STRUCTURAL ASSESSMENT OF REINFORCED CONCRETE BRIDGE STRUCTURES EXPOSED TO CHLORIDE ENVIRONMENT

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ABSTRACT: This research paper presents a new approach to develop a simple bridge rating system for Sri Lanka. This approach evaluates the current performance of concrete bridges on the basis of simple visual inspection and non-destructive tests. The main reason to conduct this research is to develop a proper bridge management system for Sri Lanka and to develop deterioration prediction curve for bridges. Also some applicable maintenance techniques are introduced according to identify condition state of the bridge based on the durability performance of the each bridge. During field inspection, the major issue to deteriorate concrete bridges was identified as chloride induced corrosion called chloride attack. To understand flexural capacity reduction and area reduction of reinforcing steel due to corrosion, Accelerated Corrosion Testing Method (ACTM) was carried out at the laboratory. By conducting load tests, the flexural capacity reduction of deteriorated concrete beam was compared with control beam. More than fifty percentage of area reduction in steel bars was observed while it reduced flexural capacity reduction more than seventy percent, compared to control beam.

Keywords: *bridge rating system, visual inspection, acceleration corrosion testing method, non-destructive tests*

INTRODUCTION

Bridges are lifelines of a nation's infrastructure and massive investments are being made in the highway sector year after year. During the last fifty years a number of reinforced concrete (RC) bridges and pre-stressed concrete (PC) bridges were build all over the country. Day by day there is a significant increase of number of bridges in highway sector. Due to high construction cost and replacement cost, maximum utilization of service period is essential for bridges. Currently major infrastructure projects are being made by the government to improve public transportation system. It includes construction of steel and concrete bridges in all classes of roads. To improve transportation system in Sri Lanka, safety is an important parameter to reduce traffic congestion in main cities, where public transportation can be improved with confidence.

Normally bridges are directly exposure to severe environmental conditions and deterioration could occur with time. This deterioration process can lead to eventual failure of the bridge. Therefore periodic bridge inspection systems are required. Also most of these bridges were designed for lower traffic volume, slower speeds, and lower geometric standards than the current utilization. Due to continuous exposure to severe environmental conditions, the performance of bridges can be varying with its life, as well as there is tendency to use existing structures without proper investigation process. For the investigation process, lack of design details of these structures, lacks of expertise to inspect and evaluate cost are the major factors of concern. To obtain better safety from existing structures, it is necessary to assess the current performance of the existing structures. Then replacement or repairing can be determined based on the inspected or predicted results.

Though there are researches that evaluate the current performance of steel bridges in Sri Lanka, reinforced and pre-stressed concrete bridges evaluation attempts are relatively less. With many bridges being older than 50 years, proper bridge management system for Sri Lanka is essential for effective utilization during the remaining service period.

Bridge management system has been recognized as essential in all the developed countries. Though Sri Lanka has thousand of concrete bridges all over the country, there is no proper investigation process to evaluate the current performance these bridges yet. Main objective of this research is to introduce the cost effective, simple bridge evaluation system to identify current condition state of bridges in different exposure conditions. It is also expected to introduce a deterioration prediction curve for bridges, in order to check whether maintenance requirements and offer rehabilitation strategies (maintenance techniques) for bridges.

METHODOLOGY

Visual Inspection and Non-destructive Testing

First it is necessary to identify suitable number of bridges for visual inspections and method of non destructive testing required for particular bridge. Bridges have important structural elements such as; deck, piers, deck layering, drainage, girders, beams, handrail and embankment. Bridges were evaluated through a visual inspection and hence its structural condition and performance could be predicted based on soundness score. The soundness score of a structural element depends on the current condition of the structural element and element weighted value. When bridge evaluation is conducted using this method, a subjective rating was assigned to the bridge components. The presence of cracks, spalling of concrete and corrosion of reinforcement offered important aspects on determining the condition state of each element. Then bridges could be rated according to National Bridge Inventory US (1995) specifications. Also usages of non-destructive tests methods (rebound hammer test and ultra-sonic pulse velocity test) for bridge inspections have gained much reliability on evaluating the structural performance. This is due to its effective ability in evaluating structural conditions of the bridge. Non-destructive testing includes methods of testing on concrete structures which do not reduce the functional capability of the structure.

Two types of non destructive tests were used during field inspections. Rebound hammer test was carried out by pressing rebound tip on the concrete surface. When tip compressed on concrete surface, it rebounded and gives rebound number. After referring to the standard graph, the related compressive strength of concrete can be used to determine the strength of the structural element. In pulse velocity test, at the beginning the trance-meter and receiver was kept at a spacing of 0.3 m and the travel time of the pulse was measured. Then pulse velocity was found by known distance and time. Then referring to standard graphs which show the relationship between compressive strength of concrete and the pulse velocity, the actual strength of the bridge element can be found. Also to increase the accuracy of results, these testing were carried out with the spacing of 0.6 m and 0.9 m. The pulse velocity test can be done by direct or indirect method. But values obtain by direct method are more reliable than indirect method. However, due to access limitations indirect method was applied to the most of the bridges. In addition, pulse velocity test was carried out to identify structural defects such as cracks, voids, etc in the bridge elements. During the inspection, it was identified that bridges along the coastal belt have deteriorated more than the bridges located inland. It is mainly due to corrosion of reinforcements caused that is by chloride induced corrosion cracking called chloride attack along the bridge girders. (see Figure 1)

Experimental Program and Test Parameters

Two reinforced concrete beams were cast in the laboratory using ordinary portland cement with maximum aggregate size of 20 mm. The cross section of the beam is 100 x 150 mm and the length of the beam is 2000 mm. The characteristic design compressive strength of concrete used is 20 N/mm^2. To avoid corrosion of reinforcing steel, the extended length of bars was coated with grease and wax. To simulate the deterioration of beams in short time period, accelerated corrosion testing method (ACTM) was adopted. The specimen is immersed in a sodium chloride (NaCl) solution bath with Cl^- concentration of 5% and that acts as electrolyte. In this method, reinforcing steel of the specimen that have to be corroded, is made as anode and copper bars in the bottom of acrylic tank is used as cathode (see Figure 2). The current supply was connected to one end of steel bar in the specimen and the other end is connected to the copper bars. The constant and continuous current supply of 0.7 Amp was applied to all the specimens until corrosion crack generated. Figure 3 shows the sequence of steps followed during the ACTM in the laboratory.

RESULTS AND DISCUSSION

Visual Inspection and Non-destructive testing

Bridge inspections were carried out along the coastel belt and rural area. Totally, twenty seven bridges were inspected, from those, fifteen bridges located along the costal belt from Hikkaduwa to Weligama

(Bridge Reference Numbers (BRN), 1 to 15) along the main road A2 and twelve bridges, in the countryside (Bridge Reference Numbers (BRN), 16 to 27). Numbering of those inspected bridges is shown according to the inspected sequence from 1-27 (see Table 1). Those inspected bridges were rated according to modified US bridge rating system according to Sri Lankan environmental conditions and type of bridge (Tables 1 and 2).
According to field inspection results, it is revealed that Hikkaduwa Bridge (BRN 5) located very close to main city shows remarkable strength reduction compared to other bridges in the coastal belt. Visual inspection details at Koggala Bridge (BRN 11) revealed that it has large amount of corroded reinforcement but it did not show considerable strength reduction as Hikkaduwa Bridge (see Figure 4). The main reason for that may be the aging of these structures. Also all the bridges located along the coastal belt show average compressive strength of concrete about 40 N/mm^2 while bridges in country region shows average compressive strength of concrete about 30 N/mm^2. Further it was noticed that most of bridges along the coastal belt have been in having a service life of less than 25 years.
Further, analysis was carried out using simple evaluation process to determine required maintenance techniques. The maintenance technique was proposed based on the inspection results and predicted soundness score of the structure. For that, most effective and critical bridge elements (girder, embankment, slab and pier) were identified and their conditions states were used. At the beginning a numerical value is assigned to bridge element considering its importance as shown in Table 3. Each bridge element condition was determined using non-destructive test results (see Figure 4) and assigned the condition state based on the test results (see Table 4). Visual inspection results were important when the access difficulties occurred to carry out the non-destructive tests. Following formula is used to determine soundness score.

Bridge Soundness Score (BSS) = ∑ (Each element condition x element weighted value)

According to the soundness score of the bridge, the required maintenance techniques are listed in Table 5. Table 6 summarizes the method used to determine soundness score values for inspected bridges with necessary recommendations and rehabilitation strategies for bridges.

Acceleration Corrosion Test Results
Acceleration corrosion testing was carried out until corrosion crack appears in the specimen. After 35 days of acceleration corrosion, the test beam showed horizontal corrosion cracks along the beam length. The development and propagation of corrosion cracks along the beam length and underneath of the beam are shown in Figures 5(a) and 5(b), respectively.
After 35 days, it was observed that crack opening increased up to average of 1.8 mm in one-side, average of 2.0 mm on the other side and the bottom crack remained unchanged. Also these cracks were propagated along the whole length of the beam causing it to split horizontally. After 41 days those openings expanded further one side up to 2.6 mm and on other side up to 2 mm (Figure 6).
The flexural capacity of two beams were checked using single point loading test as shown in Figure 7(a). Also it was revealed that there was no proper bond between concrete and reinforcement steel. At the failure load, corroded beam showed only flexural cracks along the mid-span region (Figure 7(c)). But the control beam showed both flexural and flexural-shear cracks at the ultimate failure (Figure 7(b)). After that, the test beam with corrosion cracks was carefully monitored. By inspecting the reinforcing steel, it revealed that the rib had been totally removed from the bar causing it to produce corrosion rust on the surface of the bar (see Figure 7(d)). Due to this poor bond characteristic between steel and concrete, the flexural capacity was reduced by nearly 70%. Figure 8 shows applied load versus mid-span deflection relationship for control and test beams. It observed that the reinforcing steel area reduction was around 55% due to this corrosion. These data were summarised in Table 7.

CONCLUSIONS
This research would be able to improve and modify the contents of the existing inspection sheet that is used by Road Development Authority, Sri Lanka. The proposed bridge management system offers various maintenance plans which can be directly applied to bridges in Sri Lanka. During the inspection, it is identified that most of coastal belt bridges deteriorated than the bridges located inland. It is due to the chloride attack.

It shows that significant amount of bearing capacity reduction between the control beam and test beam (around 70%). Moreover in order to evaluate the condition of existing RC structure, weight loss of the reinforcement steel lost due to corrosion is essential. While this amount cannot be measured directly without removing the reinforcement steel from the structure, it can be estimate indirectly using the width of corrosion induced cracks with the loss of reinforced section area.

REFERENCES

1. Adnan A, Alih S and Mirasa K, ‘Bridge Evaluation Through Nondestructive Testing In Comparison With Visual Inspection’, Proceeding of the 6th Asia-Pacific Structural Engineering and Construction Conference, Malaysia, September 2006, pp. B-42-B-52.
2. Dimithri V, Chernin L And Stewart M, ‘Experimental and Numerical Investigation of Corrosion–Induced Cover Cracking in Reinforced Concrete Structures’, Journal of Structural Engineering (ASCE), April 2009, pp. 376-384.
3. Minh H, Mutsuyoshi H, Taniguchi H and Nitani K, ‘Experiments on the Behavior of Post Tensioned Concrete Beams Deteriorated by Corrosion’, Proceedings of Japan Concrete Institute, 2003, pp. 875-880.
4. Minh H, Mutsuyoshi H, Konno Y and Nitani K, ‘Experimental Investigation on Chloride-Induced Corrosion in Post-tensioned Concrete Beams’, Proceedings of Japan Concrete Institute, 2004, pp. 1071-1076.

(a) Hikkaduwa town bridge **(b) Ginthota bridge** **(c) Koggala bridge**

Figure 1: Damages in Bridges due to Corrosion

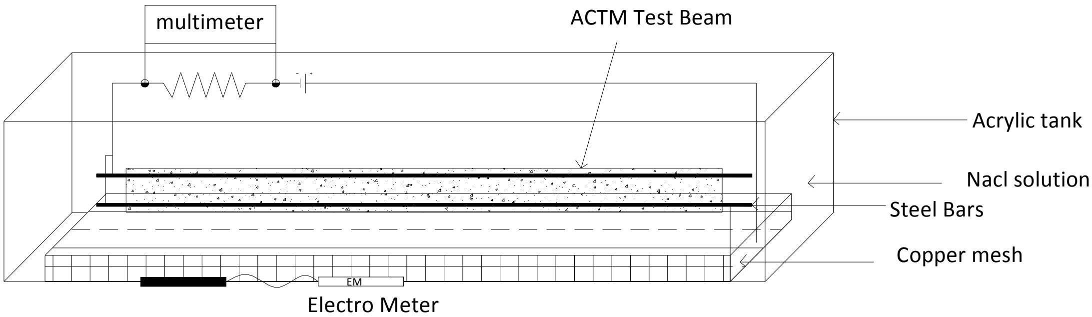


Figure 2: Acceleration Corrosion Test Apparatus

(a) Cast beams **(b) NaCl bath** **(c) Power supply unit**

(d) During ACT process **(e) After 15 days** **(f) Cracks after 35 days**

Figure 3: Corrosion Test Process

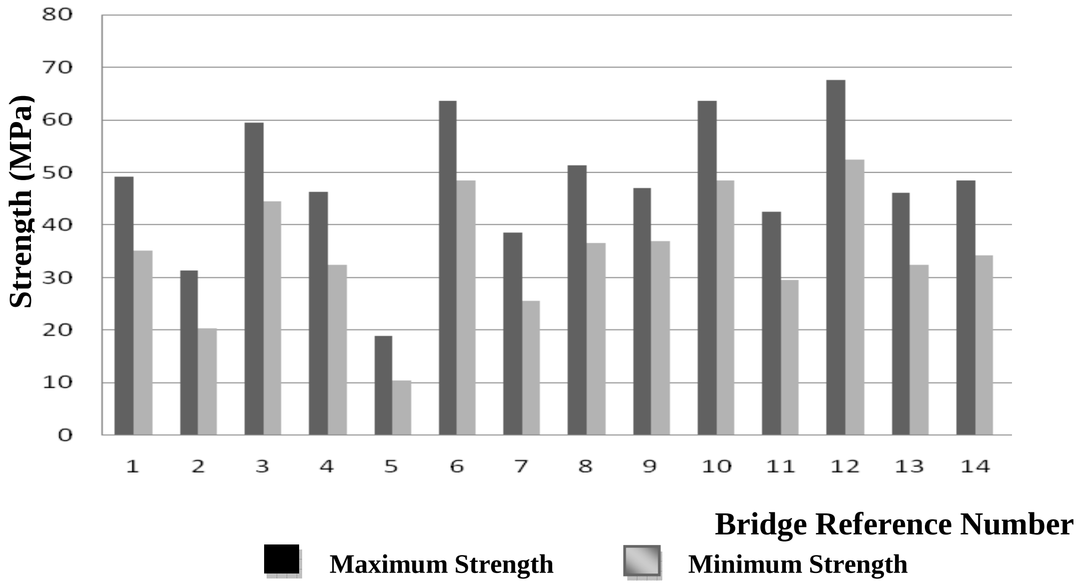


Figure 4: Inspection Summary for Coastal Belt Bridges: Beam/Deck Element

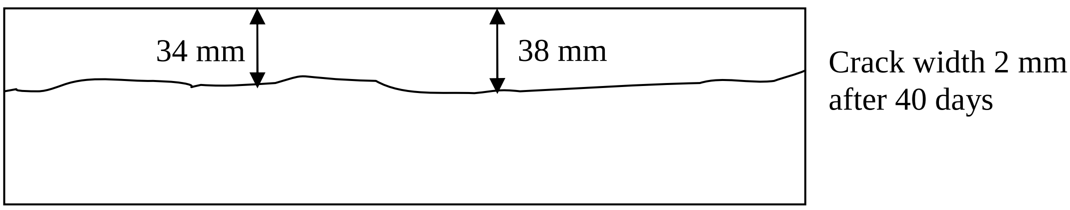


Figure 5(a): Corrosion Cracks on Side

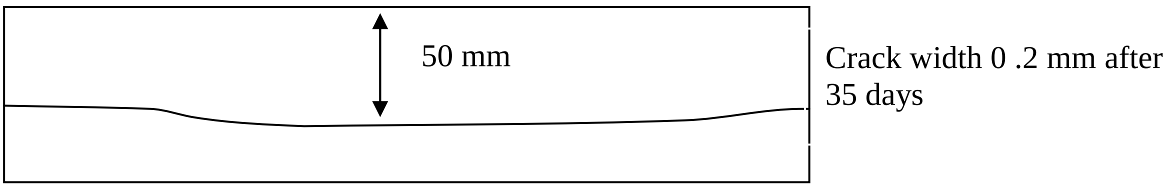


Figure 5(b): Corrosion Crack on Bottom Surface

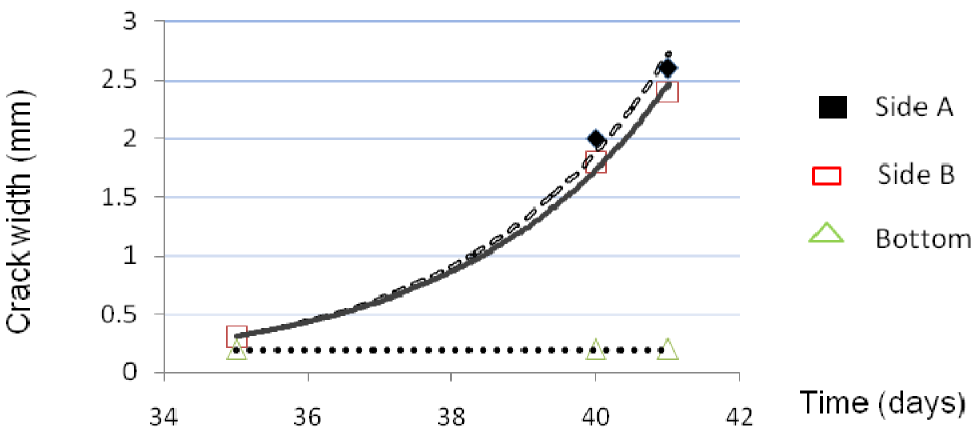
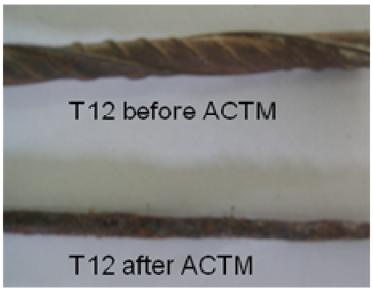


Figure 6: Crack Development with Time

(a) Single point load test (b) Control beam



(c) Corroded beam (d) ACTM results on corroded steel

Figure 7: Loading Test Process

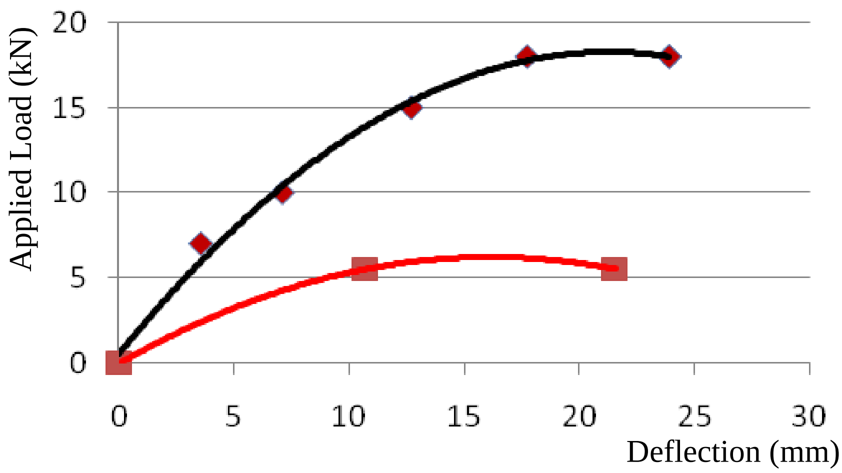


Figure 8: Applied Load vs. Mid-Span Deflection

Table 1: Bridge Reference Number and Condition State

Bridge Number	Bridge Name	Condition State	Condition Number
1	Kapu Ela bridge	Good.	7
2	Railway Across bridge	Satisfactory.	6
3	Ginthota bridge	Very good.	8
4	Dodanduwa bridge	Very good.	8
5	Hikkaduwa bridge	Critical.	2
6	Hikkaduwabridge(Town)	Good.	7
7	Gintota bridge	Very good.	8
8	Mahamodara bridge	Good.	7
9	Dewata bridge	Good.	7
10	Habaraduwa bridge	Good.	7
11	Koggala bridge	Good.	7
12	Ahangama bridge	Excellent.	9

13	Goyyapana bridge	Good.	7
14	Weligamabridge (Town)	Very good.	8
15	Polathumodara bridge	Good.	7
16	Bogahagoda bridge	Satisfactory.	6
17	Agulugaha bridge	Good.	7
18	Imaduwa bridge	Satisfactory.	6
19	Imaduwa bridge	Very Good.	8
20	Kalukadha bridge	Satisfactory.	6
21	Ambalama bridge	Very Good.	8
22	Moraliyadda bridge	Good.	7
23	Polpagoda bridge	Good.	7
24	Makumbura bridge	Good.	7
25	Kottawa bridge	Good.	7
26	Totagoda bridge 01	Satisfactory.	6
27	Totagoda bridge 01	Good.	7

Table 2: Condition State Rating (National Bridge Inventory US, 1995)

Number	**Condition state**	**Physical Description**
9	Excellent.	A new bridge
8	Very good.	No problem noted.
7	Good.	Some minor problem.
6	Satisfactory.	structural members show minor some deterioration
5	Fair.	All primary structural elements are sound but may have minor section loss, deterioration, spalling, or scour.
4	Poor.	Advance section loss, deterioration, spalling, scour.
3	Serious.	Loss of section, etc. has affected primary structural components. Local failures are possible. Fatigue cracks in steel or shear cracks in concrete may be present.
2	Critical.	Advanced deterioration of primary structural elements. Fatigue cracks in steel or shear cracks in concrete may be present or scour may have removed structural support. Unless closely monitored it may necessary to close the bridge until corrective action is taken.
1	Imminent failure.	Major deterioration or loss of section in critical structural component or obvious vertical or horizontal movement affecting structural stability. Bridge is closed to traffic but corrective action may put back in light service.
0	Failed.	Out of service. Beyond corrective action.

Table 3:Element Weighted Values

Element	**Weighted Value**
Piers	1
Deck	2
Abutment	1

Table 4: Element Condition State Value

Minimum Strength (N/mm^2)	Condition Value	Condition State
>=45	9	Excellent.
40-45	8	Very good.
30-40	7	Good.
25-30	6	Satisfactory.
20-25	5	Fair.
15-20	4	Poor.
10 -15	3	Series
10 >	0	Failed.

Table 5: Bridge Soundness Score and Maintenance Techniques Required

Bridge Soundness Score	Treatment Required
36-32	No treatment required
31-24	Simple maintenance techniques required.(Patching Repair)
23-16	Special maintenance techniques required.(Cathodic protection)
15-08	Immediate maintenance techniques required.(Retrofitting techniques)
7 >	Replacement.

Table 6: Bridge Soundness Score and Maintenance Techniques Required For Bridges with Piers

BRN	Bridge Element Condition			Soundness Score	Maintenance Required
	Pear (1)	Abutment (1)	Deck (2)		
1	7	7	7	28	Simple maintenance techniques
4	7	7	7	28	Simple maintenance techniques
8	7	7	7	28	Simple maintenance techniques
9	7	9	9	32	No treatment required
10	9	9	9	36	No treatment required
11	6	6	6	24	Simple maintenance techniques
13	7	8	8	30	Simple maintenance techniques
15	8	8	8	32	No treatment required
17	4	4	4	16	**Special maintenance techniques required**
24	4	4	4	16	**Special maintenance techniques required**
26	4	8	8	24	Simple maintenance techniques

Table 7: Loading Test Results

<table>
<tr><th>Beam</th><th>Calculated Flexural Capacity (kN)</th><th>Failure Load (kN)</th><th>Maximum mid-span deflection (mm)</th></tr>
<tr><td>Control beam</td><td rowspan="2">17.5</td><td>18.0</td><td>27.70</td></tr>
<tr><td>Test beam</td><td>5.5</td><td>21.55</td></tr>
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