

Reliability Assessment of Bridge Decks: A Case Study of Three Bridges Along Lagos – Ibadan Expressway.

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Abstract

The ageing and gradual deterioration of bridges in Nigeria needs balancing of cost-effective plans for bridge maintenance, rehabilitation and replacement. This research aims at assessing the reliability of bridges using three existing highway bridges along Lagos-Ibadan expressway as a case study. Visual inspection, sounding, half-cell potential and chloride concentration tests were utilized to evaluate the conditions of the bridges. Deteriorations were observed on the decks' surfaces. The level of corrosion on one deck was active and uncertain in the remaining two. The chloride concentrations on all the decks were within AASHTO standards and only one of the decks had delaminated. The results revealed that none of the decks needs total replacement but all require some form of rehabilitation.

Keywords

Bridge decks, corrosion, delamination, deterioration, rehabilitation, reliability.

1. Introduction

A bridge is a structure designed to provide a continuous passage over an obstacle, bridges commonly carry highways, railroad lines, and pathways over obstacles such as waterways, deep valleys and other transportation routes. Bridges are the most critical yet vulnerable elements in highway transportation networks because they are constantly being exposed to aggressive environments and are facing ever increasing traffic volumes and heavy truck-loads.

According to Min Liu and Frangopol (2006), the failure of a bridge can cause enormous adverse impacts locally to the bridge site and also globally to the transportation network. It can lead to disruption of normal traffic flows, leading to reduced network accessibility and increased user costs in terms of travel delay, detour, and extra vehicle fuel consumption as well as accidents.

Unlike in the developed countries of the world, where various researches, works, tests, and repairs are frequently done on existing traffic structures including bridges, there is little or no record about bridges in Nigeria and obvious deteriorations manifest in them. The ageing and gradual deterioration of bridges in Nigeria needs balancing of cost-effective plans for maintenance, rehabilitation and replacement. As a result of the deplorable condition of the traffic infrastructures in Nigeria, there is need for the assessment of the level of damage done to the bridges so as to classify them according to the level of repair required, hence there is a need to carry out the reliability assessment of the bridges. Reliability assessment of a bridge is the evaluation of the strength and dependability of the bridge; it is equivalent to the measurement of probability of failure of the bridge at a particular period of time.

Hamby (2003) modelled the behavior and response of structural system of South Carolina Highway bridges using SAP 2000 as the main modeling program. He noted that three factors are the main contributors to the accuracy of the bridge models. These factors include the material properties, load distribution and member end continuity. Based on these factors, Hamby proposed a number of recommendations to follow for the creation of the models. Anderson (2004) refined the data collection, testing and analysis processes of Hamby, and generated practical user manuals. These manuals provide the procedures for bridge testing, data collection and computer modeling.

Aschermann (2005) presented two different testing approaches that could be utilized in determining the health and capacity of bridges; long-term monitoring systems and live-load testing. Long-term monitoring systems can be configured for tracking dead load quantities such as cracking width openings or pier rotations over

time, or for recording the live-load structural responses such as random truck passages and wind gusts. It can also be used to track parameters that change slowly such as concrete creep or even live load induced deterioration. Live load test can be used for confirmation of predicted responses caused by super loads.

Phares (2005) presented two case studies of the diagnostic load testing system. Typical steel girder highway bridges were tested and rated and the bridges tested during the passing of a super load. Two runs for each load path was recommended to verify the consistency of the data. Diagnostic load testing was used to accurately determine the ability of a bridge to carry super loads and identification of a bridge's "reserve" strength was observed to cause a delay in bridge rehabilitation or replacement, which can result in significant, long-term cost savings.

Mondal (2005) discussed nondestructive field monitoring evaluation of three bridges; a precast, segmental box-girder bridge, a cast-in-place, curved post-tensioned bridge, and a continuous, curved steel box-girder bridge. The study aimed at understanding how continuous monitoring can be used in the management of bridge infrastructure and it revealed that field monitoring led to a reduction in the scope of planned renovations and replacements, although there were cases in which monitoring has confirmed the necessity for immediate repairs. The direct savings in both expenses and time from the short-term studies have been substantial.

Farhey (2005) developed a computer-controlled virtual instrumentation system with multiple-channel wireless site network for bridge testing and evaluation. The system was devised for static and moving-load field experimentation or long-term health monitoring using various types of electronic sensors. Sensor data was transmitted by individual wireless transceiver units to a wireless base station connected via a standard USB connection to a laptop computer. The virtual wireless infrastructure evaluation system (WISE) enabled testing a bridge in less than a day, minimizing traffic closure and, thus reducing public cost.

In contrast to other parts of a bridge, evaluation of bridge deck requires some level of difficulty because the concrete slabs are inaccessible to both sides at the same time, the asphalt coating may have variable thickness within the same deck and the thickness of delamination being sought for is small. In addition, some methods of evaluation require closure of lanes during investigation operation. Hence, deck slab requires special attention for damage assessment and repair at early stage. The damages that are common problem in concrete deck are cracking, leaching, scaling, spalling, corrosion of reinforcement, poor quality concrete, and delaminations (Khalim et al, 2011).

This study examined the decks of three overhead concrete bridges along Lagos-Ibadan Expressway with their various conditions. The selected bridges were: Iwo-road, Saw-Mill and Oremeji bridges all within Ojoo and Challenge areas in the ancient city of Ibadan. The bridges were built in 1976. Inspection reports from these bridges were used in conjunction with the results of non-destructive testing to establish the condition and corrosion potential of the bridges. Depending on the extent and the severity of deterioration manifested on each bridge deck, a recommendation to prevent, rehabilitate or replace each tested bridge is provided.

2. Method

The non-destructive testing methods used were to evaluate the carrying capacity of the bridges. The reliability assessment methods used in this research included Visual Inspection, Half-Cell Potential Testing, Sounding Hammer/Chain Testing, and Chloride Concentration Testing. The data generated were analyzed along with the present age of each bridge deck to model some *Equations of Reliability* in order to predict the future performance of each deck. An area of 1.8m by 1.8m was randomly selected on the surface of each deck within the single lane for the tests. The testing methods followed ASTM standards.

2.1 Visual Inspection

The bridge decks were inspected for any noticeable potholes, exposed reinforcement, scaling and cracking. The data generated within each of the six test areas on each bridge deck were recorded. If a protective overlay only existed on the deck, crack data were not collected because the overlay masked the true condition of the underlying concrete. However, potholes data were collected in this situation since a pothole is likely to be observed even if an overlay is present. The presence of scaling, efflorescence or exposed reinforcement was also noted on the visual inspection survey form, although no calculations were performed using these data.

2.2 Sounding

Sounding is the process of locating areas of the deck where delamination has manifested or where a portion of the surfacing has become detached from sub-surface. Delamination typically results from volume-expanding corrosion of the steel reinforcement within the deck. Two forms of sounding - *chain dragging* and *hammer sounding* were carried out in each of the test areas, Chain dragging which involved the dragging of an ordinary steel chain over the surface of the bridge deck while listening for changes in the acoustical response was used to determine the likely locations of delamination. Normal deck surface exhibits a clean and clear acoustical sound, while delaminated surface produces a dull hollow sound. After a delamination was detected using chain dragging, hammer sounding was performed by repeatedly striking the bridge deck surface with a hammer while listening to the acoustical response. The size of the delamination was then recorded on the sounding survey form. If thin overlay exists on a bridge deck, sounding can still be effectively performed but the detected delaminations can either be within the underlying concrete or result from detachment of the overlay from the concrete layer. The testing methods followed ASTM standards.

2.3 Half-Cell Potential Test

Half-Cell Potential test was carried out by connecting the negative terminal of the half-cell potential voltmeter to the already exposed reinforcement, while the positive terminal was connected to the

reference electrode. The concrete was sprayed with aqueous solution of copper sulphate (CuSO_4) before the testing to ensure adequate electrical coupling in the setup.

2.4 Chloride Concentration Test

This involved the field sample collection and laboratory testing. The test method for water-soluble chloride in mortar and concrete according to ASTM standards were used to determine the chloride concentration of each sample. This method requires that sample particles which were obtained through the use of the hammer drill in the field passed through a No. 50 (0.046mm) screen. Water was added to the dry samples, and the mixtures were then boiled for 5 minutes and subsequently cooled for 24 hours. Filtration was used to separate the soluble chloride ions from the pulverized concrete particles, and the solution was treated with 3 ml of nitric acid followed by 3 ml of hydrogen peroxide. The solution was again heated, but just until boiling, and then cooled for an additional 24 hours before a laboratory chloride-ion selective probe was used to determine the chloride content of the solution.

3. Results and Discussion

The collected data were used to calculate values in the categories of visual inspection, sounding, half-cell potential, and chloride concentration. The procedures for each of the data together with their relevant threshold values are subsequently discussed.

3.1 Visual Inspection Data

The type, severity, and location of visual distress were recorded on distress survey forms for the three decks tested. If polymer overlay is present throughout the surface of any bridge deck, cracks are believed to be masked by the protective overlay and therefore information on cracks was not obtained. Calculated visual data include crack width, crack severity, and crack density. Crack severity is a function of the average crack width; the cracks were classified as hairline, narrow, medium, or wide based on the widths given in Table 1. Pothole density was calculated by dividing the surface area of potholes by the entire test area. Crack data and crack severity are summarized in Table 2. For parameters resulting from

repeated measurements, the average and standard deviation were computed for each deck and are shown in the appropriate tables. In all cases, a hyphen indicates that a measurement could not be obtained or is not applicable.

Although crack severity, crack density, pothole size, and pothole density currently have no established, universally accepted threshold values, it was suggested that action should be taken if the average crack width is greater than 1.6mm and moderate crack density or efflorescence in the vicinity of the cracks exist. In addition, the deck should be replaced if 10 to 50 percent of the deck is affected by potholes (AASHTO, 1999). Compared to these thresholds, the data collected in this research suggested that none of the three bridge decks would need replacement as crack widths were less than 1.0mm and there were no potholes on the deck.

Table 1 Crack width categories

Category	Crack Width (mm)
Hairline	< 0.1016
Narrow	0.102 to 0.254
Medium	0.254 to 0.762
Wide	> 0.762

Table 2 Crack width, severity and density

Deck location	Crack Width		Crack Severity	Crack Density (cm/m ²)
	Average (mm)	Std. Deviation (mm)		
Bridge 1 @ Iwo- Road	0.863	0.533	Wide	39.00
Bridge 2 @ Saw-Mill	0.330	0.152	Medium	67.44
Bridge 3 @ Oremeji	0.432	0.229	Medium	73.27

3.2 Sounding Data

From the sounding data collected (Table 3), the average delamination size was calculated in millimeter square, and delamination density in millimeter square per square meter of test area. As with visual distress, no universally accepted threshold values exist for delaminations. However, maintenance action is suggested if 5 to 10 percent of the deck is affected. Compared to these thresholds, the data suggest that no maintenance is presently required for delaminations on any of the three decks.

3.3 Half-Cell Potential Data

Half-cell provides a reliable indicator of corrosion activity, although the rate of corrosion cannot be quantified. Based on the states of corrosion defined in Table 4 and the average half-cell potential measurements obtained in the research, each of the tested decks is rated in Table 5.

Table 3 Sounding data

Bridge ID.	No. of Delaminations	Delamination Size		Delamination Density (mm ² /m ²)
		Average (mm ²)	Std. Dev. (mm ²)	
Bridge 1	0	-	-	0.000
Bridge 2	1	18.60	-	0.926
Bridge 3	0	-	-	0.000

Table 4 Half-Cell potential threshold values for corrosion

Half-Cell Potential (V)	State of Corrosion
< -0.35	Active
-0.35 to -0.20	Uncertain
> -0.20	Inactive

Table 5 Half-Cell potential data

Deck ID.	Half-Cell Potential (V)		State of Corrosion
	Average	Std. Dev.	
Bridge 1	-0.33	0.17	Uncertain
Bridge 2	-0.39	0.10	Active
Bridge 3	-0.34	0.07	Uncertain

3.4 Chloride Concentration Data

The chloride concentration in units of pounds of chloride per cubic yard of concrete was calculated in this study at the depth of the top of the reinforcement, which is the shallowest location at which corrosion may begin. The chloride concentration at this depth was calculated at each test area by linear interpolation between laboratory-determined chloride concentrations above and below this point. The accepted chloride concentration threshold for corrosion initiation of black bar is 1.186 Kg per m³ as specified by the Federal Highway Administration (see Tables 6).

Table 6 Chloride concentration data

Deck ID.	Cover		Chloride Concentration (Kg/m ³ Concrete)	State of Corrosion
	Average (mm)	Std. Dev. (mm)		
Bridge 1	58.42	12.45	0.0007	Inactive
Bridge 2	43.18	7.87	0.0005	Inactive
Bridge 3	73.66	10.92	0.0000	Inactive

3.4.1 Correlation and Regression Analysis

A full correlation analysis was performed to investigate the relationships between variables associated with deck damage. Developing a model to predict damage before it manifests on the deck would particularly facilitate preventive maintenance treatments. A model was developed to approximately predict any future deterioration of any of the three bridges. Practically, there is high degree of correlation between the damage variables and the lifespan of bridge decks i.e. the greater the life of service of bridge decks, the higher the level of deterioration if other factors are constant. The relationship can be reasonably and practically be assumed to be linear with no deterioration at the first or initial stage of the bridge deck. Linear regression was used to develop equations relating each of the damage variables to the ages of the respected bridge decks.

3.5 Model Equations for Bridge 1 (Iwo-Road)

a) Cracks:

Equation of a Straight line ($y = mx + C$). But $C = 0$, because at initial stage, deterioration is negligible, Therefore, $y = mx$. Consider the present number of years of the bridge deck, (1976-2012). At $x = 36$ yrs, $y = 39.00 \text{ cm/m}^2$, $m = 39/36$ and

$$y = (39.00x / 36) \text{ cm/m}^2 \quad (1)$$

where $x =$ number of years and $y =$ a general equation for future crack analysis.

(b) Half-Cell:

$y = mx + C$, but $C = 0$; at $x=36$ yrs, $y = -0.33 \text{ V}$, $m = -0.33/36$. Generally,

$$y = - (0.33x / 36) V \tag{2}$$

where V= Half-cell potential and y = The equation for future deterioration.

(c) Chloride Concentration:

y = mx+ C, but C=0 because deterioration is negligible initially
 y = mx, at x=36yrs, y = 0.0007 kg/m³ Concrete m = 0.0007/36,
 Generally,

$$y = (0.0007x / 36) \text{ gram/m}^3 \tag{3}$$

The equation governing future Chloride analysis.

3.6 Model of Equations for Bridge 2 (Saw-mill)

(a) Cracks:

y = mx + C, but C=0 because deterioration is negligible at initial stage. Therefore, y = mx. Considering the present number of years of the bridge deck, (1976-2012), At x = 36yrs, y = 67.44 cm/m²;
 m = 67.44/36,
 y = 67.44x /36 cm/m² \tag{4}

A general equation for future crack analysis.

(b) Sounding:

y = mx + C, but C = 0; at x=36yrs, y = 0.926 mm²/m²;
 m= 0.926 / 36; generally,
 y = (0.926x / 36) mm²/m² \tag{5}

The equation for future delamination density.

(c) Half-Cell:

y = mx + C, but C = 0; at x=36yrs, y = -0.39 V, m= -0.39/36.
 Generally,
 y = - (0.39x / 36) V \tag{6}

The equation for future deterioration.

(d) Chloride Concentration:

y = mx+ C, but C=0 because deterioration is negligible initially
 y=mx, at x=36yrs, y =0.0005 Kg /m³, m = 0.0006/36. Generally, y
 = (0.0006x /36) gram /m³ \tag{7}

The equation governing future Chloride analysis.

3.7 Model of Equations for Bridge 3 (Oremeji)

(a) Cracks:

$y = mx + C$; but $C=0$ because deterioration is negligible at initial stage. Therefore, $y = mx$

Considering the present number of years of the bridge deck, (1976-2012). At $x = 36$ yrs, $y = 73.27 \text{ cm/m}^2$; $m = 73.27/36$, & $y = (73.27x / 36) \text{ cm/m}^2$ (8)

A general equation for future crack analysis.

(b) Half-Cell:

$y = mx + C$, but $C = 0$; at $x=36$ yrs, $y = -0.34 V$, $m = -0.34/36$.

Generally,

$y = - (0.34x / 36) V$ (9)

The equation for future deterioration at x number of years of service of the deck.

3.8 Modelling of General Equations for Reliability

Assessment

In this research, four major research methodologies were used namely: Visual Inspection (25%), Sounding test (25%), Half-Cell Potential test (25%) and Chloride Concentration (25%). To evaluate the reliability of a deck based on these four methodologies, the reliability of the deck (in %) in each of the methodologies should be obtained and subsequently added to get the total or actual reliability of the deck (AASHTO, 2002). Table 7 shows the bridge treatment category. The general reliability assessment equation can be obtained by interpolation and simplification of the *AASHTO standards*, the actual evaluation of each bridge deck under each deterioration test were added together to get overall Reliability.

Table 7 Bridge treatment categories

Reliability	Recommendation
80% & above	Preventive
between 50% & 80%	Rehabilitation
< 50%	Replacement

3.9 Example of Bridge Deck Computation

Bridge 1 @ Iwo-Road:

3.9.1 Cracks Evaluation

Average Crack Width = 0.864 mm
 If Crack Density = 39.00cm/m² over an area of 2.0064 x 10⁷ mm². Then, Average Crack length = 7827.264 mm
 Area of Cracks = (0.864 * 7827.264) = 6762.756 mm²
 Percentage Cracks = (6762.756 / 20064000)*100 = 0.0337 %

3.9.2 Pothole Evaluation

Percentage Pothole over a total area of 2.0064 x 10⁷ mm² = 0 % = Pph % (since there is no pothole)

3.9.3 Delamination Evaluation (Sounding Test)

Percentage of Delaminated surface over a total area of 2.0064 x 10⁷ mm² = 0 % = Pst % (since there is no Delaminated Surface)

3.9.4 Half-Cell Potential Evaluation

Average Half-Cell Potential = Phc = -0.33 Volt

3.9.5 Chloride Concentration

Average Chloride Concentration = Pcc = 0.0007 Kg/m³
 All the above estimated evaluations are substituted into the Equation 10 to get the overall Reliability of Bridge 1. The remaining bridge decks are estimated in this same way to obtain their final Reliability (Table 8)
 Reliability (%) = Rcc (%) + Rhc (%) +Rst (%) +Rph (%) + Rct (%)
 or

$$\text{Reliability}(\%) = 100 - 12.50(Pcc + Pst) + 69.44Phc - 0.25(Pph + Pct) \tag{10}$$

Table 8 The actual bridge deck reliability evaluation

Deck ID	Reliability	Recommendation
Bridge 1 @ Iwo-Road	77%	Rehabilitation
Bridge 2 @ Saw-Mill	72%	Rehabilitation
Bridge 3 @ Oremeji	76%	Rehabilitation

4. Conclusion and Recommendations

The level of deterioration suffered by concrete bridge decks might vary due to many factors such as: varying rolling vehicular loads using them, number of years of service of concrete bridge decks, etc. While standards or threshold values for various non-destructive condition assessment methods were already established by earlier research, this work focused on their application to be able to evaluate the strength of three concrete bridge decks. It also focused on the statistical and analytical generation of some equations which can be applied for future assessment of the three concrete bridge decks under study.

Deteriorations such as cracks, potholes, poor expansion joints, damaged and blocked water drains, exposed reinforcement, damaged side rails, etc observed on the reinforced concrete bridge decks were due to poor maintenance. Half-Cell potential test showed that the level of corrosion in one of the concrete bridge decks is active while uncertain in other two. Chloride concentration test revealed that level of concentration in the concrete bridge decks has not exceeded the limiting standard value specified by AASHTO (i.e. 1.18657 Kg/m^3 Concrete). Sounding test revealed that only one of the concrete bridge decks has delaminated.

Various deterioration coefficients of the three bridge decks over years were derived. The derived coefficients give the approximate level of deterioration at any year. Also, the three bridge decks were eventually evaluated and rated. None of the three bridge decks evaluated requires total replacement but only some level of rehabilitation. It is hereby recommended that some rehabilitation works such as provision of cover to all the exposed reinforcements are required urgently to keep the concrete bridge decks in good condition. In addition, regular assessment of bridge decks should be done to have an idea of the kind of maintenance required from prevention, rehabilitation to total replacement.

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