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Lifetime reliability-based optimization of post-tensioned box-girder bridges

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ABSTRACT

This paper presents a lifetime reliability-based approach for the optimization of post-tensioned concrete box-girder bridges under corrosion attack. The proposed approach is illustrated by determining the optimal life-cycle cost and CO_2 emissions of several initial designs of post-tensioned box-girder bridges with different objectives, i.e. the lowest initial costs, the longest corrosion initiation time, or the maximum safety. The study was conducted in two steps. Firstly, the Pareto set presents initial designs considering the cross-section geometry, the concrete strength, the reinforcing steel and the prestressing steel. Secondly, the maintenance optimization was conducted with the proposed method, aimed at minimizing the economic, environmental and societal impacts of the bridge while satisfying the reliability target during its life-span. Effective maintenance is able to extend the service life of the bridge with the minimum cost and CO_2 emissions. It is indicated that a durability-conscious initial design is particularly beneficial for life-cycle performance. Besides, the emphasis on the initial design can also have an effect on the life-cycle performance of bridges. It is found that designs with longer corrosion initiation time are associated with lower life-cycle cost, especially when using concrete of higher strength. Findings from the current paper also indicate that optimal maintenance strategies are more likely to be those with fewer maintenance actions that repair all deteriorating structures simultaneously.

1. Introduction

Sustainable development requires a balance among the economic, environmental and societal pillars. In addition, the Brundtland Report proposes a long-term vision to maintain the resources necessary to provide future needs [1]. This objective has been applied to the civil engineering field in different lines of research. Some researches deal with design optimizations aimed to achieve the maximum benefit from the minimum resources [2–5]. Environmental concern has led to the incorporation of CO_2 emissions and energy consumptions as important criteria [6–10]. Moreover, environmental effects from other industries during the civil engineering activities have also been studied in order to reduce the total CO_2 emissions [11,12]. Other studies focus on the life-cycle perspective. Sarma and Adeli [13] presented a review on cost optimization of concrete structures and stated that the focus of further research should switch from initial cost optimization to life-cycle cost optimization. This has led to an increased number of studies on life-cycle performance of structures [14–17], aiming at optimizing the maintenance cost of structures. Frangopol and Soliman [18] pointed out that maintenance actions must be effectively planned throughout the life-cycle of structures to achieve the maximum possible life-cycle benefits under budget constraints.

A major portion of the life-cycle cost of long-span coastal bridges is attributed to the maintenance of corroded components [19]. A maintenance action can delay the damage propagation or reduce the degree of damage, and consequently, extend the service life of a deteriorating structure [20]. Neves and Frangopol [21] mentioned that including condition states alone is not enough to reflect the safety and serviceability of a bridge. Thus, both condition and safety levels have been used as objectives in maintenance optimization [22–24]. Later, Dong et al. [25] considered the environmental and societal aspects of maintenance actions. Sabatino et al. [26] used multi-attribute utility theory to assess various

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aspects of structural sustainability considering risks associated with bridge failure and risk attitudes of decision makers. Penadés-Plà et al. [27] reviewed the sustainable criteria used for decision-making at each life-cycle phase of a bridge.

The performance of a structure is affected by several uncertainties. Among these, uncertainties in load effects, material properties and damage occurrence and propagation should be highlighted [28]. Many design codes, including the Eurocode, have adopted the partial safety factors to take into account the uncertainties arising from geometry, material properties, load effects, and design models. During the planning of maintenance actions, stakeholders should also be well aware of the uncertainties involved in the deterioration process and potential inspections/interventions [17]. A proper consideration of uncertainties can lead to significant economic benefits for both initial design and life-cycle performance [29].

This paper presents a lifetime reliability-based approach for the optimization of post-tensioned concrete (PTC) box-girder road bridges through two steps. Firstly, the study relies on a novel multi-objective optimization technique developed by García-Segura et al. [30] to arrive at a set of optimum initial bridge solutions considering initial cost, overall safety factor and corrosion initiation time, constrained by the requirements of the design code. Secondly, maintenance optimization is conducted with respect to a design service life of 150 years to determine the optimal maintenance actions in terms of maintenance costs and environmental impacts. The maintenance actions considered in the study can delay the damage propagation, which in turn extends the bridge service life. The economic, environmental and societal impacts are examined. During the maintenance optimization, the societal impact due to traffic disruptions is associated with either economic costs or CO_2 emissions based on existing studies [25]. The comparison of life-cycle cost and CO_2 emissions among the initial designs under consideration provides guidance for designing sustainable PTC box-girder road bridges in a coastal zone.

2. Pareto front of optimal bridge designs

The paper studies the design of a PTC box-girder road bridge located in a coastal region. The initial designs under consideration are selected from a set of alternative tradeoff solutions located on a Pareto front associated with three objectives: initial cost, overall safety factor, and corrosion initiation time. The determination of these objectives are described in detail in the following sections. Bridge designs are obtained from the following optimization scheme:

Given

A PTC box-girder road bridge with a width of 11.8 m and three continuous spans of 35.2, 44 and 35.2 m.

Goal

Find the optimal bridge design of a PTC box-girder described by 34 variables regarding the geometry, the reinforcing and prestressing steel, and the concrete grade. Fig. 1 shows the geometric variables of the bridge section as well as the longitudinal and transverse reinforcement. The diameters of rebars are denoted as $LR_{1\text{-}10}$ and $TR_{1\text{-}8}$ for longitudinal and transverse steel respectively. Note that the deck is divided into two zones: pier zones (L/5 on both sides of the piers) and girder zones (the rest of the span). In pier zones, rebars with diameters of LR_7 and LR_9 are provided as extra reinforcement in the top and bottom slab, respectively. In the girder zones, rebars with diameters of LR_8 and LR_{10} are extra reinforcement in the top and bottom slab, respectively. Regarding transverse steel, an extra reinforcement with diameter of TR_4' is placed at the same position as TR_4 and covers the support zone (L/5 on both sides of all supports). In all zones, TR_9 is fixed at 12 mm. The number of longitudinal rebars per meter (N_{LR}) as well as the spacing of the transverse reinforcement (S_{TR}) does not vary along the longitudinal axis of the bridge section. The post-tensioning steel is formed by strands symmetrically distributed through the webs. The variables associated with post-tensioning steel are the distance from the pier section to the point of inflection as a ratio of the span length (L_{pi}), the eccentricity in the external spans as a ratio of half of the bridge depth (e_p), and the number of strand (N_S). The eccentricity in the midspan of the central span and in the supports is set to be the maximum value allowed in the design code. The prestressing force in each strand is fixed as 195.52 kN. Finally, the last variable under consideration is the concrete grade (f_{ck}). All these 34 variables should be selected to simultaneously optimize the following objectives:

- Minimize the initial cost of material production and construction
- Maximize the overall safety factor with respect to the ultimate limit states
- Maximize the corrosion initiation time

Subject to

The requirements related to the ultimate and serviceability limit states described in Fomento [31,32], are based on the Eurocodes 1 and 2 [33,34]. The ultimate limit states considered herein include shear, shear between web and flanges, punching shear, flexure and torsion, whereas the serviceability limit states examined herein include deflection and cracking. In addition, the codes require the decompression of prestressing strands in coastal environments, i.e. decompression must not occur in the concrete located 100 mm above and under the strands [33]. For serviceability limit states associated with bridges, the codes also limit the instantaneous and time-dependent deflection due to precamber effects to 1/1400th of the main span length under the characteristic combination [31], and the deflection associated with the frequent value for the live loads is limited to 1/1000th of the main span length [32]. The geometrical and constructability requirements are also examined according to the codes. Load effects take into account of the traffic loads [32], the self-weight of parapets (5 kN/m) and asphalt (24 kN/m^3), the thermal gradient [32], the

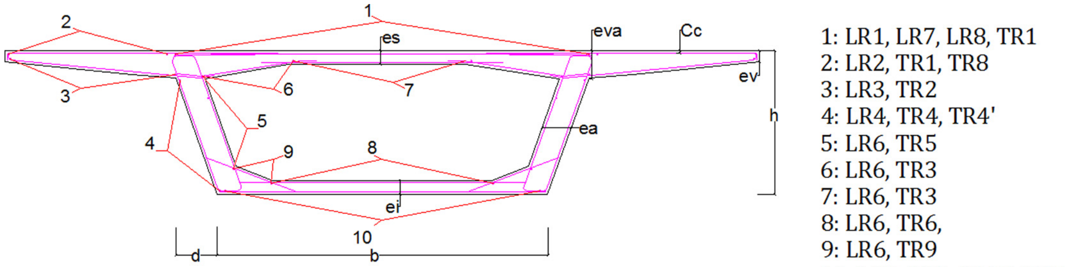

Fig. 1. Variables regarding geometry and reinforcing steel of the PTC box-girder road bridge.