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Full Length Research Paper

Serviceability of concrete bridges in Malaysia focusing on susceptibility to atmospheric chloride corrosion

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This paper identified the common damage types found in concrete bridges with special reference to chloride corrosion from recent inspection results on three concrete bridges owned and operated by three different organizations in Malaysia. The approach was to determine the serviceability of the concrete bridges resulting from deterioration and damage. The causes and resulting impact on serviceability were presented and methods to minimize the impact were proposed. Inspection standards, types of deterioration, methods to determine the extent of the deterioration and damage were studied and compared between the three examples. Chloride attacks were found to be a common natural cause for deterioration. Quality of construction materials and structural design were found to be in other areas which could be improved. The state of serviceability of the cases was average. More frequent scheduled inspections by skilled inspectors and proper maintenance work would further improve the overall management of these bridges.

Key words: Chloride corrosion, common damage type, concrete bridge, structural reliability, test procedure.

INTRODUCTION

A bridge would need to be inspected regularly and frequently to ensure that it would always be in a safe condition for use to prevent premature failure (Akib et al., 2011; Jumaat et al., 2011). A concrete bridge could maintain its serviceability for more than a hundred years if it was properly maintained. Although, catastrophic failures seldom occurred, it would be necessary to take steps to ensure integrity and safety at all times. Inspection surveys must be done and corrective actions taken immediately. Corrosion and loss of section is the most common type of problem (Ng and Muhamud, 2009). Worldwide, there had been a great number of bridge failures. This had been due to ageing and inadequate resources for operation and maintenance. There had been a shift in focus of attention and priority from constructing new bridges to maintaining existing ones.

Damage type

One of the important factors examined during a bridge inspection is the type of damage encountered. Specific management systems had been developed in different countries for the domestic use. Some systems were also developed at the state and regional levels like those in Texas and Indiana. There were also specific systems developed for bridge management in a rural environment and other situations as described by Gralund and Puckett (1996).

System reliability

The threshold chloride concentration to initiate corrosion is 0.15% soluble chloride (Hansson and Sorensen, 1998).

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Table 1. Bridge owners in Malaysia.

Route	Authority/Owner	No. of bridges	Notes
Federal-Peninsular	JKR Federal	>7000	Include culverts
KTMB	KTMB	>920	Exclude culverts
Federal-Sarawak	JKR Sarawak	>890	Include culverts
Federal-Sabah	JKR Sabah	>780	Include culverts
Toll highway	LLM/JKR/DBKL	>560	Exclude culverts
DBKL	DBKL	>225	Include culverts

Hydroxide ions protect steel from corrosion. The threshold in terms of the ratio of chloride content to hydroxide content, [Cl^-] / [OH^-] is between 2.5 to 6. Presenting the chloride threshold level as chloride to hydroxyl concentration ratio in the pore solution of concrete would be an improvement over the more commonly used total chloride content (Glass and Buenfeld, 1997). It was found by Li and Sagüés (2001) that active corrosion for all three surface conditions took place in the pH 12.6 saturated calcium hydroxide ($Ca[OH]_2$) solution (SCS) and pH 13.3 SPS1, when the [Cl] reached threshold levels. Studies on atmospheric chloride contents around Kuala Lumpur were conducted by Mustafa and Yusof (1994) and Sulaiman et al. (2005). Loto et al. (2011) evaluated the inhibition of potassium dichromate on the corrosion protection of mild steel embedded in concrete at ambient temperatures. Non-destructive evaluation for bridge management and time-variant reliability of reinforced concrete bridges under environmental attack had been examined (Enright, 1998; Ismail et al., 2011).

Bridges in Malaysia

There are only about 10,000 bridges in Malaysia. There are four parties or corporations who own and are responsible for the design, operations and maintenance of bridges, namely; the Public Works Department (JKR), which is a department within the Ministry of Works; the Malayan Railways (KTMB), which is a privatized government corporation; the Kuala Lumpur City Council (DBKL), which is associated with the Ministry of Local Government; and the Malaysian Highway Authority (LLM), which is part of the Ministry of Transport. Table 1 shows the breakdown of these bridges according to the owners and operators.

Inspection standards

A systematic program of intrusive and non-destructive test (NDT) inspection and maintenance of bridges is critical in order to determine the type and extent of damage. It could involve visual examination against a standard check-list or based on a standard manual issued by an authority like the JKR (JKR, 2003; Ng, 2000; Ng et al., 2000). A data model was developed to support automated imaging inspection of concrete bridges by utilizing a framework for an automated bridge inspection methodology (Abudayyeh et al., 2004).

Structural deterioration

Damage can be due to chemical attack, cracking, spalling, reinforcement corrosion and scouring. Rafiq et al. (2004) pointed out that uncertainties associated with modeling of deteriorating bridges can be reduced by the effective use of health monitoring systems. Reliability-based prediction of chloride ingress and reinforcement corrosion of aging concrete bridge decks was investigated by Amleh et al. (2002). Embedded system of fibre-optic sensors had also been developed for *in-situ* applications (Stewart and Rosowsky, 1998). Uncertainty modeling of chloride contamination and corrosion of concrete bridges and prediction of onset of corrosion in concrete bridge decks using neural networks and case-based reasoning was carried out by Lounis (2005). Sensitivity analysis of simplified diffusion-based corrosion initiation model of concrete structures exposed to chlorides was conducted by Zhang and Lounis (2006).

MATERIALS AND METHODS

Three examples were taken, involving three different owners and operators. Inspection standards provided by JKR were examined and utilized to evaluate the health conditions of each bridge. Essentially, the documents consist of operating instructions, inspection procedures test methods and standards. The types of deterioration and damage were noted, and methods to determine the extent of the deterioration and damage were studied. *In-situ* tests, visual inspection and laboratory tests were common methods of evaluation of deterioration and damage of concrete bridges. Superficial inspection is unscheduled and carried out whenever an opportunity arises. Principal inspection is intensive and scheduled. Special inspection is carried out for unusual circumstances which may include elements of research. This study may be considered as a special inspection. An inspection could be for the purpose of data collection, inventory audit and condition check. Ratings ranging from 0 to 5, similar to those practiced in other countries are used to evaluate the health conditions of bridges. Zero would mean inability to access the damage area, 1 signifies no damage, 2 means

Table 2. Summary of types of damage for each bridge.

Type of damage	Endau-Mersing	Seberang Perai	Mahameru road
Chloride corrosion	Severe	Fair	Not Indicated
Honeycombing	Severe	Not Indicated	Not Indicated
Cracks	Not Indicated	Servere cracks	Not Indicated
Rust staining	Not Indicated	Fair	Not Indicated
Mould growth	Not Indicated	Fair	Not Indicated
Mechanical damage	Not Indicated	Not Indicated	Fair
Overall Impact	Fair	Serious	Minimal

means slight damage, 3 indicates slightly critical, 4 being critical and 5 means heavily damaged which affects safety and requires immediate attention. Maintenance practices nationally and internationally were examined. Maintenance inspections involve simple cleaning, removal and replacements of damaged components, minor restoration work, localized repair and water-proofing, localized painting to prevent corrosive gas ingress and lubricating and greasing. Inspection equipment requirements include measuring equipment, recording equipment, safety equipment and access equipment. The procedures to be followed before an inspection exercise are planning, execution and preparation of a check-list. A report is finally prepared. Reports from owners and contractors on the maintenance and inspection of subject bridges were analyzed. Discussions with owners and consultants from the industry and academia were made. Visits and personal inspection and observation of the bridges were also made to gain first-hand knowledge.

RESULTS AND DISCUSSION

Three concrete bridges owned and operated by different organizations follow, giving examples of damage and corrective actions taken on each case. They were undertaking inspection and repair work at about the same time. The summary of the types of damage for each bridge is given in Table 2.

Endau-Mersing (JKR)

The Endau-Mersing bridge could be considered to be sited practically by the sea. It is situated a few kilometers from the South China Sea on the East Coast of Peninsular Malaysia, spanning across the Endau river in the district of Rompin, Pahang. The surrounding environment could be considered as near-coastal and rural with thin forest land. This bridge is 397.32 m long and was built in 1974. The type of construction was pre-stressed concrete. Laboratory tests following the JKR guidelines were carried out on the concrete, soil and water samples from the surrounding area to determine the level of chlorides. The test method used for the determination of chlorides in water was ASTM D4327 and for chlorides in soils and concrete was ASTM D1411-09. *In situ* tests carried out included the test for the surrounding and surface water. The test on the concrete sample indicated that the chloride levels were beyond the threshold limit for corrosion. It was categorized as serious as the depth of the affected zone had gone beyond the concrete cover. Repair on the bridge was done by the bridge division of the JKR. It was found that for this bridge, the columns experienced severe corrosion and honeycombing. This is exceptional as compared to the other bridges investigated. Pore lining treatment was carried out together with cover by silane and siloxine to reduce the absorption of moisture, chloride ions and carbon dioxide. There was no indication of any cracks or rust-staining and there was no mechanical damage detected. Overall, conditions of the bridge were considered fair. The rating could be considered to be between 1 and 2 requiring minor restoration and localized repair.

Seberang-Perai (KTMB)

The Seberang-Perai bridge is located a few kilometers from the sea. The bridge could be considered practically by the sea being about 5 km from the Straits of Melaka on the West Coast of Peninsular Malaysia and was built in 1967 as a swing bridge to allow boats to pass under it. The surrounding environment could be considered as near-coastal and rural with open rice fields. The bridge is 220 m long and it was the pre-stressed concrete beam type. Srinivasan and Srinivasan (2010) had described the concrete construction of Malaysian railways (KTMB) bridges and Kumpulan Ikram Pte Ltd. (KISB) (2003), the advisor appointed by KTMB, had also examined the concrete bridge construction of the company. The job scope involved structural tests, sources of concrete deterioration, maintenance and repair methods. This case study focused on Pier 1 only. The following were the types of damage experienced by the bridge on this pier. There was corrosion observed and this could be caused by chloride attack or by electrolytic reactions. The method of repair employed was again to replace or to clean the corroded parts followed by epoxy resin injection and patching using modified shrinkage polymer. The state of chloride corrosion could be described as fair. There was no indication of honeycombing of the concrete, but there were major, medium as well as fine cracks found to be present on this pier. They could all be clearly seen with the naked eye. The cracks were measured using a crack gauge. For the case of major cracks (CE>1 mm) and medium cracks (0.5 mm<CW<1 mm), the damage was repaired using the formwork grouting method. In the case of fine cracks, epoxy resin was injected into the cracks. Rust staining as a result of corrosion of the reinforcement could be seen with the naked eye, but would be categorized as fair. This kind of damage was repaired by replacing or by cleaning the corroded reinforcement, and patching it with modified shrinkage polymer. In the case of this bridge, the pier was located in the river. Mould and marine growth was evidently present, although it could still be considered as a fair state of affairs. No mechanical damage could be detected; however, maintenance work on the Seberang Perai bridge needed to be carried out urgently because the damage from cracks, spalling, honeycombing and corrosion were getting critical. While the site visit was done, the bridge was in fact undergoing repair work by the contractors. Overall, the conditions of the bridge were considered to be slightly critical. The rating could be considered to be between close to 2 requiring minor restoration and localized repair due the presence of cracks. Among the three bridges evaluated this is the worst case.

Mahameru road (DBKL)

The Mahameru road bridge is about 35 km from the Straits of Melaka. This bridge is located in Kuala Lumpur on a highway built in the seventies. The surrounding environment could be considered as urban. The overall health conditions of the bridge could be described as good. There was no indication of chloride corrosion, honeycombing, cracking or rust staining, and there was no mould growth. Slight damage on this bridge was due to the presence of gaps at the joints which could be caused by traffic or non-homogeneous materials mixture and general materials of construction abuse. The gaps spoiled the aesthetics of the bridge surface and also slowed down traffic. The repair method used was by plugging the joint with asphaltic, which involved a modified bonding polymer mixed with good grade aggregate. Old joints and bolts were replaced with new ones. The joints with gaps were caulked with heat resistant polyurethane foam before a bonding agent was applied. Metal bridging plates were placed at the joints to cover the gaps. More bonding agent materials were poured to fill up any gaps between the plates. This was followed by compaction of the road and finally bitumen was placed at the joints and allowed to dry and harden. Overall, conditions of the bridge were considered fair. The rating could be considered to be between 1 and requiring minor restoration and localized repair of the gaps at the joints.

General conditions

From Table 2, it could be noticed that the most persistent damage experienced by concrete bridges in Malaysia was corrosion due to chloride attack. This is in line with common damage experienced in other countries. The difference is that while the cause in Malaysia is atmospheric chlorides, the cause in most other countries is de-icing salts in the winter months (Amleh et al., 2002). Due to lack of resources in terms of funds and skilled manpower, the management system could not be implemented fully and effectively. This holds true for most countries. There was still high dependence on ad-hoc approaches to repair and refurbishment work. Most of the deterioration and damage originated from natural causes, although, there were also some, which were due to human factors, such as accidents and impacts by vehicles and boats, blocked drainage systems and sub-standard designs. Serviceability could be classified as moderate since there had not been any major failures involving human lives. However, concrete bridges in Malaysia had experienced many kinds of deterioration and damage that would cost a lot of money to repair and refurbish. The levels of atmospheric chloride ions could not be too different from one site to another. The concentrations of these items would accumulate with time, and the on-set of corrosion would depend on the physical and chemical conditions within the matrices of the concrete and the levels of moisture absorbed. As pointed out before, the overall mechanism was complex. Once the thresh-hold levels were reached, corrosion would start.

Conclusions

Malaysia has a comprehensive bridge management system, but a system is as good as the people who implement it. However, serviceability of concrete bridges in Malaysia could be considered as moderate since some steps which can be done to reduce the overall costs of maintenance and operations are application of standard designs, more frequent inspections by skilled inspectors to detect onsets of damage at an early stage and research and development for better materials and techniques in concrete bridge design, construction and maintenance and operations which all together would mean an investment in skilled human capital. Embedded corrosion monitoring sensors might also be considered.

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