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Technical Note:

Condition Assessment of the Deteriorated Reinforced Concrete Bridge

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Abstract: A comprehensive assessment was conducted to an old reinforced concrete bridge in Brunei Darussalam. This bridge is about 30-40 years old, and has already shown signs of concrete distresses. The main concern was the integrity of the columns, beams and deck, as signs of concrete deteriorations were readily noticeable, e.g. cracks, delaminations, exposed rebar, and concrete spalling. Both visual inspection and non-destructive tests were performed on site. For more detail evaluation, concrete core samples were extracted and sent for testing. Based on information gathered during the investigation and the results of laboratory testing, the reviewed concrete columns were found in bad condition and required immediate repair. The main cause of this concrete distress was the reinforcement corrosion. The vertical column reinforcements were badly corroded and could not function as designed. Without initiating a repair program, it should be prepared for progressive deteriorating conditions, eventually leading to a structural at-risk scenario.

Keywords: Condition assessment; concrete deteriorations; nondestructive test; laboratory testing.

Introduction

The existing reinforced concrete bridge was constructed approximately 30 to 40 years prior to the assessment. The bridge served as a main link between two districts in a single lane carriageway. Due to a significant increase of traffic load, another lane supported by independent piers was added. The dimension of the subject bridge was approximately 48m (length) by 6m (width) and 4m (height). The bridge was supported by 4 beams (approximately 800 x 800mm) and 12 columns (approximately 550mm diameter and 2000mm height). The General View of the bridge is shown in Figures 1a and 1b.

Figure 1a. Bridge General View

Figure 1b. Bridge Underside View

The objectives of the works were to evaluate the existing condition and causes of concrete deteriorations found in columns, beams, and deck of the bridge. Works were performed based on ACI 364.1R-07 [1] and ACI 228.2R-13 [2] within the following scope:

- Reviewed available project documents relative to the subject structure
- Performed a visual inspection of accessible concrete surfaces (ACI 201.1R-08 [3]) noting areas of concrete cracking, delamination, spalling, staining and other significant features (i.e. mapping).
- Assessed representative portions of the structure and performed an acoustic impact survey (i.e. soundings) (ASTM D-4580 [4]) at selected locations over accessible concrete member surfaces in an effort to detect subsurface voids and/or delaminations (i.e. internal separations).
- Performed Non-Destructive testing techniques including Rebound Hammer Testing (ASTM C-805 [5]) and Ultrasonic Pulse Velocity (UPV)

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testing (ASTM C-597 [6]) at representative areas throughout the structure to ascertain consistency and quality of the structure in-situ.

- Collected concrete cores in representative reinforced concrete structural members, using wet rotary diamond core drilling techniques (ACI 214.4R-10 [7]). Core and drill holes were filled with shrinkage compensating repair mortar after core and powder sample extraction.
- Submitted collected core and powder samples for laboratory analysis that included:
  a. Depth of Carbonation Testing: Carbonation depths were determined using a modified phenolphthalein pH indicator solution sprayed onto freshly fractured concrete surfaces. Visual observation of the resultant spray surface color tints revealed the existing concrete environment and current susceptibility to corrosion activity.
  b. Compressive Strength Testing of Concrete Core Samples (ASTM C-42 [8]). Test results provided strength values and are indicators of the relative quality of the concrete.
  c. Water Soluble Chloride Ion Content of Hardened Concrete Tests (ASTM C-1218M [9]): Chemical extraction test results determined the chloride ion level within the concrete. The detected level is an indicator of the potential electrochemical process of embedded metal corrosion within the concrete mass.

Literature Review

Carbonation is the reaction of carbon dioxide from the air with calcium hydroxide in concrete, which results in product formation of calcium carbonate. The reaction product has a lower pH (i.e., more acidic) than the parent material and effectively "depassifies" the alkaline environment of concrete. An alkaline environment is necessary for a passive film to form on the steel reinforcement to inhibit the electrochemical process of corrosion. The generally accepted pH value of minimum 9.8 has been determined as a depassification threshold, below which the concrete mass can be assumed as an "active participant" in the corrosion process.

During embedded steel corrosion activities, the steel metallurgy changes, with corrosion products requiring and occupying more space than the parent material. As such, significant tensile stresses are exerted on the concrete in the immediate proximity of the corroding steel. Although inherently strong in compression, concrete is relatively weak in tension; therefore, unrestrained portions of the concrete mass (i.e. protective cover overtop of embedded reinforcing bars) will crack at the corroding bar interface. Under some conditions, a chloride content of as little as 0.15% by weight of cement is sufficient to initiate corrosion of embedded steel in concrete, in the presence of oxygen and moisture (ACI 222R-01 [10]).

As expansion forces created during embedded metal corrosion product formation or minerals re-crystallizing in micro cracks exceeded the tensile strength of the concrete material, the concrete separated from the "parent" substrate along a conical failure plane, causing the concrete structure to suffer from delaminations (internal separation) and spalling. The spalls always progress along the path of least resistance whereby the failure initiates at the corroding metal/concrete interface and extends toward the unrestrained outer surface, i.e., through the unreinforced concrete cover (ACI 224.1R-07 [11]).

Field Investigation

Field investigation work was performed, which consisted of Visual Inspection, Acoustic Impact testing, Ferroscan Pachometer survey, Rebound Hammer testing, Ultrasonic Pulse Velocity, measurements in concrete dimensions, collection of concrete core and concrete powder samples.

Visual Inspection (ACI 201.1R-08 [3])

Accessible areas of the concrete structure comprising the Bridge were visually examined to document observed deterioration in the form of cracks, delaminations, efflorescence, spalls, etc. The locations of observed deterioration within the bridge's concrete structure, together with all the nondestructive tests performed, were plotted in the mapping and are shown in Figures 2a to 2d.

The column concrete within the top 300mm from the beam soffit was generally in good condition. The concrete in the next 1200mm was in a very bad condition which mostly appeared to suffer from cracks, delaminations, and concrete spalling. The bottom part of the column, which is approximately 500mm from the pile cap, was full of barnacles and appeared to be in good condition.

The beam concrete seemed to be in good condition. Isolated and small areas of delaminated concrete and exposed rebars were found. The underside of the deck slab also seemed to be in good condition as well, except some localized minor delamination, spalling, and exposed rebar.

Discussions presented in the following sections are generally related to the corrosion-induced deterioration of the reinforced concrete observed within the beams, columns, and deck the Bridge.

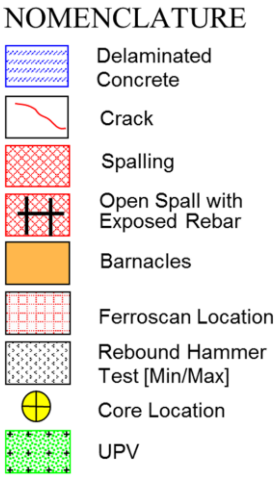

Figure 2a. Mapping Nomenclature

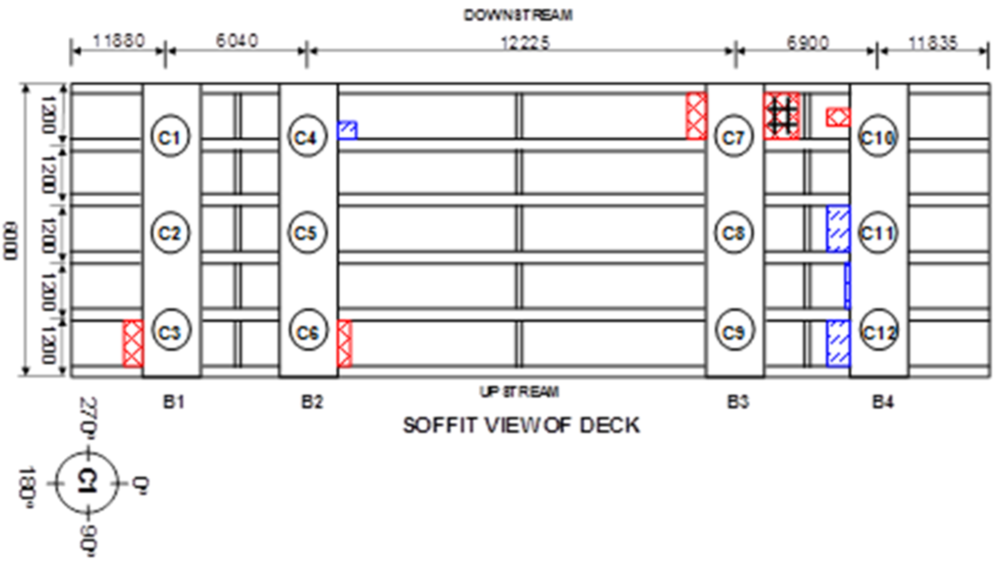

Figure 2b. Bridge Deck Mapping and Orientation

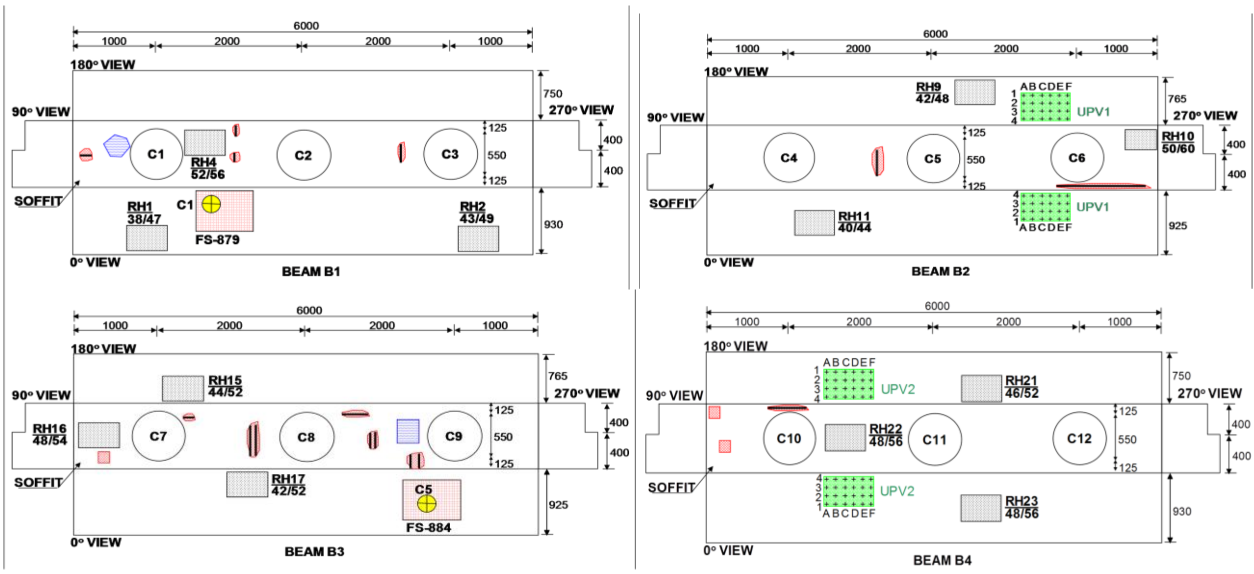

Figure 2c. Bridge Beam Mapping

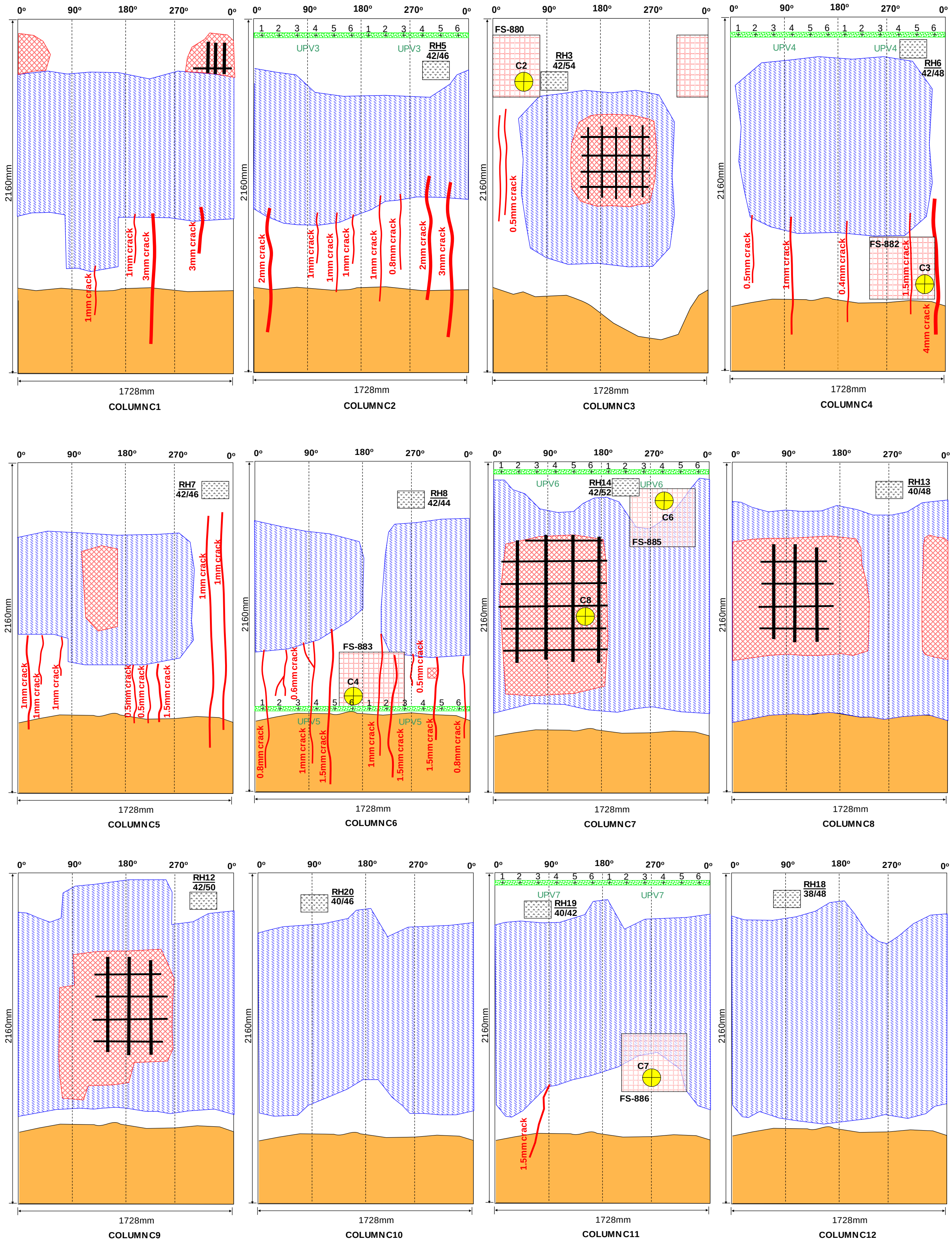

Figure 2d. Bridge Column Mapping

Cracking

Cracking observed at the subject structures typically took the form of fine to wide cracks. At a few locations however, cracking though was observed to be faulted (i.e. uneven crack shoulder edges). Faulted crack patterns observed were typically associated with stresses created during the embedded metal corrosion process within concrete as shown in Figure 3.

Delamination

Areas of internal separations (i.e. delamination) were detected at numerous locations on columns between 500 to 1700 mm high from the pile cap, as shown in Figure 2d. Generally, these delaminated areas were associated with embedded reinforcing steel corrosion. Some detected delaminations are shown in Figures 4a and 4b.

Spalling

The spalling observed appeared to be primarily related to the embedded reinforcement corrosion. Concrete spalling exposing severely corroded rebars were found in many locations in the columns, showing serious concerns in its structural integrity. The exposed reinforcements (rebars) found on the beams and deck were mainly due to insufficient concrete cover [~10mm] or debris which was not cleared during concrete placement. Some of the observed concrete spalling were shown in Figures 5a to 5d.

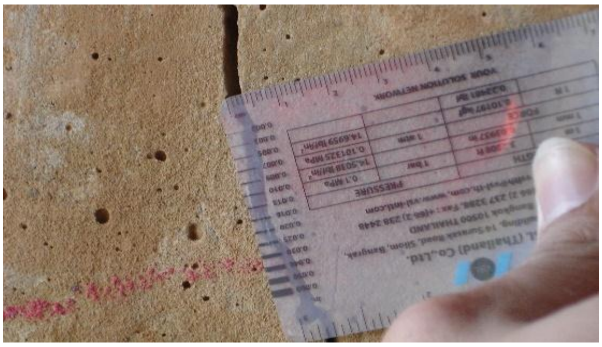

Figure 3. Three mm Crack Found on Column C1

Figure 4a. Delamination Detected on Column C2

Figure 4b. Delamination Detected on Beam B1

Figure 5a. Cracking, Delamination, and Spalling with Exposed Rebar on Column C1

Figure 5b. Concrete Spalling Exposing Severely Corroded Rebars on Column C9

Figure 5c. Exposed Rebar with 10mm Cover on Beam B1 Soffit

Figure 5d. Concrete Spalling with Exposed Corroded Rebars on Deck Soffit

Acoustic Impact Testing (ASTM D-4580 [4])

Generally, unsound (i.e., delaminated) areas were in the immediate proximity of cracks in the concrete columns. This test was conducted on the accessible surfaces of the Bridge columns and beams only. Most of the concrete in the middle length of columns were found delaminated. Significant conditions detected in reinforced concrete structures during mechanical sounding (Acoustic Impact Test) are plotted in mapping shown in Figures 2b to 2d.

Rebound Hammer Testing (ASTM C-805 [5])

This method is not intended as an alternative for strength determination of concrete – but rather the scale number values provide qualitative comparisons between similar concrete materials. Typically, a series of 10 readings are performed approximately 25 mm apart with test results recorded and tabulated.

Twenty three randomly selected locations were tested with Rebound Hammer testing (shown in Figure 6). A total of 230 readings were taken. Interpolating concrete strengths derived from Rebound Hammer manufacturer Data Charts, revealed a mean interpretative compressive strength of 45 to 68 N/mm² and 43 to 56 N/mm² for beams and columns, respectively. A summary of Rebound Hammer readings is presented in Table 1.

Figure 6. Rebound Hammer Test on Column C3

Table 1. Summary of Rebound Hammer Test Results

No.	Location	Orientation	Surface condition	Measurements			Interpretive f_c' (N/mm^2)
				High	Low	Aver	
1	Beam B1 (0° View)	Horizontal	Dry	47	38	43	45.62
2	Beam B1 (0° View)	Horizontal	Dry	49	43	46	52.21
3	Column C3 (Between 90° and 180° View)	Horizontal	Dry	54	42	48	56.09
4	Beam B1 (180° View)	Horizontal	Dry	56	52	54	68.26
5	Column C2 (Between 270° and 0° View)	Horizontal	Dry	46	42	44	48.41
6	Column C4 (Between 270° and 0° View)	Horizontal	Dry	48	42	45	50.30
7	Column C5 (Between 270° and 0° View)	Horizontal	Dry	46	42	44	48.41
8	Column C6 (270° View)	Horizontal	Dry	44	42	43	46.55
9	Beam B2 (180° View)	Horizontal	Dry	48	42	45	50.30
10	Beam B2 (Soffit)	Overhead	Dry	60	50	55	58.73
11	Beam B2 (0° View)	Horizontal	Dry	44	40	42	44.70
12	Column C9 (Between 270° and 0° View)	Horizontal	Dry	50	42	46	52.21
13	Column C8 (270° View)	Horizontal	Dry	48	40	44	48.41
14	Column C7 (Between 180° and 270° View)	Horizontal	Dry	52	42	47	54.14
15	Beam B3 (180° View)	Horizontal	Dry	52	44	48	56.09
16	Beam B3 (Soffit)	Overhead	Dry	54	48	51	52.34
17	Beam B3 (0° View)	Horizontal	Dry	52	42	47	54.14
18	Column C12 (90° View)	Horizontal	Dry	48	38	43	46.55
19	Column C11 (Between 0° and 90° View)	Horizontal	Dry	42	40	41	42.88
20	Column C10 (90° View)	Horizontal	Dry	46	40	43	46.55
21	Beam B4 (180° View)	Horizontal	Dry	52	46	49	58.06
22	Beam B4 (Soffit)	Overhead	Dry	56	48	52	53.89
23	Beam B4 (0° View)	Horizontal	Dry	56	48	52	64.12

Ultrasonic Pulse Velocity (UPV) Testing (ASTM C-597 [6])

The relative quality and homogeneity of concrete can be evaluated by statistical comparison of pulse velocities measured at grid points established on a concrete structure. A total of seven locations were selected on beams and columns for this nondestructive test (Figures 7a and 7b). The UPV test location and the orientation of its gridline is shown in Figures 2a to 2d.

Stable results were obtained for the beams and most of the columns (with sound concrete) which ranged from 3.20 to 3.61 km/s. UPV Test on Column C2 [UPV 3] and Column C6 [UPV 5] gave very low average reading, which were 1.64 and 0.90 km/s, respectively. These very low results suggested that there could be excessive voids between the two transducers, either caused by the poor compaction of concrete or the concrete are beginning to experience internal separation. In general, the results of these tests show that the concrete samples were in good condition, except for the Columns C2 and C4 where the reading shows very low value. The results of UPV Test are presented in Figures 8a and 8b.

Figure 7a. UPV Test on Beam B4

Figure 7b. UPV Test on Column C2

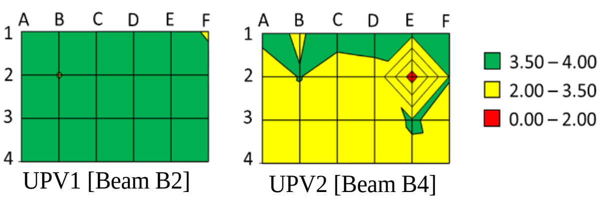

Figure 8a. UPV Test for Beams [km/s]

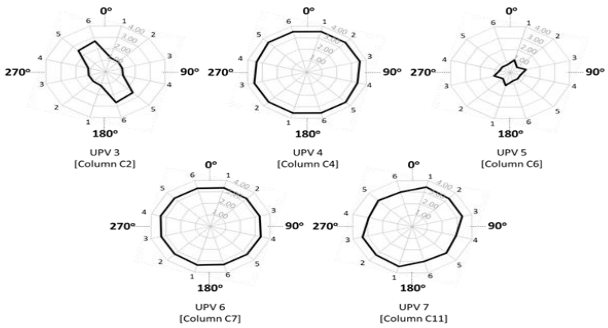

Figure 8b. UPV Test for Columns [km/s]

Ferroscan Pachometer Survey

A total of seven locations were surveyed over the columns and beams in the immediate proximity of concrete core locations (Figure 9a). Reinforcing steel bars configurations detected with the Ferroscan instrument were used to determine core locations. Two scans were conducted within the beams, while the five remaining were conducted on randomly selected columns. Results of the survey indicated reinforcement arrangements.

Concrete Core Sample Extraction (ACI 214.4R-10 [7])

Eight concrete core samples were collected using wet rotary diamond core drilling techniques on the Bridge beams and columns at selected locations (Figure 9b). Concrete core samples were visually examined and photographed prior to concrete laboratory testing. Concrete Core Data Logs are presented in Table 2. Concrete core holes were patched with shrinkage compensating repair mortar subsequent to sample collection

Figure 9a. Pachometer Survey on Column C3

Figure 9b. Core Sample Extraction on Column C4

Table 2. Concrete Core Data Logs

Core ID	Extracted From	Dimensions L (mm)	Dimensions D (mm)	pH Reading	Compressive Strength	Aggregate Characteristics	Top Surface	Bottom Surface	Other Remark	Core Photo
C-1	Beam B1 0° View	170	69	9-11 Top 15mm	36.30 N/mm^2	Granite max aggregate size 25mm	Smooth Surface	Fractured Surface	Few Voids noted along the core (max diameter of void ~22mm)	
C-2	Column C3 0° View	86	69	9-11 Top 20mm	32.53 N/mm^2	Granite max aggregate size 15mm	Smooth Surface	Fractured Surface	Few Voids noted along the core (max diameter of void ~3mm)	
C-3	Column C4 270° View	70	69	11-13 Throughout	Not Tested	Granite max aggregate size 20mm	Smooth Surface	Fractured Surface	Fracture cracks and few voids noted along the core (max diameter of void - 3mm)	
C-4	Column C6 180° View	85	69	11-13 Throughout	Not Tested	Granite max aggregate size 25mm	Smooth Surface	Fractured Surface	Fracture cracks and few air voids noted along the core (max. size - 6mm dia).	
C-5	Beam B3 0° View	175	69	9-11 Top 15mm	34.71 N/mm^2	Granite max aggregate size 30mm	Smooth Surface	Fractured Surface	Few air voids noted (max. size - 6mm dia)	
C-6	Column C7 270° View	86	69	9-11 Top 30mm	31.07 N/mm^2	Granite max aggregate size 20mm	Smooth Surface	Fractured Surface	Few air voids noted (max. size - 10mm dia)	
C-7	Column C11 270° View	55	69	13 Throughout	Not Tested	Granite max aggregate size 20mm	Fractured Surface	Fractured Surface with Rust Stain	Few air voids noted (max. size - 5mm dia)	
C-8	Column C7 180° View	65	69	11-13 Throughout	41.10 N/mm^2	Granite max aggregate size 20mm	Spalled Surface	Fractured Surface	Few air voids noted (max size - 3mm dia)	

Laboratory Tests

Laboratory testing on extracted concrete core samples included Carbonation Depth Determination, Compressive Strength of Concrete Cores, and Water Soluble Chloride Ion Content of Hardened Concrete (powder samples extracted from core samples).

Carbonation Depth Determination

pH color indicating solution ("Rainbow Indicator") results indicated pH values between 9-11 and 9-13 for beams and columns, respectively. The higher the pH value indicates the more alkaline the concrete is. Carbonation depths are denoted on the concrete Core Logs presented in Table 2. Carbonation was detected throughout the Core C-3, C-4, and C-8. No Carbonation was found on Core C-7, while the rest of the cores indicated 15mm to 30mm from the top surface.

Compressive Strength (ASTM C-42 [8])

Compressive strength tests were performed on five cores of laboratory quality. Results of the compressive strength tests on submitted cores ranged from 34.59 to 43.10 N/mm^2. Information on sample selected for testing and test results are shown in the concrete core logs presented inTable 2.

Water Soluble Chloride Ion Content (ASTM C-1218M [9])

Water soluble chloride ion (Cl^-) tests were performed on six concrete powder samples extracted from the core samples, between 0 to 100mm below the surface of the concrete for the beams, and 0 to 25mm for the columns (due to short length of cores). Results from chloride tests are expressed as a function of the weight of concrete samples or, assuming 15% of cement content, water-soluble chloride (Cl^-) is computed as a percentage by weight of cement. Water soluble chloride percentage for beams ranged from 0.27% to 0.53% (by weight of cement) and 0.27% to 3.07% for columns. A maximum threshold limit of 0.15% is recommended by ACI (ACI 222R-01 [10]). The tabulated results for water soluble chloride ion content test is presentedin Figure 10.

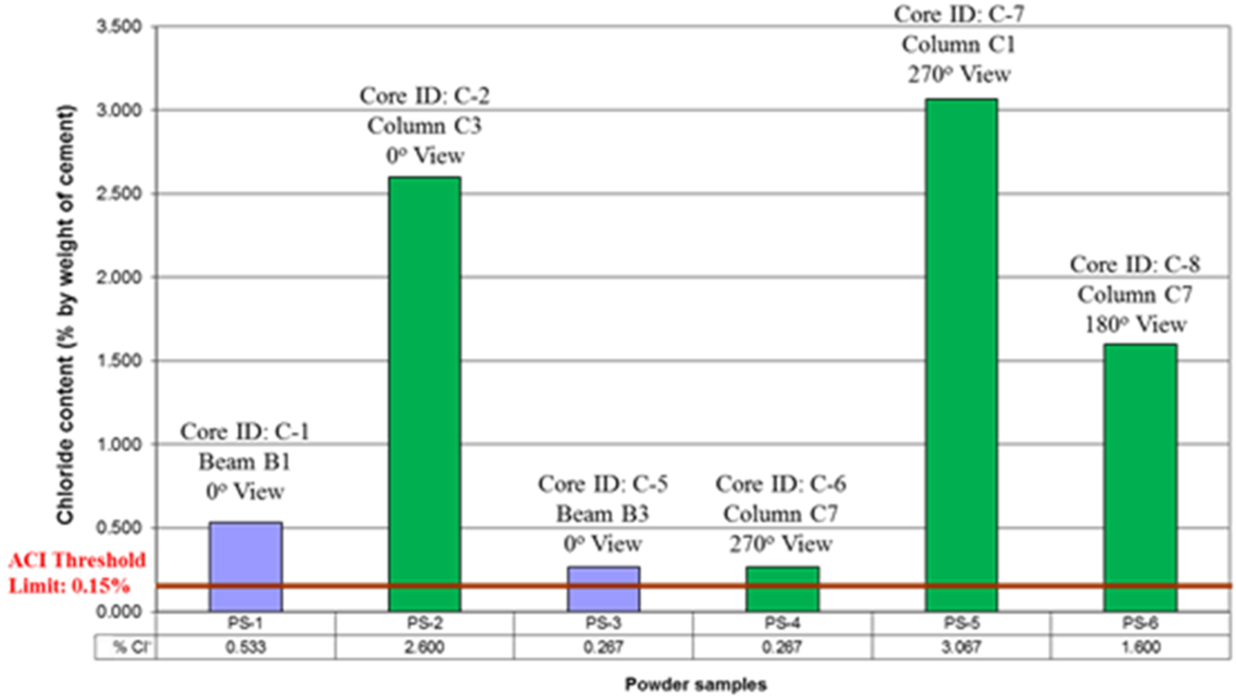

Figure 10. Tabulated Results for Water Soluble Chloride Ion Content Test

Analysis

The analysis of the reinforced concrete structure is presented in the following sections.

Concrete Material Properties

Compressive strength results for five concrete cores indicate that concrete strength ranges from 34.59 to 43.10 N/mm^2 with an average of 39.50 N/mm^2. The American Concrete Institute (ACI) allows extracted concrete core samples, subjected to laboratory compression testing, to represent 85% of the design compressive strength due to the destructive nature of the core extraction process (ACI 318R-05 [12]). Based on ACI guidelines, the average compressive strength value exceeds 46 N/mm^2.

Rebound Hammer conducted on the structures revealed relatively consistent concrete material properties. In general, testing data revealed that the concrete can be considered to be generally uniform in terms of quality. "Bad" condition concrete is found on some locations of Column C2 and C6, where the UPV tests show very low readings. Carbonation detected in the subject structure was within the concrete cover. Hence, concrete material carbonation does not appear to be a significant contributor to the observed distress at the subject structure.

Corrosion Survey (ACI 222R-01 [10])

Concrete powder samples extracted from the concrete cores were tested for water-soluble chloride ion (Cl^-) content. Water soluble-chloride ion content for the column and beam is found to be in the range of 0.27% to 3.07% which exceeds the recommended ACI threshold by approximately 20 times. Corrosion of reinforcements in the subject structure is likely caused by such high content of chloride ion in the concrete. From the exposed rebars and spalled concrete areas found in columns, it was noted that the reinforcement was badly corroded and the entire cross sections were almost gone. Rust stain and internal cracks and rust stains were also found in the core holes (Figure 11)

The concrete cover for column ranged from 40 to 90mm, whereas the concrete cover for the beam was noted to be approximately 40mm. However, some localized areas exhibited concrete spalling due to corrosion with concrete cover of approximately 10mm only. From the water stain found on the columns during the site investigation, it is noted that the tidal splash zone covers approximately 1300 to 1400mm column height and it is these areas that exhibit the most severe concrete damage.

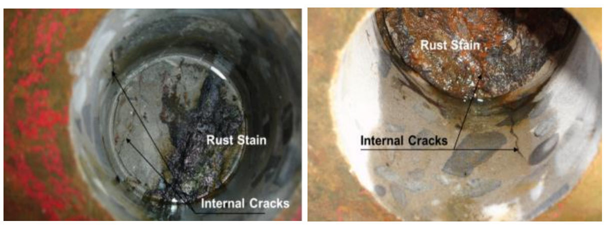

Figure 11. Rust Stain and Internal Cracks Found Inside the Core C-4 and Core C-3 in Location on Column C6 and Column C4, respectively.

Concluding Remarks

A detail and comprehensive condition assessment on the deteriorated reinforced concrete bridge is presented, which includes Visual Inspection, Non-Destructive Tests (Acoustic Impact, Rebound Hammer, Ultrasonic Pulse Velocity), and Laboratory Tests on the extracted concrete core samples (Carbonation Depth, Compressive Strength, and Water Soluble Chloride Ion Content). Based on the results obtained from this assessment, the bridge columns were found to be in a bad condition. The steel reinforcement corrosion was found to be the major cause of the deteriorations. An emergency repair program is required to prevent further progressive deteriorations which will lead to a structural at-risk scenario.

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