Journal of Environmental Management 197 (2017) 41–49

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Research article

Comparative life cycle cost assessment of painted and hot-dip galvanized bridges

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ARTICLE INFO

Article history:
Received 14 January 2017
Received in revised form
6 March 2017
Accepted 7 March 2017
Available online 17 March 2017

Keywords:
Life cycle cost assessment
Steel bridge
Painted
Hot-dip galvanizing
Maintenance scenario

ABSTRACT

The study addresses the life cycle cost assessment (LCCA) of steel bridges, focusing on the maintenance activities and the maintenance scenario. Firstly, the unit costs of maintenance activities and their durability (i.e. the time between two activities) are evaluated. Pragmatic data are provided for the environment category C4 and for three activities: Patch Up, Overcoating and Remove & Replace. A comparative LCCA for a typical hypothetic steel girder bridge is carried out, either painted or hot-dip galvanized (HDG), in the environmental class C4. The LCC versus the cumulated life is provided for both options. The initial cost of the steel unpainted option is only 50.3% of the HDG option. It is shown that after 'Overcoating' occurring at 18.5 years, the total Net Present Value (NPV) of the painted option surpasses that of the HDG option. A sensitivity analysis of the NPV to the cost and service life parameters, the escalation and discount rates is then performed. The discount and escalation rates, considerably influences the total LCC, following a non-linear trend. The total LCC decreases with the discount rate increasing and, conversely, increases with the escalation rate increasing. Secondly, the influence of the maintenance scenario on the total LCC is assessed based on a probabilistic approach. A permutation of the three independent maintenance activities assumed to occur six times over the life of the bridge is considered and a probability of occurrence is associated to each unique scenario. The most probable scenarios are then classified according to their NPV or achieved service life. This approach leads to the definition of a cost-effective maintenance scenario i.e. the scenario, within all the considered permutations, that has the minimum LCC in a range of lifespan. Besides, the probabilistic analysis also shows that, whatever the scenario, the return on investment period ranges between 18.5 years and 24.2 years. After that period, the HDG option becomes economic.

1. Introduction

This paper is divided into three main parts. Following this brief introduction, Section 2 describes the two coating systems and their respective maintenance activities. Section 3 mainly focuses on the determination of the cost and service life parameters necessary to perform the life cycle cost assessment (LCCA) and on the description of the hypothetic bridge. These parameters are based on the literature and on interviews with experts and are independent from the presently chosen hypothetical bridge. Two hypothetical bridges are considered as functional units: a painted steel bridge and a hot-dip galvanized steel bridge. A comparative LCCA is then achieved in Section 4, in which three maintenance events are considered. The variables of the LCCA are (1) the nominal maintenance event costs, (2) the moment of maintenance, which itself depends on the durability of the protection system, (3) the discount and escalation rates and (4) the maintenance scenario. Concerning the maintenance scenario, two cases are envisaged: the Model sequence (Section 4.1, fixed scenario) and the probability approach (Section 4.2, 729 scenarios), in which the plausibility of the considered scenarios is assessed by corroborating it to a probability of occurrence.

2. Considered coatings and their maintenance over time

2.1. Exposure categories

Every kind of structural steelwork is attacked by corrosion, the

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http://dx.doi.org/10.1016/j.jenvman.2017.03.022
0301-4797/

type and speed of which as well as distribution over the surface (generalised or localized) are influenced by environmental factors (Hempel, 2012). The standard EN ISO 12944-2 (ISO, 1998) defines six exposure categories for paint coatings, as provided in Table 1. This study considers the category C4. A similar classification scheme exists for the corrosion of metals and is defined in EN ISO 9223:2012.

2.2. Surface preparation

Several methods of protection against corrosion exist, but the most often used for steel bridges is the application of protective coatings, the maintenance of which causes cost. The surface preparation (solvent cleaning, hand and power tool cleaning, abrasive blast cleaning or water jetting) ensures the adhesion of the first coat layer, also known as primer, on the substrate (Hudson, 2000; International Paint Ltd, 2011). It significantly affects the performance of the whole coating system, no matter the system or application method. Surface preparation is the leadoff act in any coating operation. Generally, there are three initial surface conditions: the bare, shop primer covered and painted steel surfaces. For the latter, the surface condition must be assessed before the surface preparation can occur. Therefore, a rating system based on the rusted surface and its distribution is provided by the standards. In the present paper, depending on the maintenance events, different surface preparation according to EN ISO 8501-1 and EN ISO 8501-1 (ISO, 2007; ISO, 1994) will be considered.

2.3. Paint system

For paint systems, a zinc-rich primer is applied onto the prepared surface, followed by one or more undercoat(s) and the finish. The primer ensures the adhesion of the subsequent layer as well as the corrosion protection with the contained noble metallic particles. Organic (such as zinc epoxy) and inorganic zinc-rich (zinc ethylsilicate solvent-based, or alkali silicate water-borne) primers exist. In both category, solvent-based and water-borne coatings are present. Solvent-based are less susceptible to the atmospheric conditions (such as high humidity) during the curing phase, they contain a high content of volatile compounds and are flammable. Water-borne solvents have the advantage to contain less to no volatile compounds but humidity can prevent the water from evaporating, increasing the development of spot rusting. The undercoats accomplish the barrier function. The purposes of the finish are chiefly the UV-radiation protection and aesthetics. The primer and the undercoats are often applied in paint shops and the finish on site. This information will be important when the cost of the initial painting operations and of the subsequent maintenance activities will be evaluated.

In general, the maintenance of deteriorated coatings differs with the intensity of corrosion and the dimension of the surface to be treated. The literature distinguishes three main activities corresponding to three states (Berman et al., 2013), cleaning is not considered herein:

- ‘Patch Up’, also known as ‘Touch up’, is the activity with the lowest impact on the original coating system. Surface cleaning and preparation is made on localized areas and, subsequently, an application of a compatible new coat patch is done. According to (El Sarraf and Mandeno, 2008), this causes higher labour cost compared to other maintenance activities due to the size of the treated surface. ‘Patch Up’ is usually required directly after the erection to repair damages that occurred during construction or transportation, or simply to paint surfaces that were left uncoated on purpose (before welding on site for instance). The area maintained by ‘Patch Up’ ranges between 2% and 5% of the whole surface.
- ‘Overcoating’ consists of either the removal of small deteriorated areas or of a whole layer of coating. Afterwards the whole surface gets a new compatible coating layer. According to (American Iron and Steel Institute, 2007), this yields to a service life extension of 12–15 years, with no indication of the environment category. It is often the most economic technique, especially for lead based painted bridges (American Iron and Steel Institute, 2007; NZ Transport Agency, 2014).
- In the case of ‘Remove & Replace’, all rusted areas and existing coatings are removed, the whole surface is prepared and a new coating system is applied. The containment activities (to avoid environmental contamination and to protect the job during painting) usually cause a drastic increase of the cost.

2.4. Metal coating system

Metal coatings are applied via thermal metal spray or batch hot-dip galvanizing. In the latter, steel members to EN ISO 1461 (ISO, 2012) are dipped into a bath of molten zinc (with minimum 98.5% zinc and minor elements for process control or present as impurities) at a temperature of 450 °C (Bauen mit Stahl, 2001a, 2001b).

Compared to on site painting which is quite flexible to demand and today not strongly limited due to its flexible nature, the galvanizing industry does not have the capacity to galvanize all the steel bridges that are built today mostly due to the size of the involved section. But the available capacity is sufficient to cope with the type of steel bridges that are viable for galvanizing. Besides, if the size exceeds the bath geometry, so called double dipping can be applied, by partly immersing the member.

Two associations, Zincinfo NL and EGGA, report that the total tonnage of steel galvanized in Europe is 7 million tonnes per annum with a current capacity utilisation of 56%. If we estimate that 20% of the current production is capable to process steel sections longer than 12 m (i.e. for bridges), the relevant capacity is 1.4 million tonnes. Scaled up to 100% capacity, the total capacity is 2.5 million tonnes.

In (NZ Transport Agency, 2014) and EN ISO 14713-2 (ISO, 2009a, 2009b), guidance for the maintenance of metallic coatings, either thermal metal sprayed or hot-dip galvanized, is provided. If galvanized steel needs to be maintained, ‘Patch Up’ (as for paint

Table 1
Exposure categories for paint coatings according to EN ISO 12944-2.

Categories		Typical exposure
C1	negligible	–
C2	low	Low pollution, mostly rural areas
C3	medium	Moderate pollution, urban/industrial areas, coastal areas with low salinity
C4	severe	Industrial areas, coastal areas with moderate salinity
C5-I	industrial	Industrial areas with high humidity and aggressive atmospheres
C5-M	maritime	Coastal and offshore regions with high salinity