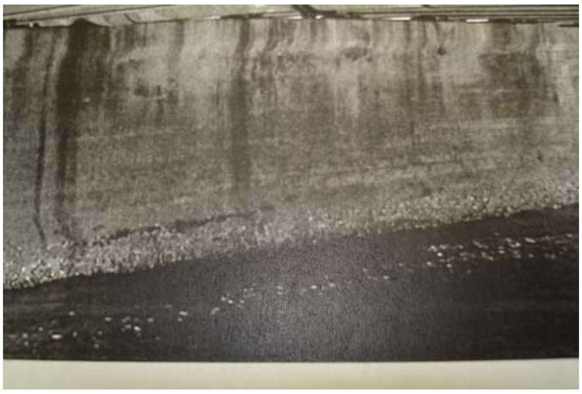
The development of the above rules presents an opportunity in developing a software diagnostic tool. The authors believe that the above approach of using different reasoning techniques to directly identify the distress mechanism (without having to traverse through a series of questionnaires) is new and effective. Furthermore, during regular inspections, it is often difficult to identify the correct mechanisms that display similar distress symptoms. With the above approach, it is possible to segregate and identify the correct mechanism. This has potential cost benefits in choosing the appropriate laboratory test methods during detailed investigations.

In order to verify the adequacy of these rules they were tested “blind” against another (previously unused) case study bridge. This is presented in the next section.

5 APPLICATION OF RULE-BASED APPROACH (EXAMPLE)

This (test) case study bridge was constructed in the 1940’s and subsequently widened in the 1960’s. It comprises a four-span RC deck, steel I-girder bridge, supported by pier walls founded on cast in-situ piles. The affected pier elements have vertical cracks at the chamfered edges (Refer to Photograph 5) and consistent symptoms of rusting, staining, delaminations are apparent (Refer to Photograph 6). The cracks and other associated distress are observed to be greater in the tidal zone.

Photograph 5. Cracking observed on the chamfered edges of the pier.



Photograph 6. Evidence of staining, rusting and delaminations on the sides of the pier

Analysis of the above bridge symptoms using the techniques developed above reveals the following active (applicable) rules

- The affected element is under the influence of the tidal zone.
- Significant cracks at the chamfered ends of the pier are due to the double diffusion of chlorides.
- Evidence of spalling, rusting, staining.
- Age of the structure.

Note that the first two are “High” probability rules and the following two are “Medium” probability rules. Since laboratory tests on concrete samples are not available, it was inferred that the distress could be attributed to the chloride induced corrosion and that further analysis of concrete samples could confirm the presence of this mechanism. These inferences were observed to be in complete agreement with expert opinions and were further confirmed based on inspection reports.

6 CONCLUSIONS

- Identifying the “real” mechanism causing distress is central to the management of bridge structures.
- Methods adopted in the evaluation of distress are a combination of visual inspections and laboratory tests.
- Development of a Rule-based matrix from case histories has the advantages of transparency and simplicity.
- Several levels of validated rules are required in evaluating the distress mechanisms in bridges.
- A comprehensive “inference framework” is required in analysing the database of rules.
- The Rule-based matrix presented in this paper, provides a promising solution towards the development of expert systems.

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