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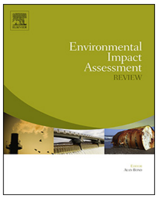

Reliability-based maintenance optimization of corrosion preventive designs under a life cycle perspective

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ABSTRACT

Sustainability is of paramount importance when facing the design of long lasting, maintenance demanding structures. In particular, a sustainable life cycle design for concrete structure exposed to aggressive environments may lead to significant economic savings, and to reduced environmental consequences. The present study evaluates 18 different design alternatives for an existing concrete bridge deck exposed to chlorides, analyzing the economic and environmental impacts associated with each design as a function of the maintenance interval chosen. Results are illustrated in the context of a reliability-based maintenance optimization on both life cycle costs and life cycle environmental impacts. Maintenance optimization results in significant reductions of life cycle impacts if compared to the damage resulting from performing the maintenance actions when the end of the service life of the structure is reached. The use of concrete with 10% silica fume has been shown to be the most effective prevention strategy against corrosion of reinforcement steel in economic terms, reducing the life cycle costs of the original deck design by 76%. From an environmental perspective, maintenance based on the hydrophobic treatment of the concrete deck surface results in the best performance, allowing for a reduction of the impacts associated with the original design by 82.8%.

1. Introduction

Sustainability seeks to ensure on-going development without compromising the capacity of future generations to meet their own needs. In this context, the construction sector is one of the main environmental and economical stressors (Worrell et al., 2001); as such, special attention has been paid in recent years to sustainable design of structures. In particular, concrete bridges are the subject of particular interest in regard to the design approach, due to the existing long service life requirements and to the extensive material consumption associated with their construction and maintenance. Along the lines of sustainable structural design, research has been conducted on the cost optimization of concrete bridge design (García-Segura et al., 2014; Martí et al., 2013; Yepes et al., 2017), and also on the minimization of CO_2 emissions and energy consumption (García-Segura et al., 2015; García-Segura and Yepes, 2016; Martí et al., 2016) resulting from bridge construction activities.

According to the long-term perspective on which the sustainability concept is based, life cycle assessment has become an internationally recognized method when dealing with the sustainable design of concrete bridges. Within this framework, the three pillars on which sustainability is based, namely society, environment and economy, have been covered to a greater or lesser extent. Hammervold et al. (2013) compare the life cycle environmental impacts of three bridges built in Norway, assuming routine repairs during the use phase. Zhang et al. (2016) include uncertainty in the evaluation of the environmental impacts. Du et al. (2014) and Penadés-Plà et al. (2017) compare alternative bridge designs from an environmental point of view. On the other hand, Eamon et al. (2012) compare the life cycle costs of reinforcement alternatives for concrete bridges. Navarro et al. (2018a) evaluate the costs associated with alternative bridge designs in coastal environments. A general conclusion is that the maintenance and use phase of a concrete bridge is the main source of impacts during its life cycle, both environmentally and economically. An adequate maintenance strategy is essential in order to reduce the life cycle impacts of the structure (Frangopol and Soliman, 2016). Studies have been carried out that optimize the maintenance costs of concrete bridges (Kendall et al., 2008; Safi et al., 2015; Frangopol, 2011). García-Segura et al. (2017) include environmental criteria in the maintenance optimization of bridge decks.

Maintenance and its impact are crucial for concrete structures in aggressive environments, where deterioration plays a major role over

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the term of their service life. Although there are several ways that concrete bridges may deteriorate in severe environments, experience shows that the most important threat to concrete structures is chloride-induced corrosion of the reinforcement (Valipour et al., 2017). Over the last few decades, different preventive measures have been developed to increase the corrosion resistance of concrete structures exposed to chlorides, thus leading to extended service lives and consequently to lower maintenance needs. However, lower maintenance needs do not always lead to the minimum of environmental and economic (Navarro et al., 2018a) impacts. A sustainable design of a concrete bridge in a coastal environment involves selecting the most suitable prevention alternative in terms of life cycle impacts, attending to the optimal maintenance strategy associated with it.

In this sense, this paper is devoted to shedding light on the way that different corrosion prevention measures may influence the results of optimum maintenance strategies from both the economic and the environmental points of view. To do so, a real concrete bridge deck subject to a marine environment is considered for the study. This bridge deck is modelled and assessed by means of both a life cycle cost analysis (LCCA henceforth) and an environmental life cycle impact analysis (LCA henceforth) with respect to a design service life of 100 years. Reliability-based maintenance optimization is performed for each of the analyzed preventive measures. Results will be presented and discussed for the optimal environmental and economic maintenance strategies.

2. Materials and methods

LCA is a widespread methodology that in recent years has taken firm root and been standarized (ISO, 2006a; ISO, 2006b) in the international context. LCCA, on the contrary, although in a fairly advanced stage of development (Hunkeler et al., 2008), still lacks an ISO standard that helps the integration of both assessment methodologies. In order to provide a comparative analysis on a consistent basis, the present study applies the ISO 14040 methodological framework for the LCC assessment (Swarr et al., 2011). According to ISO 14040, the assessment should be carried out in four phases: the definition of goal and scope, the inventory analysis, the impact assessment and the interpretation of the results.

2.1. Goal and scope definition

The present study focuses on particular preventive design alternatives applied to a real concrete bridge deck in a coastal environment. The bridge of Ensenada do Engano in Spain is analyzed. A cross-section of the bridge deck is shown in Fig. 1. The bridge, which is 721 m long and has a span distribution of 41 m + 9 × 70 m + 50 m, crosses over an estuary, with the deck less than 9 m above the mean sea level. The bridge consists of a box girder deck, with a section height of 3.2 m and a total width of 11 m. The concrete cover of the deck is 30 mm. The concrete mix of the deck is assumed to consist of a cement content of 400 kg/m^3, and a water/cement ratio of 0.45. A passive reinforcing steel in the amount of 100 kg/m^3 of concrete is considered. It shall be noted that, according to the Spanish design codes for marine environments, the bridge is designed to remain uncracked. This will be assumed for the rest of the study.

This study considers alternative designs for the described case study (called reference design or REF hereafter) based on the prevention strategies that are usually assumed for concrete structures exposed to marine environments. Firstly, increasing the original concrete cover of the steel reinforcement from 30 mm to 45 mm and to 55 mm (named here CC45 and CC55) has been considered. Secondly, a reduction in the water to cement ratio from the existing w/c = 0.45 to w/c = 0.40 and to w/c = 0.35 (alternatives W/C40 and W/C35 respectively) has also been considered. Reducing the water/cement ratio results in concretes with lower porosity, thus reducing the chloride diffusivity throughout the cover. The third type of preventive measure evaluated consists in the partial substitution of the concrete by fly ash or silica fume in the original concrete mixture. Additions of 10% and 20% fly ash (called here FA10 and FA20), and 5% and 10% silica fume (alternatives SF5 and SF10) have been considered. As with fly ash and silica fume additions, polymer-modified concretes also result in denser concretes, thus contributing to an increase in the durability of concrete by hindering chloride diffusion. Consequentlly, additions 10% and 20% styrene butadiene rubber latex (designs PMC10 and PMC20) have been considered. The aforementioned percentages are expressed as a fraction of the cement content in the original mix. It shall be noted that the presented concrete mixes are assumed to replace completely the reference design mix.

The use of corrosion inhibitors is a usual way to extend the service lives of concrete structures in agressive environments. The present study considers two types of inhibitor, namely an organic inhibitor used as an additive to the original concrete mix (design OCI hereafter), and a migratory inhibitor, which is applied to the concrete surface and penetrates the concrete cover, thus reacting with the concrete and increasing its resistivity (alternative MIG). The study also evaluates the use of galvanized steel (design GALV) and stainless steel (design INOX) instead of the ordinary steel of the reference design in the bridge structure. The use of durable steels increases the amount of chlorides needed to start the corrosion process, thus extending the service life of the design. In addition, the application of a hydrophobic product to the exposed deck surface (alternative HYDRO) and the application of a sealant product (alternative SEAL) in order to prevent chloride ingress in the concrete cover have been considered. Finally, large structures in marine environments are also protected by means of impressed current

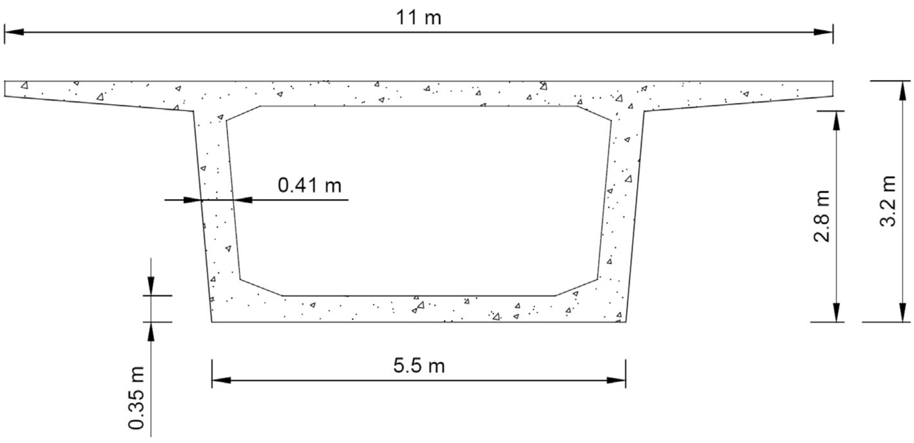

Fig. 1. Cross-section of the concrete bridge deck at Ensenada do Engano (dimensions in m).