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Recommendations concerning the inspection and maintenance of bridges and viaducts

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ABSTRACT: Due to various events related to the collapse of bridges and viaducts in concrete in Brazil and the world, the attention of the technical community for these elements' inspection and maintenance issues of grows increasingly. The interest in maintaining the bridges and viaducts in good condition is great and overall, as they are part of the basic infrastructure and represent a significant portion of the patrimony of the countries. Even if they are subject to depreciation over time, because of the exposure to the environment and the use, it is unworkable and unacceptable, economically and environmentally, that bridges and viaducts are simply replaced when they reach the end of their design life. Thus, this article provides recommendations for an adequate investigation of the main causes of deterioration of these structures in order to elaborate a proper inspection plan and maintenance and consequently the extent of their service life.

1 INTRODUCTION

Due to various events related to the collapse of bridges and viaducts in concrete in Brazil (for example, the drop of the drinking water pipeline support bridge in Socorro[1] and the partial collapse of the Remédios Bridge[2], both in São Paulo) and the world (as the case of Lowe's Motor Speedway Pedestrian Bridge[3]), the attention of the technical community for these elements' inspection and maintenance issues of grows increasingly. The interest in maintaining the bridges and viaducts in good condition is great and overall, as they are part of the basic infrastructure and represent a significant portion of the patrimony of the countries.

According to the National Bridge Inventory (NBI) of the U.S. Department of Transportation (FHWA, 2014), in the United States, by 2014, 610,749 bridges were cataloged, of which 63,552 (about 10%) had structural deficiencies. According to the American Society of Civil Engineers (ASCE, 2013), the investment required to maintain and the country's infrastructure (maintenance and improvement of the conditions and the current performance) would be 121 billion dollars.

In Brazil, it is estimated that 6,612 works of art of the federal roads under the responsibility of the Transportation Infrastructure National Department (DNIT) correspond to a value of 13 billion reais (Brazil, 2012). The bridges, viaducts, walkways and pedestrian bridges administrated by state agencies and local must be added to this number, about which no one knows for sure the size of the problem. The SINAENCO, in 2006, estimated for the State of São Paulo, a legacy of infrastructure equivalent to 7.83 billion reais.

Even if they are subject to depreciation over time, because of the exposure to the environment and the use, it is unworkable and unacceptable, economically and environmentally, that bridges and viaducts are simply replaced when they reach the end of their design life (Transit New Zealand, 2001). Thus, it is essential to understand in depth the aging process of these special works of art in order to improve the design procedures and the execution of new works, producing them most durable and more economical (Helene, 1998). Therefore, it is necessary the establishment of adequate inspection and monitoring procedures, as well as dominium of the current knowledge of concrete structures deterioration mechanisms, which apply to all structures.

2 HISTORIC

According to McLinn (2009), the unexpected collapse of the Silver Bridge, which occurred on De-

[1] Published in a front-page headline in the "*Jornal da Tarde*" of 22 June 1988. "*Adutoras caem, Zona Sul fica sem água*".

[2] SANTOS et al. *Recuperação e reforço da Ponte dos Remédios*. ESTE-REESTRUTURA Engenharia Ltda. e TECPONT Engenharia de Projetos S/C Ltda.1997.

[3] CORROSION FAILURES: Lowe's Motor Speedway Bridge Collapse. Available in: <http://www.nace.org/CORROSION-FAILURES-Lowes-Motor-Speedway-Bridge-Collapse.aspx>. Accessed on 05 nov. 2015.

cember 15, 1967 and resulted in the death of 46 people, was the precursor of the US bridges inspection policy review. Biannual inspections were established by law in 1968, and load limits for projects were set, nonexistent until then, which should also be considered in maintenance.

Thus, Americans are prodigies in conducting reliable surveys on the incidence of pathological manifestations on bridges. Wardhana and Hadipriono (2003) studied and cataloged the causes of the collapse of 536 bridges in the United States between 1989 and 2000 and found the results shown in Table 1.

Table 1. Breakdown of events, US only (Wardhana and Hadipriono, 2003).

Category	Percent	Percent
Flood	165	32,8%
Scour	78	15,5%
Collision	59	11,73%
Overload	44	8,75%
Deterioration	43	8,55%
Earthquake	17	3,38%

As it can be seen, during the studied period, the corrosion of steel accounted for about 8.5% of the collapses of bridges in the United States. However, a study conducted in 2002 by the FHWA in conjunction with the National Association of Corrosion Engineers (NACE) shows that the total estimated annual cost of corrosion in the United States is of $276 billion, about 3.1% of GDP. This data shows that while the management of corrosion has improved over the last few decades, the United States should find more and better ways to encourage, support, and implement corrosion control practices.

Muñoz and Valbuena (2004) evaluated 244 bridges the Colombian road network and found that corrosion is among the most frequent damage, reaching 43% of the support of concrete bridges and being a concern in 23% of the columns of the analyzed concrete works, in the period between 2001 and 2002.

From the technical point of view, several other studies have been developed to explain, diagnose and remedy the phenomenology involved in the reinforcement corrosion, which among the pathological manifestations of reinforced concrete in the world, is presented with a high incidence of 14% to 58% (Nince and Climaco, 1996; Rincon et al., 1998).

At the Brazilian level, there are still few available data and surveys. Magalhães, Folloni e Furman (1989) conducted extensive survey on 145 viaducts and bridges of São Paulo, classifying 22 as high risk and 18 as medium risk, and 58% of the total had steel corrosion problems.

Laner (2001) evaluated 11 viaducts, 23 bridges and 12 walkways of the city of Porto Alegre, checking the occurrence of corrosion in the decks by 60%, 56% and 33% of the analyzed elements, respectively. The numbers corresponding to the corrosion of columns and beams are also significant, of the order of 60%.

Vitório e Barros (2013) analyzed the structural damage and the conditions of stability of 100 Brazilian road bridges, detecting spalling and advanced corrosion on the decks (45 cases) and columns (11 cases), classifying the structures analyzed as potentially problematic (38%), tolerable (35%), and critical, which may suffer structural failure (3%). Only 24% of the bridges were considered without major problems. The study also confirms the historical lack of maintenance culture, demonstrating that the absence of policies and strategies for the conservation of infrastructure works, especially bridges and viaducts, has caused serious consequences, particularly with regard to the risks to users and material damage.

The problem of reinforcement corrosion in concrete structures unfortunately has great impact and has caused accidents such as the partial collapse of one of the slabs of the old Arena Fonte Nova in 2007 (CREA-BA, 2007), which fatally killed seven people and wounded about 20, and the interdiction of the Remédios bridge, in 1997 (Santos et al., 1997), which caused inconvenience in city traffic for seven months.

To prevent corrosion in new works it is necessary updated and comprehensive technical knowledge of the problem. In the case of repairs and recoveries, knowledge requirements are even stricter, demanding techniques and specific materials for each case, and thus the study of corrosion of steel one of the subjects of great importance for the development of current engineering.

Bridges maintenance reaches gigantic proportions in countries with temperate climates, especially in regions with snow. In these regions, it has been employed anti-icing salts based on sodium chloride which is a relatively inexpensive and very efficient material to ensure the vehicles safely. The resulting solution flows by structures, penetrates and percolates in concrete pores and reaches the reinforcement, depassivating it and promoting important electrochemical corrosion.

It is convenient to take advantage of the knowledge and practices already generated and experienced abroad, especially those already available in rich countries with temperate climates, but it is essential to study our reality and create and establish our own maintenance programs. The deterioration and aging of bridges in tropical and equatorial climates is very different from temperate and cold climates. It is worth questioning whether the new works design and inspection procedures adopted in Brazil have taken into account these particularities.

3 DIAGNOSIS OF SAFETY AND DURABILITY

As discussed earlier, the conservation of works of social importance is an important part of the economy of a country. For this conservation to be effective, it is necessary perform inspections and periodic inspections for the development of an accurate diagnostic of safety and durability. These activities are meant as preventive maintenance, and should be proceeded by qualified and experienced professionals.

It is understood by **diagnosis** the collection of symptoms, mechanisms, the potential causes and origin of pathological problems of a structure. It is noteworthy that during its formulation, even before the visual inspection, should be made an anamnesis of the problem by collecting oral information and a survey of all available documentation about the work, such as plants, technical specifications, daily work, test report, among others.

Then, a detailed inspection should be conducted on-site, accompanied by a laboratory analysis on samples taken from the structure. Inspections are especially for detection and investigation of deterioration processes like corrosion and fatigue and for detection of changes in the structural systems. Therefore it is necessary to conduct inspections repeatedly. If the question cannot yet be duly clarified, it is recommended to proceed with a specific bibliographic research and, as appropriate, with a technological or scientific research. Followed all these recommendations, it is possible understand adequately the issue and elaborate the diagnosis of the situation.

The **prognosis** can be understood as a prediction made from the diagnosis performed, about the future conditions of the issue. At this, it is estimated the residual life of the structure, as well as any corrective actions to be taken immediately and in the long term, according to the technical and economic point of view.

Naturally, the **intervention project** is the next step, which describes the alterative therapy or correction of the problem, followed by a technical evaluation of the solution adopted by on-site performance tests or laboratory and the record of the case. Again, if the solution of the problem has not yet been found, should be performed bibliographic and / or scientific research.

That said, and in accordance with the recommendations Andrade (1992), a report of structure analysis standpoint the durability and safety should contain at least the following chapters:

a) Nature of work: should be brief and report all issues that will be clarified throughout the report;
b) Anamnesis or case history: should present all data provided by the interested and relevant to the case as well as the name of the technicians who carried out the inspection and persons who attended them;
c) Preliminary inspection: Your writing should be careful and it is appropriate that the details that will influence the final diagnosis are mentioned. Include photos, a description of the constructive aspects of interest, environmental characterization and identify the pathological manifestations by characteristic areas (facade, floor, etc.) and describe the parts of the structure that will be the subject of a detailed inspection;
d) Detailed inspection: must be properly specified the locations of the samples were extracted, the sampling plan and the adopted tests, which will be discussed in the next chapter of this article. Each result obtained must be accompanied by a brief critical assessment;
e) Security and durability diagnosis: must present a brief general introduction of the causes of the observed problems and an assessment of the influence of the quality of the concrete, its porosity and atmospheric moisture content in the corrosion rate, being referred reputable publications to as foundation. It should be even related the influence of other factors in the observed occurrences and those that possibly have raised doubts;
f) Prognosis of the situation: in this chapter must be provided an estimated residual life of the structure, as well as the actions to be taken from a technical, security and economical point of view;
g) Study of alternatives: can present the correction alternatives of the problem, describing the intervention procedures;
h) Definition of the correction: according to the technical and economic feasibility, should be presented in this chapter the most appropriate solution and applicable to the case;
i) Detailed project of the intervention: The detailed corrective intervention projects should be the result of a specific document, independent of the diagnosis;
j) Conclusions: can be written to summarize clearly the observations made and the diagnosis of the problem, including recommendations suggested.

It is emphasized that this document must be prepared in such a way that allows for further development of a Maintenance Plan, in order to ensure proper operation and durability to the work of art in question, thus confirming the objective of increasing its service life.

4 INSPECTION AND FIELD TESTS

The detailed inspection of bridges and viaducts structures aims to survey the subsidies necessary and satisfactory to draw up a precise diagnosis and prognosis. This involves performing various tests and inspections relating the normative requirements of ACI (1993), ASTM (1996), the ASCE (2000), CIB (1993), the RILEM (1991) and CEB (1983), which will be properly described as follows:

a) Inspection to survey the condition of structural bearings, expansion joints, floor drain and cell sections, luggage wheels, railings and sidewalk;
b) Analysis of all existing landfills, the presence of steps on the pavement, settlements, erosion and drainage of the side slopes;
c) Photographic record of the main structural elements and its anomalies;
d) Analysis of the structure during its loading (support equipment, vibration, noise, etc.), using laser, electronic gauges, etc.;
e) Verification of adaptation to the required template and in the case of rivers, the area available for flow;
f) Testing and characterization of concrete: cores extraction, pull-off tests, thickness of carbonation, concrete mix reconstitution, chloride content, equilibrium moisture content, soluble salt content, electrical resistivity, ultrasound, rebound hammer, thermography, georadar, radiography, pachometry , absorption and void volume, compressive strength, modulus of elasticity, pH of the solution present in the interstitial pores and the concentration of chloride and hydroxyl groups in the aqueous extract;
g) Testing and characterization of reinforcements: diameter and type, any loss of mass and diameter, chemical composition, tensile strength and folding;
h) Tests on concrete-reinforcement-environment system: corrosion potential and polarization resistance.

As it can be seen, there is a wide range of methods with varying expense and accuracy. The choice of the data acquisition method highly depends on the inspection objective and with that on the assessment procedure. (Rücker et al., 2006).

Aiming to guide the choice of tests to be performed, Table 2 provides a comparison between research means with respect to its ability to detect various defects of concrete elements.

Table 2. Capability of investigating techniques for detecting defects in concrete structures in field use (adapted from AASHTO, 2000).

Method based on	Capability of Defect Detection				
	Cracking	Corrosion	Wear and Abrasion	Chemical Attack	Voids in grout
strength	N	P	N	P	N
sonic	F	G[2]	N	N	N
ultrasonic	G	F	N	P	N
magnetic	N	F	N	N	N
electrical	N	G	N	N	N
nuclear	N	F	N	N	N
thermography	N	G[2]	N	N	N
radar	N	G[2]	N	N	N
radiography	F	N	F	N	N

Notes: G = good; F = fair; P = poor; N = not suitable
[1] Beneath bituminous surfacing;
[2] Detects delamination.

To be able to make a sufficient conclusion about a material property, tests have to be carried out on an adequate number of samples. Statistics of the test results can than be used for determining the site-specific characteristic value of the tested property (Rücker et al., 2006).

5 TYPICAL INTERVENTIONS IN BRAZILIAN BRIDGES AND VIADUCTS

Inspections programs and surveys on Brazilian bridges and viaducts, conducted by several researchers, show that:

a) It is common the use of structural reinforcement through external prestressing at the sideview of the beams, thereby increasing its bearing capacity and enabling its adaptation to new legal loads;
b) Some of these structures receive structural reinforcement by placing rolled metal profiles, to replace the beams damaged by accidental vehicle shock or disrespect to the maximum height permitted (vertical clearance);
c) Certain works receive cement and sand mortar coating, in all apparent surfaces (columns, beams and slabs), which starts to function as additional layer of protection;
d) Some special road bridges receive localized repairs, using cement and sand mortar, to correct concreting failures, broken corners by shocks vehicles, parts where there was spalling by expansion of corrosion products of reinforcement and failures in joints of concrete placement;

e) It is usual that in localized repairs there is not a complete release of corroded reinforcement, exposing them to achieve the healthy portion of the bars;
f) Typically, the cleaning of reinforcement is not performed by effective abrasive systems, in order to completely remove any residue of steel corrosion;
g) In the repair of structures in environments with strong chlorides aggressiveness, are not used modern techniques features such as passive paintings of the original reinforcement, based on zinc-rich primers, which could extend the service life of structures;
h) Despite the intense corrosion process observed in certain bars, additional reinforcement are not adopted at longitudinal reinforcement in order to compensate the reduction in cross-section of the steel;
i) The reconstruction of the original section of the structural elements has been obtained by applying mortar with the help of a trowel, being ineffective for the complete filling of existing voids between the bars.

As already known, recovery services poorly performed or conducted result in highly expensive additional work because the problem turns out to be aggravated, rather than being solved. When the causes and the means of propagation anomalies are not properly removed, they remain active under the layer of repair carried out, making impossible their visual monitoring. Thus, only these will be rated as a further reduction of the cross section of the reinforcement occurs, as in the case of corrosion of steel, for example.

Corrective intervention of pathologies in existing structures should be the most careful and objective as possible, in order to avoid his return, as well as its continuity even after the repair and protection services. It should be checked the depth and breadth of external attack and the degree of reinforcement depassivation, they can occur even without external evidence.

In the last thirty years, the international technical community has been dedicated to this issue by developing a series of new tools, resources and evaluation techniques and diagnosis of damaged structures, it is not reasonable to perpetuate the unfortunate situation described.

6 RECOMMENDATIONS AND CONCLUSIONS

6.1 *About the project*

In the aspects of structural safety, the reinforcing structure designs add a higher load capacity to that effectively required. However, the durability point of view, there is still much to evolve. It is not more convenient to use characteristic strength of concrete at 28 days less than 35MPa, not employing drip edge, develop a poor drainage and waterproofing project, use coatings lower to 4 cm, not provide access for inspection of box culvert, did not predict support for jack of replacement of support equipment, not dimension in detail expansion joints, not design guard rails durable, guard wheels, etc.

In general, according to Braga (1996) recommendations, projects should include safety, aesthetics, functionality, durability, constructability and maintainability concerns.

6.2 *About the execution*

Most of the small failures are related to the implementation phase, such as lack of control of the concrete cover thickness, honeycombs, concrete joints misplaced, the finish of exposed concrete, concrete texture, and others. A good design, a rigid specification and effective control of execution are needed.

6.3 *About the inspections*

The brazilian standard ABNT NBR 9452:2012 has three distinct modes of inspections, specifically:

a) Registration: basically involves surveying the main structural elements from the standpoint of safety and durability;
b) Routine: Objective keep updated the registration of the work being carried out with regular intervals and less than one year, or in exceptional occurrences;
c) Special: it is a more detailed visual and instrumental inspection in order to interpret and evaluate possible non-compliances detected during routine inspection, and should be performed with frequency less than 5years.

To guide the inspection to be carried out, the standard brings in its Annex A an extensive script containing all the data to be collected, which must be accompanied by a photographic documentary. For special inspections, specifically, the procedure to be adopted must meet the above flowchart in Appendix B of this standard.

It is necessary to define and adopt terms such as: restoration, rehabilitation, maintenance, conservation, intervention, repair, reinforcement, protection, prevention, correction, periodic, routine, special, registration, reference, detailed, etc. which have been used indiscriminately for different purposes.

6.4 *About the corrective and preventive maintenance*

There is no doubt that the biggest problem of the structures is related to durability, not to the structural aspects. Only at a later stage, when there is no preventive maintenance, the problem becomes a structural safety issue. Obviously, it is more convenient to work in terms of prevention.

In the Brazilian context, unfortunately, the culture of preventive maintenance is non-existent, always having to resort to corrective actions, with much higher costs, consequently.

Furthermore, often during corrective maintenance, solutions are adopted to evaluate only its cost, thus neglecting the performance concepts and hence the service life of the structures.

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