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Review

Corrosion Fatigue of Road Bridges: a review

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In this paper a review is presented about studies involving the fatigue and the corrosion of bridge elements. Reviewed reports include steel structures and steel-reinforced concrete bridges, classified as experimental and theoretical approaches. A special section has been dedicated to particular studies that deny any corrosion – fatigue relationship, thus involving pure corrosion or pure fatigue approaches. Most of the reports deal with the uncoupled corrosion – fatigue, in which the corrosion environment and cyclic loading do no coexist during the experiments. Most of the studies consider the exposition to the aggressive environment, followed by the strength or fatigue testing of the corroded material. Results from these approaches reveal that in some cases the strain level is more significant (up to 85 times more), while in others the corrosion level is the most significant factor (up to 11 times more). The studies that considered the coupled corrosion-fatigue phenomenon, whether circumstantially or systematically, reveal the greatest effects (from 20 to 30% reductions in fatigue strength). Furthermore, it is found that a realistic loading time-history has not been applied, regardless of the approach selected. Future works should focus on coupled corrosion – fatigue phenomenon, proposing standard procedures for structure design. Also, realistic force time-histories should be considered.

Keywords: Corrosion, fatigue, collapse, analytical techniques, structural analysis, bridge failure, infrastructure.

1. INTRODUCTION

Corrosion has been defined as the deterioration of a material by reaction to its environment [1]. Attending the origin of the word “corrosion”, such deterioration would be the literal gnawing of the material [2]. Fatigue of a material, on the other hand, has been described as the process of cumulative damage in a benign environment that is caused by repeated loads [3], which is equivalent to a progressive fracture [4]. If the fatigue occurs under an aggressive environment, that phenomenon is known as corrosion fatigue [3]. Corrosion fatigue is thus the process in which a metal fractures prematurely under conditions of simultaneous corrosion and repeated cyclic loading at lower stress levels or after fewer cycles than would be required in the absence of the corrosive environment [5].

The phenomenon of corrosion fatigue can be described as a type of environmental assisted cracking [6; 7]. In this respect, however, environmental assisted corrosion assumes no influence of variable stresses, and is studied through fracture mechanics approaches [8]. While the phenomenon of corrosion was originally observed in metals, ferrous metals in particular, such phenomenon can occur also in non-metallic materials [9; 10]. The corrosion of metals can be characterized by a chemical reaction that can occur between different metals (electrochemical, fretting, crevice), or between the vulnerable metal and the corrosive media (pitting, etching). In particular, pitting, instead of uniform corrosion, would be the more structure damaging phenomena [11]. Together with Stress Corrosion Cracking, fretting fatigue is another form of corrosion influenced by stresses [5].

In the case of road bridge infrastructure, its elements are exposed to different loads while exposed to corrosive environments [12]. In particular, a highly aggressive situation occurs when salt is used to deice bridge decks, melting the ice and pouring brine into the bridge structure [13]. Bridges over rivers also suffer such exposure to chemically aggressive environments [14]. While loads on the bridge derives from wind, earthquakes and even thermal variations that result in stresses, the most significant force perturbation to the bridges derives from the axle loads associated to the trucks using such infrastructures [15].

Innovative approaches to cope with such infrastructure damage issues include the heating of the bridges [16], dry air ventilation [17], and the use of corrosion resistant materials such as aluminum [18], fiber-reinforced polymers [19; 20], or stainless steel [21]; or protective coatings [22]. On the side of dynamic loads from traversing vehicles and the vibration of bridges, vehicles equipped with bridge friendly suspensions have been proposed [23, 24], as well as bridge vibration suppression active systems [25]. In the case of steel reinforced concrete bridges (RC), the use of corrosion inhibitors has also been considered [26].

Fracture of the materials in the context of road bridges takes different characteristics [27]: brittle fracture due to local corrosion attack or hydrogen enbrittlement; stress corrosion cracking, due to anodic stress corrosion cracking or hydrogen induced stress-corrosion cracking; and corrosion fatigue.

Although not always recognized as a coupled phenomenon, fatigue and corrosion of bridges is mentioned as an important cause of bridges collapse [28; 29; 30], or the combination of overloading and fatigue [31]. In the case of the cables that support bridges, a particularly dangerous characteristic of corrosion fatigue is the poor visual evidence of the damage [32]. While in the case of steel bridges the corrosion is associated to the direct attack of the environment, in the case of the steel used as concrete bridges reinforcement, its damage is the result of complex interactions, in which the reinforcing steel will not corrode unless the PH of the concrete drops due to carbonation [33]; or the chloride content of the concrete reaches the corrosion threshold of the reinforcement [34; 35].

In this paper a review is presented of the literature on corrosion fatigue of bridges. Reports are grouped into families according to the approaches applied (experimental and theoretical). Particular topics concerning corrosion and fatigue are reviewed separately, as in the case of the bonding between steel and concrete, or the reports that explicitly or implicitly deny any fatigue – corrosion coupling. Some recommendations for future research are discussed.

2. EXPERIMENTAL APPROACHES

Due to the complexity of the phenomena involved, corrosion fatigue has been studied mainly experimentally, assessing specific materials and environments.

2.1. Experimental approaches

Apostolopoulos [36] tested under laboratory conditions a steel alloy (S500s, Tempcore), to study the effect of the strain level and the corrosion duration on the number of loading cycles for low cycle failure. The corrosive environment consisted of a NaCl solution, sprayed onto the material at 35 ^{0}C within a special environmental chamber. Corrosion effects were realized through weighing of the specimen during the testing period. Three different levels of strain ε were considered about the zero-stress condition (± 1%, ± 2.5%, and ± 4.5%), for corrosion durations from 10 to 90 days. Up to a 14% loss of the specimen mass was measured. The testing procedure, however, did not involve the exposition to the corrosive environment while the harmonic stresses were applied. That is, after the different periods of corrosion exposition, the sample was tested for low cycle fatigue strength.

Figure 1 illustrates a graph created with Apostolopoulos´ data, describing the effect of both the corrosion duration and strain level on the number of cycles to failure. These results suggest that although corrosion duration and strain level affect the low cycle fatigue of the specimen, the former seems to be more influential. In order to objectively assess the relative effect of corrosion duration and strain level, a sensitivity formulation is defined, based upon the ration of the relative variation of the outputs and the relative variation of the inputs, for the *j*- variation range, as follows:

$$S_j = \frac{((O_{i+1} - O_i)/O_i)_j}{((I_{i+1} - I_i)/I_i)_j} \tag{1}$$

where O is the output (cycles to failure) and I are the inputs (the strain level or the days of corrosion duration); i corresponds to one of the resulting ranges for the variations of inputs and outputs, ranging from 1 to 2 in the case of the strain sensitivity (three values of strain corresponding to two ranges of variation), and from 1 to 6 for the days of corrosion duration. Figure 2 illustrates sensitivity S for both variation of strain level and variation of exposition duration. These results confirm the greater influence of strain level variation on the number of cycles to failure, being up to 85 times more influential than corrosion duration.

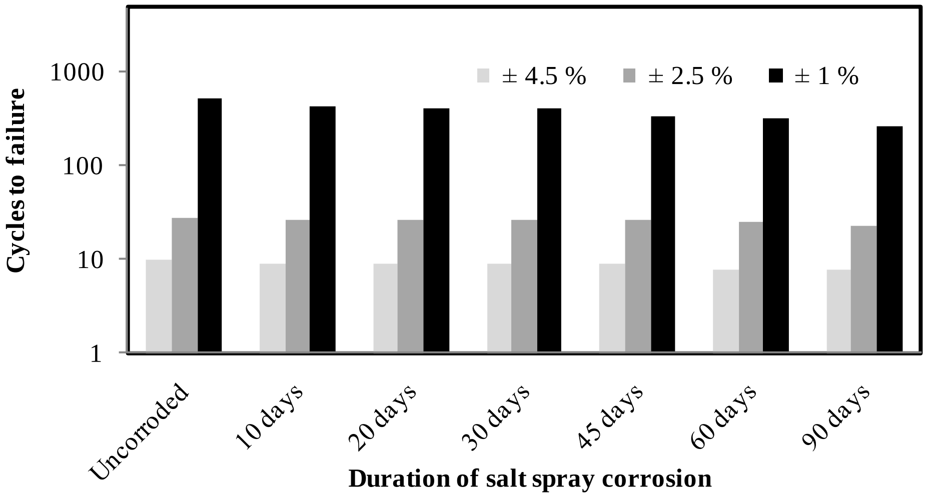


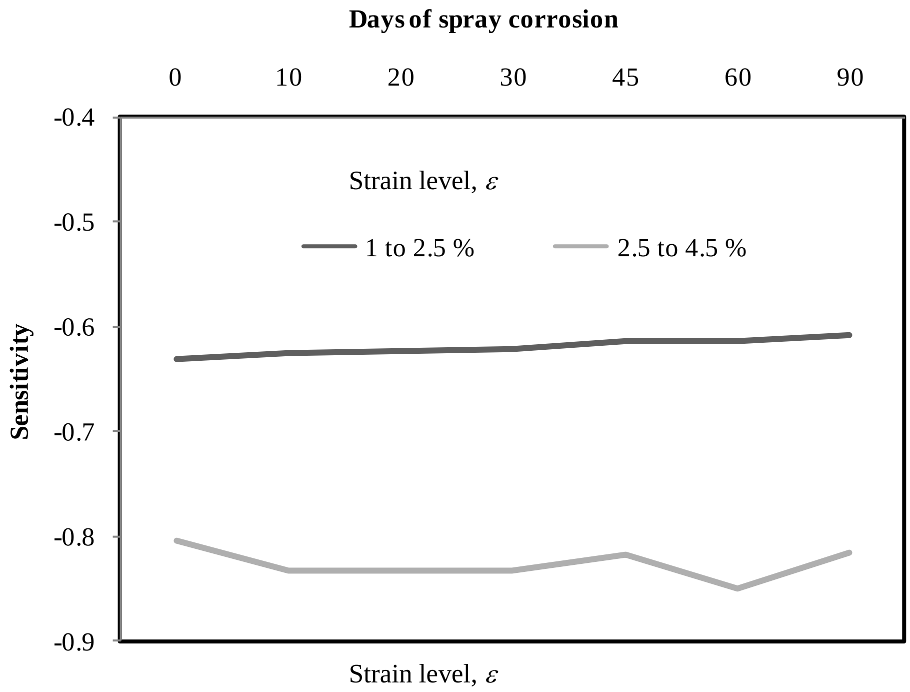
Figure 1. Effect of strain level (ε) and corrosion exposition on the cycles to failure (with data from Apostolopoulos [36]).

It should be noted that these experimental results could be underestimating the combined effect of corrosion and stressing, as the exposition to corrosion and the stressing were not simultaneous. Longer durations would also be influencing the surface finish and the consequent stress concentration, further affecting the fatigue strength of the material.

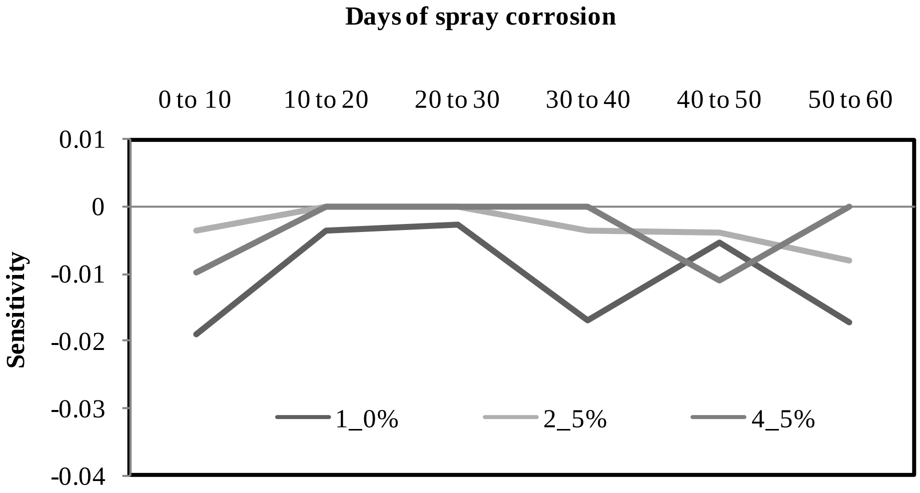
A simultaneous fatigue – corrosion experiment is reported by Wahab and Sakano (37], of specimens subject to biaxial stresses. Results showed a reduction in the fatigue strength of the material. Such fatigue strength reductions are revealed as a function of stress cycles: 7% and 11%, for 100 and 320 thousand stress cycles.

Nakamura and Suzumura [38] report the laboratory testing of galvanized wires used in suspension and cable-stayed bridges. The testing procedure consisted of producing corroded wires in laboratory, which were testing for fatigue strength in dry and wet conditions. Results validated the effectiveness of the zinc layer to preserve the properties of the wire, and the low concentration of diffusive hydrogen into the material. However, the authors associate the fracture of the specimens to a combination effect, involving corrosion, cyclic stresses and diffusive hydrogen. Comparative fatigue tests under dry and wet conditions revealed the significant effect of corrosion and fatigue coupling (20% reduction of the fatigue strength).

Ahn and Reddy [39] report a study aimed at assessing the effect of type of loading (static, fatigue) and water/cement ratios on the durability of steel reinforced concrete beams. They find that cyclic loading and corrosion duration influences the ultimate strength of the elements, in a range from 22 to 14%, as a function of the corrosion environment. Also, that beams subjected to fatigue loading deteriorated faster than those statically loaded. The experimental setup was based upon simply supported beams.



A: Sensitivity to strain level.



B: Sensitivity to corrosion duration.

Figure 2 Sensitivity of the days to failure to strain level and exposition duration (with data from Apostolopoulos [36]).

3. THEORETICAL APPROACHES

Bastidas-Arteaga et al. [40] propose a probabilistic model for RC structures, stressing the concept of a coupled effect of corrosion and cycle loading on the reinforce steel life. They assume three stages for steel deterioration, with two of them being influenced by the stresses applied, as follows: corrosion initiation and pit nucleation, with no effect of applied stresses; pit-to-crack transition, and crack growth, which are influenced by the stress level. For the first stage of material deterioration, authors consider the inclusion of chloride into the material structure, causing pitting of the material as a function of the level of environment aggressiveness. Such level of aggressiveness is defined in terms of the distance from the coast, from a low aggressiveness (at 2.8 km from the coast) to extreme aggressiveness, in which the structure is subjected to wetting and drying cycles. Such distance from the coast was characterized in terms of different properties, as follows: (1) a chloride surface concentration (CSC), (2) an expected threshold corrosion rate (TCR), and (3) a concrete cover (CC). The magnitudes of these properties varied from low to high as follows: CSC from 0.35 to 7.35 kg/m^3; TCR from 0.5 to 10 μA/cm^2; and CC from 40 to 55 mm, signifying percentage increments of 2000, 1900 and 37.5%, respectively. For such levels of aggressiveness, different loading cycles were considered, and applied in long term perspective (hundreds of years), at a rate from 0 cycles per day, to 2000 loading cycles per day.

Figure 3 illustrates some Bastidas-Arteaga results regarding the effect of loading cycles and corrosion level on the material total life. These results identify the corrosion level as the more influential factor. Use of the sensitivity equation (1) for determining the relative influence of each of the two factors considered reveals that changing of corrosive environment (from low to extreme), is 14 times more influential on total life than the variations in cyclic loading. While these results are based upon some experimental data, the validation of this approach at long term is still pending. On the other hand, it seems that some specific experiments should be carried out to validate the assumption made about the independence of the corrosion initiation from the stress level.

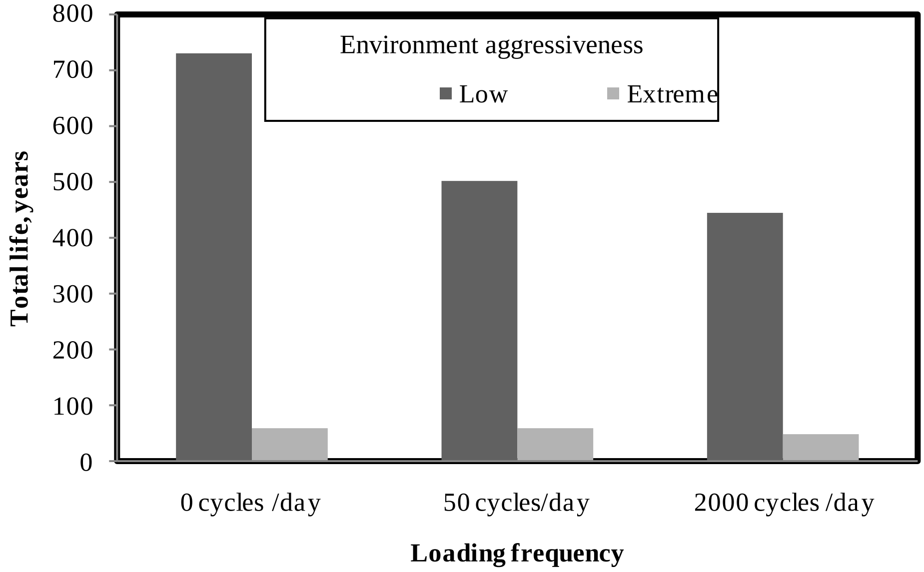


Figure 3. Effect of loading frequency and environment on the RC structure life (with data from Bastidas-Arteaga [40]).

Maes et al. [41] propose a model of corrosion fatigue for the bonded prestressing strands of post-tensioned concrete bridge decks, based upon a 21-parameter formulation involving loading, bridge design and environment. Aggressiveness of environment is characterized in terms of temperature, conductivity of the fluid surrounding the strands, and oxygen concentration (creating from a neutral to an extremely aggressive environment). Failure of the reinforcement is characterized in terms of the number of broken strands. Simulated results from this research consider the broken strands as a function of time and level of environmental aggressiveness. Figure 4 illustrates the effect of corrosion level and corrosion duration on the number of broken strands. While part (a) of this figure takes the broken strands as the independent variable, part (b) takes the time as the independent variable. These figures thus illustrate the corrosion duration to produce the same damage, and the damage variation with corrosion duration.

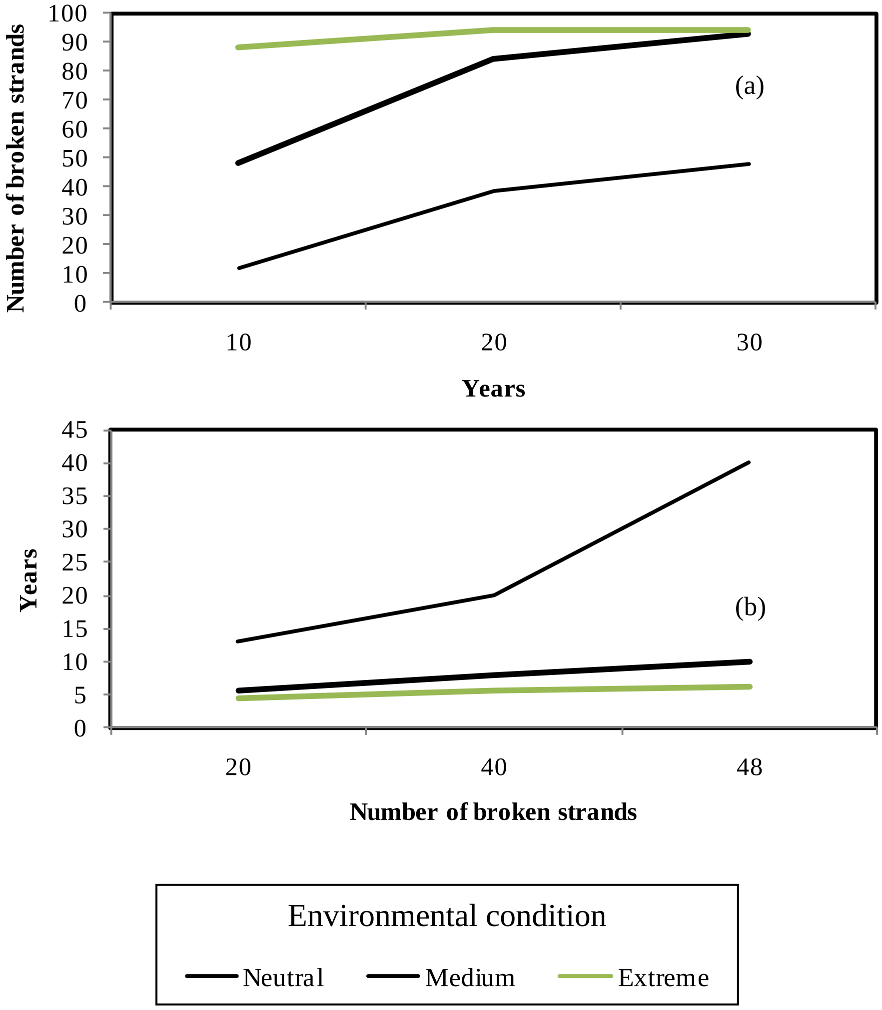


Figure 4. Effect of time on strands damage as a function of environment (With data from Maes et al. [41]).

According to these results, changing the environment from neutral to extremely aggressive signifies relative increments in material damage that decrease with the exposure time considered: 7 times for 10 year-term, 2.4 times for the 20-year term; and 2 times for the 30-year term. On the other hand, the same damage (broken strands) is produced in reduced periods of time when increasing the aggressiveness of the environment: changing from neutral to extreme environment produces a reduction in time of 65%, 72% and 85%, respectively for 20, 40 and 48 broken strands. Furthermore, these results suggest that in the case of the extreme environment, there is a very little sensitivity of the number of broken strands to corrosion duration. Additionally, a neutral environment would produce 28 broken strands in 27 years, while under the extreme environment, that damage would be produced in 1.5 years. That is, 94% less time.

Limitations of the described methodology include that it does not simulate the coupling effect of corrosion and fatigue as a function of stress level. However, the authors state that the reliability of the infrastructure would be a function of the severity of the environment and the average daily traffic, so that 5% of the trucks would be causing up to 95% of the infrastructure damage.

While recognizing corrosion and fatigue as the main contributor to bridge deterioration, Nishikawa et al. [42] focus on bridge elements design to prevent cracks derived exclusively from fatigue due to high truck loads and poor structural designs. They propose different design modifications in stringers and girders.

Hwan-Oh et al. [43] propose a comprehensive methodology to assess reinforced concrete decks considering traffic loads and the environmental effect, to assess the reliability of such structures. In the paper a mixed approach is considered, including coupled and un-coupled corrosion-fatigue phenomenon as a function of the type of stress (bending and shearing). For the bending stresses an uncoupled corrosion-fatigue approach is considered, collecting corrosion initiation and reduction-of-area equations for the reinforce steel, in terms of corrosion parameters such as diffusion coefficient and surface concentration. For such reduction of area of the steel, the variation of bridge deck strength is calculated.

For shear, punching, stress the analysis is based upon the $S - N$ curves that consider dry and wet slab conditions. Log-log results for such testing conditions indicate two parallel lines, with the wet slab revealing a decrease in fatigue strength of 30% when compared with the dry slab condition.

Lindquist et al. [34] report measurements of chloride concentration in concrete bridge decks, characterizing the effect of cracks on the diffusion of chloride in concrete. While the authors recognize the influence of different factors for concrete cracking, including load, they infer that shrinkage and settlement are the dominant causes. They find cracks as the medium for chloride diffusion and reinforce damage.

4.BONDING STRENGTH AND CORROSION FATIGUE

Shi and Zhang [44] propose a formulation thorough which they assess the effect of corrosion and fatigue on bond strength, including the damage of the steel and the damage of the concrete, separately or together. The damage of the concrete would be a consequence of the damage of the reinforce steel. It is defined an environmental acceleration factor, as a function of loading frequency and stress ratio. According to its formulation debond length increases in about 10% when corrosion fatigue is considered.

5. BRIDGE STRUCTURES STUDIES AND REPORTS THAT NEGLECT FATIGUE-CORROSION COUPLING

While it has been stated that the coupling of fatigue and corrosion phenomena occurs in any bridge structure [40], there are some reports that explicitly or implicitly deny such coupling, whether it is on the side of corrosion, denying any fatigue effect; or on the side of fatigue, denying any corrosion effect.

5.1. Fatigue approach studies

De Corte et al. [45] theoretically analyze the fatigue failure of ribs in orthotropic plated bridge decks, in particular, the rib to the floorbeam joint. The authors identify some stress concentrations potentially leading to fatigue, as the result of tire loads applied at certain locations on the structure. The reason for neglecting any corrosion contribution for such orthotropic all-steel bridges decks seems to derive from design measures undertaken specifically to prevent any humidity in the structure, even through the use of dehumidification techniques [12].

Issa et al., [46] report the full scale testing of overlays installed on bridge decks, considering bonding properties of the overlays after being subject to temperature variations. Acceptable performance during static testing of a prototype is reported, once that cycle loading was applied.

Sih et al. [47] report and analytical/experimental study, to characterize the effect of crack shape and size on the fracture strength and crack growth fatigue life of bridge cable steel wires. They calibrate a theoretical model, identifying stages of microcracking and macrocracking.

Siegert et al. [48] report field strain measurements in concrete prestressed short span bridges, during a 256-day period. The bridges were heavily trafficked. With these data the authors extrapolate expectance results for more than 50 years. A linear relationship is found between the total weight of the vehicle and the strain at the mid-span portion of the bridges. Extrapolation of results reveals that the bridge will have an acceptable performance, beyond 100-year horizon.

Mahmoud [49] reports a fracture mechanics approach to model the failure of cable wires for suspension bridges. The author finds that fracture toughness criterion is more realistic than fracture strength of the wire.

Systems to predict remaining lives of bridge structures, based upon weigh in motion techniques, have been proposed without consideration of the potential environment effect [50]. The same concept is considered by Leendertz and De Boer [51] when analyzing the stress level significance on bridge life.

Regarding heavy vehicle – bridge interaction studies, Jacob reports evaluations of the effect of heavy vehicles on bridge fatigue [15].

Chaallal et al. [52] report the theoretical and experimental modeling of a multiple support bar modular bridge expansion joint. As a first stage, the authors consider static calibration of a theoretical model. Fatigue loading was then applied to the full-penetration welded structure composed by a center 3-m beam and 4 1-m-length support cross bars. Working environmental conditions for these elements correspond to Montreal, Canada (Jacques Cartier Bridge over St. Laurent River). The stress – number of cycles for failure curves are obtained for stress levels realized through two hydraulic actuators. Equivalent stresses were calculated using Miner´s rule. A characterization is performed on the number of cycles at first crack, which occurred around the welds. Figure 5 illustrates Jacques Cartier Bridge with a panorama revealing the harsh weather conditions under which that bridge works.

Figure 5. Jacques Cartier Bridge over St. Laurent River, Montreal, Canada (December, 2007).

O´Connel and Dexter [53] report measurements and simulations of traffic-related dynamic stresses occurring in selected elements of two steel bridges, including Bridge No. 9340 over the Mississippi River, in Minneapolis. Details of such investigation are given in other specific report about Bridge No. 9340 [54]. The research was conducted to characterize the stress ranges derived from traffic; further evaluating the potential cracking and remaining life of the bridge, and identifying potentially-needed periodical inspections.

The structure was composed of trusses joined through welding and riveted gusset plates. Strain-gauge instrumented structural elements included chords (upper, lower), and diagonals. No details about the number or strain rosettes are described, only that the gauges were arranged to avoid bending stresses in the diagonals, and stress concentrations in the chords. No gusset plate was instrumented. While the first loading and measurements involved known-weight heavy vehicles moving on the bridge, the second set of measurements were taken during a 58-hr period of normal traffic. Results revealed that the stresses in the instrumented elements were lower than the fatigue threshold of the material. However, some recommendations were made about the periodic inspection of welding sections.

Recently published preliminary results on the collapse of the 9340 Bridge [55], indicate as the probable cause for the failure a combination of situations that include an inadequate load capacity of gusset plates; an increase in bridge weight; and a concentration of traffic during the day of the collapse. Corrosion is explicitly denied as a contributor for the failure.

5.2. Corrosion approach studies

Ismail and Ohtsu [56] report laboratory testing of reinforced slabs, aiming at characterizing the corrosion rate of ordinary and high-performance concrete when subject to chloride attack. They find that ordinary performance concrete exhibits greater corrosion rates when subject to sodium chloride solutions.

In reporting the costs of corrosion for the United States economy, in the range of $ 8.3 billion dollars annually for highway bridges, Koch et al. [57] implicitly refer to the effect of corrosion fatigue on bridges deterioration. However, the authors simplify the corrosion fatigue phenomena as “one of chloride-induced corrosion of the steel members, with the chlorides coming from deicing salts and marine exposure”.

Liu and Weyers [58] report a five-year experimental study of 44 concrete slabs aiming at the calibration of a regression model for the corrosion deterioration of the slabs. During the testing period different conditions and parameters were monitored, including temperature, corrosion rate, and electric resistance of the concrete slabs. Results indicate that corrosion rate diminishes with time, from around 0.15 $\mu A/cm^2$ to 0.05 $\mu mA/cm^2$ for the 5-year period, with the concrete electric resistance presenting differences lower than 3%. The data suggest that the corrosion rate is a function of the temperature, ohmic resistance of the cover concrete, chloride content and corrosion time.

5.3. Uncoupled fatigue – corrosion studies

Fisher [59] presents a simplified approach that neglects corrosion-fatigue coupling, defined from the perspective that fatigue strength of the materials is affected by the corrosion-caused reduction in resisting area. Such approach has been also considered for assessment of the integrity condition of concrete bridges [60].

Li et al. [61] assumes a probabilistic approach for analyzing failure of SR concrete structures, focusing on the effect of steel corrosion on concrete failure as a result of the pressure on the concrete, exerted by the corroded reinforce steel by-products. Probability functions include a stress level factor. In a previous report [62], Li presents experimental results of the effect of stress condition on chloride content. Three conditions of loading are considered, no-load, load-unload involving crack of the material, and static load. Results indicate the drastic effect of stress on chloride content, doubling such concentrations.

While there exists specific testing methodologies for the corrosion-fatigue characterization of materials [63], no specific considerations about this phenomenon have been included in the standard bridge design procedures [64].

6. DISCUSSION

It has been presented a critical review of the literature concerning the corrosion fatigue of bridge infrastructures. This review suggests some contradictory facts about the importance of corrosion fatigue and about the role of fatigue and corrosion in coupled fatigue-corrosion phenomenon. On the one hand, cable wires are studied from a corrosion fatigue perspective, but also from a fatigue-only perspective. On the other hand, the studies considering corrosion and fatigue exhibit different trends, involving contradictory significances of corrosion environment and fatigue loading. Such differences are numerically important (85 times more sensitive the strain level; or 7 times more sensitive the corrosion environment).

While the approaches can be correct, as some of them refer to different infrastructure situations, it seems that a clarification is necessary to have an objective perspective of the phenomena involved.

With respect to the experimental approaches under laboratory conditions, the equipment used does not correspond to a moving load on the bridge. It is well known that the transient stresses in the bridge elements are a function of many factors, including the speed of the vehicle and its position on the bridge. The effect of the stress history has been identified as an influential characteristic in stress assessing studies [65; 66].

7. CONCLUSIONS AND RECOMMENDED FUTURE RESEARCH

In this paper a critical review has been presented about studies involving the fatigue and the corrosion of bridge elements. Reports include steel structures and steel-reinforced concrete bridges, classified as experimental and theoretical approaches. A special section has been dedicated to particular studies that deny any corrosion – fatigue relationship, involving pure corrosion or pure fatigue studies.

So, the investigations have included the analysis of different phenomena: coupled corrosion – fatigue; uncoupled corrosion – fatigue, and isolated studies of corrosion and fatigue.

Most of the reports, however, deal with the uncoupled corrosion – fatigue phenomena, in which the corrosion environment and cyclic loading do no coexist during the experiment. Most of the studies consider the exposition to the aggressive environment, followed by the strength or fatigue testing of the corroded material. Results from these approaches reveal that in some cases the strain level is more significant (up to 85 times more), while in others the corrosion level is the most significant factor (up to 11 times more). The studies that considered the coupled corrosion-fatigue situation, whether circumstantially or systematically, reveal greater effects on fatigue strength, with reductions in the order of 30% when compared with the uncoupled situation.

A realistic loading history, however, has not been considered, regardless of the approach selected (experimental or theoretical). Future research should focus on objectively determining the significance of the corrosion – fatigue phenomenon, potentially proposing standard procedures for bridge structures design. Also, realistic force histories should be considered.

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