Can Stainless Steel Reinforcement Bar Facilitate More Sustainable Railway Bridges? A Review of Life Cycle Cost and Carbon Analysis

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Abstract

Railway bridges are fundamental fixed assets. Keeping these bridges operational is of the utmost importance as costs caused by rail diversions or delays due to maintenance or replacement activities can be substantial. Reinforced concrete (RC) is a commonly used construction material for bridges as it offers versatile and economical designs. The corrosion of steel reinforcing bar (rebar) is however known as the main cause of premature deterioration of RC bridges. Stainless steel rebar, which is inherently corrosion resistant, offers a promising solution to the rebar corrosion problem in RC bridges. This paper presents a review of the current literature studies on Life Cycle Cost (LCC) and Life Cycle Assessment (LCA) of RC bridges which considered stainless steel rebar as a corrosion prevention method. A summary of the key findings together with a discussion on the analysis of the parameters which impact the outcomes of the LCC and LCA studies is firstly presented and suggestions for future LCC and LCA studies are provided. The paper concludes with an outline for future work for investigating the suitability of stainless steel rebar in RC railway bridges.

Keywords: stainless steel, reinforcement bar, life cycle cost, life cycle assessment, reinforced concrete bridges

1. Introduction

Railway bridges are fundamental fixed assets and keeping them operational is of the utmost importance as costs caused by traffic diversions and delays due to maintenance or replacement can be substantial [1]. Reinforced concrete (RC) is a commonly used material for bridges and is perceived as versatile, durable, and economical. However, RC bridges are subjected to many modes of deterioration of both concrete and steel reinforcing bars (rebar) as a consequence of their age, heavy use, and also climate and environmental factors. This is particularly important for RC bridges located in coastal regions where seawater is present in the atmosphere and also in areas where regular use of de-icing salts is required during the winter periods. These chloride containing environments lead to the initiation and propagation of chloride-induced rebar corrosion, which is considered as the most critical deterioration mechanism [2] and a major cause of concern for the durability of RC structures.

Stainless steel rebar can provide a solution to the rebar corrosion problem in RC structures as it has superior corrosion resistance compared with the traditionally used carbon steel rebar. The inherent corrosion resistance of stainless steel rebar is due to a transparent and tightly adherent self-healing thin layer ($5x10^{-6}$ mm) of chromium-rich oxide that forms on its surface. Reducing or eliminating the need for repair due to reinforcement corrosion provides the railway sector with an opportunity to reduce operational costs and environmental impact of RC railway bridges. This is particularly urgent given the twin imperatives of reducing rail industry costs in a situation where future demand and revenue levels are particularly uncertain, and reducing embedded carbon associated with rail infrastructure to meet net zero carbon targets. There is, to the authors' knowledge, presently no specific life cycle cost and life cycle assessment for RC railway bridges that consider stainless steel RC as a corrosion prevention method. However, there are several life cycle cost and life cycle assessment studies on stainless steel RC bridges in general. This paper provides a review of the current life cycle cost and life cycle assessment of stainless steel RC bridge studies to investigate the suitability of stainless steel rebar for RC railway bridges. Knowledge gaps are identified and the paper concludes by setting out the corresponding research work required to fill these gaps.

2. Life Cycle Cost (LCC) Studies

Life cycle cost studies quantify and assess the total cost of an infrastructure asset over its entire service life in terms of present money value i.e. net present values (NPV). Therefore, as a minimum LCC includes construction costs, maintenance costs, end-of-life costs and residual value of construction materials, often alongside additional costs such as user costs. Table 1 compares the initial material and construction costs as well as the life cycle cost of RC bridges employing stainless steel rebar or carbon steel rebar. In all the reported studies, stainless steel rebar was used as direct substitution for carbon steel rebars, apart from the study by Polder et al. [8], where parts of the structure were only reinforced with stainless steel and the studies by Dahlstrom & Persson [9] and Sajedi & Huang [11], where the stainless steel reinforced bridges were based on modified designs. In terms of the initial material cost, a 0.5 % to 185 % increase in cost is reported by the different studies considered. On the other hand, the life cycle cost comparisons show that over the service lives of RC bridges, stainless steel rebar offers a more cost-effective alternative, with a range of stainless steel-to-carbon steel LCC ratios varying from 0.656 to 0.974, depending on the assumed discount rate.

Study	**Initial cost increase SS/CS (%)**	**Service life & repair schedule (years)**		**LCC SS/CS**
		CS	**SS**	
McGurn [3]	0.5	80; 25,50,75	-	0.868
Kepler et al. [4]	121.6	75; 25,50	-	0.731
Schnell & Bergmann [5]	12.0	75; 40*	-	0.881
Cope et al. [6]	11.6	100; 20,40*,60	50,75	0.806
Mistry et al. [7]	20.0	79; 10,25,40,50*,60,75	44,59,79	0.712
Polder et al. [8]	4.2	100; 30,40,50,60,70,80,90	-	0.656
Dahlstrom & Persson [9]	19.0	50; 25	-	0.662
Navarro et al. [10]	185.5	100; Every 7.1 years	-	0.974
Sajedi & Huang [11]	10.3	75; Every 5 years, overlay 20,41,61	-	0.682
Cadenazzi et al. [12]	23.6	100; 45,55,65,75*	-	0.896

Table 1: Results of life cycle cost (LCC) studies comparing stainless steel (SS) reinforced concrete bridges to carbon steel (CS) reinforced concrete bridges. *Bridge/bridge component reconstruction.

As stated above, the discount rate is a major influencing factor on the outcome of LCC studies. In LCC studies the discount rate, which denotes the change in money value, is used to discount future costs when converting the costs encountered at different points in times into that at a single time. The higher the discount rate, the lower the future value of money compared to the present value will be. The LCC of stainless steel RC bridge options, assuming that little or no maintenance is required, is not significantly influenced by the discount rate. However, the LCC of carbon steel RC bridges, which have a lower initial cost, but require more maintenance during their service lives compared to stainless steel RC bridges, is much more sensitive to the discount rate. Therefore, higher discount rates decrease the influence of maintenance costs, particularly maintenance nearer the end of the service life of a structure as this will receive the greatest discount. Hence to obtain meaningful comparison results, LCC studies should utilise a discount rate which account for future uncertainties and do not undervalue future costs. For example, LCC studies set in the UK should use the HM treasury Green book's step down discount rate of 3.5% (0-30 years), 3% (31-75 years) and 2.5% (76-126 years). The discount rate percentage where the LCC performance of carbon steel RC bridges becomes greater than that of stainless steel RC bridges is called the discount rate threshold. Although, this threshold varies between the different studies, it usually occurs at low discount rates e.g. 3% and 2% as reported by Mistry et al. [7] and Cadenazzi et al. [12] studies, respectively.

Many of the present LCC studies assume that stainless steel rebar should be used as a like-for-like substitute for carbon steel rebar, but this assumption ignores any differences in the mechanical and physical properties of stainless steel rebar. Consequently, this assumption does not consider any potential savings from optimising stainless steel RC bridge design. However, the studies by Dahlstrom and Persson [9] and Sajedi and Huang [11] did optimise the stainless steel RC bridge by reducing the required rebar area, reducing concrete cover and relaxation of maximum crack widths in the concrete cover. This optimisation of stainless steel RC design was achievable by considering the higher yield strength and corrosion resistance of the considered stainless steel rebar in comparison with carbon steel rebar. Comparing the Navarro et al. [10] and Sajedi and Huang [11] studies, which use the same discount rate and similar repair schedules, optimised design in the Sajedi and Huang study lead to a significantly reduced initial cost of the stainless steel RC option. As expected, the optimised design led to a higher difference in LCC between stainless steel RC and carbon steel RC as reported in Table 1. However, these savings could be furthered if the design of RC bridges considers more of the favourable mechanical properties of stainless steel rebar such as the high ductility and high levels of strain hardening. Therefore, further research into stainless steel rebar and stainless steel RC structural elements is required to improve design guidance for stainless steel RC bridges and structures in general. In addition to optimising design, selective use of stainless steel rebar in vulnerable areas of an RC bridge by Polder et al. [8] resulted in a similar LCC difference to optimised stainless steel RC bridge design as shown in Table 1.

The location of the bridge, level of chloride concentration and the volume of traffic, can influence the outcome of LCC performance of stainless steel RC bridges. Val and Stewart [13] and Hasan et al. [14] demonstrated that, as expected the initial cost of a stainless steel RC bridge can be higher in marine and coastal environments where chloride concentrations are greater and more corrosion resistant stainless steel rebar grades may be required. User cost for RC highway bridges, such as the extra cost to commuters caused by diversions (extra fuel cost and lost production time), has been considered in a few studies ([6], [10], [9]). The conclusion from these studies indicates that, in terms of user costs, stainless steel rebar outperforms carbon steel rebar and other corrosion prevention methods due to the reduced or no maintenance requirements. For example, if user cost is considered in the Cope et al. [6] study the LCC difference between stainless steel and carbon steel rebar increases from 0.806 to 0.752. The greatest impact of user cost on LCC is achieved in high volume traffic bridges where maintenance and repairs have the greatest economic cost.

The use of stainless steel rebar has been compared with various other corrosion prevention methods and the conclusions of these studies are mixed. Navarro et al. [10] demonstrated that stainless steel rebar performed poorly, in terms of LCC, in comparison with other corrosion methods due to the greater initial cost of stainless steel rebar compared with the other corrosion prevention methods analysed. However, Navarro et al. [10] assumed that corrosion of carbon steel rebar is prevented through the removal of concrete before the chloride threshold (chloride concentration which initiates corrosion) is met and replaced with new uncontaminated concrete. This assumption relies on replacement concrete having the same durability as the original concrete which is based on many parameters (including observing best repair practices and the skills of the workers conducting the repair) [15] and that maintenance will be carried out before corrosion of rebar begins. However, an economic recession, like that in 2008, could lead to a reduction in maintenance spending [16], thus resulting in this required maintenance not occurring and increasing future costs. Studies which compared stainless steel rebar and fibre-reinforced-polymer (FRP) rebar have contradictory conclusions ([8], [12]). Hence, further LCC studies which compare optimised stainless steel and FRP RC bridge designs are required. The LCC performance of an optimised stainless steel RC bridge or the selective use of SS rebar has been demonstrated to outperform other corrosion prevention methods in a LCC context ([11], [8]).

The use of stainless steel rebar in RC bridge structures were shown to lead to potential LCC savings depending on the aforementioned parameters. However, future LCC studies of RC bridges with stainless steel should include the following recommendations. The present LCC studies assume an exponential discount rate that could undervalue future costs, therefore potentially creating an ethical dilemma of prioritising the needs of the present generation over the needs of future generations. Therefore, the use of hyperbolic discount rates (which reduce the discount rate over time) may reduce the possible undervaluing of future maintenance costs. The design of stainless steel RC bridges should be optimised to utilise the material and physical properties of stainless steel rebar, like that by [11] and [9], for a more equal comparison between stainless steel RC and other corrosion prevention methods. Furthermore, study periods of 125+ years should be investigated, and associated embedded and operational carbon should be included and monetised in LCC studies.

3. Life Cycle Assessment (LCA) Studies

Life cycle assessment studies focus on quantifying and comparing the environmental impacts of an infrastructure asset throughout its life cycle. LCA studies comparing the environmental impacts of stainless steel and carbon steel RC bridges have been carried out by a number of studies ([7], [12], [18]) and the conclusions of these studies differ based on the LCA methodology selected and the impact categories included.

Both Mistry et al. [7] and Cadenazzi et al. [12] used *mid-point methodologies*, which compare environmental impact in the middle of a cause and effect chain (e.g. kg of carbon dioxide (CO_2) equivalent), and involve comparing different environmental impacts at an individual level. The individual impact categories investigated in both of these studies were global warming potential, photochemical oxidant creation, acidification and eutrophication (ozone depletion was also included by Cadenazzi et al. [12]). In terms of a cradle-to-gate approach, stainless steel rebar was shown to perform less favourably in all the investigated environmental impact categories compared to carbon steel rebar. However, when considering the environmental impacts over the whole life cycle, i.e. adopting a cradle-to-end of life approach, stainless steel was shown to have a superior performance due to the lower or no maintenance works required.

Navarro et al. [18] used an *end-point methodology* (ECO-Indicator 99) that assesses the environmental impact at the end of a cause and effect chain (e.g. respiratory effects), and encapsulates the entire environmental impact of various impact categorises into a single score for different design options. In the ECO-Indicator end-point methodology, 10 impact categories, which are similar to mid-point individual impact categories, are quantified into three weighted damage categories – these are human health impacts, ecosystem damage and use of resources. The scores for stainless steel RC options were evaluated and compared to the reference carbon steel RC option, which was given a baseline value of 100 – scores lower than this baseline value indicate improved environmental impact.

The stainless steel RC option was found to outperform the carbon steel RC option in the human health impacts damage category. In the ecosystem damage category, the stainless steel RC outperformed carbon steel RC in two out of the three impact categories; these are the land-use and acidification and eutrophication which scored 43 and 62, respectively. Nevertheless, the ecotoxicity impact category score of stainless steel RC was 8.53 times greater than carbon steel RC, due to its greater amount of heavy metals, such as chromium and nickel, which resulted in stainless steel performing poorer in the ecosystem damage category. The use of resources damage category is made of two impact categories: fossil fuel extraction and mineral extraction. Although the stainless steel RC option has a fossil fuel extraction score of 35, the mineral extraction score was 13.18 times greater than the carbon steel RC option. The stainless steel RC option was therefore regarded as having a worse overall environmental impact than carbon steel RC option due to its overall poorer performance in the ecosystem damage and the use of resources damage categories. However, the mineral extraction impact value by Navarro et al. [18] is questionable as it is not discussed if any recycled steel is used in the production of the stainless steel rebar, which on average contains 44% recycled steel [19], and hence, the stainless steel RC mineral extraction impact category value could be lower if this is considered.

Additionally, Navarro et al. [19] considered the impact of using other LCA methodologies on the outcome of LCA studies and found that the ReCIPe[i] LCA methodology, which combines the ECO-indicator end-point methodology with a mid-point methodology, resulted in the stainless steel RC bridge having a better LCA performance than

[i] Is an acronym of the initials of the institutions that developed ReCIPe: RIVM, Radboud University, CML and PRé.

the reference carbon steel RC bridge. However, the performance of stainless steel RC using the ReCIPe methodology was still poorer than other corrosion prevention options. Furthermore, in all the present LCA studies, irrespective of the methodology, stainless steel rebar is used as a like-for-like replacement for carbon steel. Therefore, any potential reductions in the amount of reinforcement bar, as considered in the Sajedi and Huang LCC study [11], which could lead to lower environmental impact is not considered in these studies.

In all the comparison studies, the present literature agrees that the carbon footprint of stainless steel RC bridges is lower than that of the reference carbon steel RC bridges. In the Mistry et al. [7] and Cadenazzi et al. [12] studies, it is shown that the global warming impacts, measured in units of kg of CO_2 equivalent, of carbon steel RC design is between 31-70% greater than that of stainless steel RC design. In terms of the climate change potential, based on the contribution of CO_2, the ECO-Indicator score of carbon steel is reported to be 30% [18] greater than the stainless steel RC option. Hence, although stainless steel rebar and other RC corrosion prevention methods are not entirely carbon neutral, reducing the overall embedded and operational carbon is still of crucial importance, as lower carbon emissions are easier to offset with carbon negative projects e.g. afforestation and reforestation.

Based on the limited LCA research, the choice of LCA methodology has been shown to be an important influencing factor on the outcome of LCA studies on RC bridges. While mid-point methodologies provide insight into the impact of individual environmental parameters, they do not provide a single LCA score to allow comparison of different design options. In contrast, end-point methodologies provide a single LCA value to compare different design options, and are therefore viewed as a more relevant measure to decision makers. It is recommended that in future LCA studies both the mid-point and end-point methodologies should be used in tandem. Furthermore, due to the climate crisis it is suggested that greenhouse gas emissions be categorised as a damage category in end-point methodologies and be weighted alongside human health impacts, ecosystem damage and use of resources. Moreover, LCA studies should use optimised stainless steel RC bridge design and include longer study periods.

5. Conclusion and Future Work

Creating more economical and environmentally conscious railway infrastructure is of the utmost importance due to the uncertainty around the future demand and revenue of the rail sector and the need to reduce the carbon footprint of infrastructure to meet net-zero targets. The present LCC and LCA literature has demonstrated that the minimal maintenance/maintenance-free service life of stainless steel RC can result in bridges with reduced LCC and carbon emissions compared with carbon steel RC. The influencing parameters which determine the outcomes of LCC (discount rate, optimised stainless steel RC design and location) and LCA studies (methodology) have been discussed. To build upon the findings from the current literature, the following recommendations are made for future assessment of stainless steel reinforced concrete bridge structure:

- A joint LCC and LCA study which compares an optimised stainless steel RC bridge design with a present carbon steel RC bridge design (using historic bridge maintenance data of the carbon steel RC bridges included to create a realistic maintenance schedule) for a true comparative study.
- LCC and LCA studies that consider a range of case study railway bridges with different geographical locations subjected to different levels of chloride concentration and traffic volumes.
- An LCC approach that uses a discount rate methodology which will not undervalue future costs.
- LCA assessments that are based on both the mid-point and end-point methodologies for an improved understanding of the associated environmental, and the monetisation of LCA into LCC.
- Green house gas emissions are categorised as a damage category in LCA.
- LCC and LCA studies which also incorporate Social Life Cycle Assessment (SLCA) in a UK rail context.

Acknowledgment

The authors thank Network Rail and EPSRC for their professional and financial support of this research. Furthermore, the authors thank all those who provided comments on the paper and the continued support from the University of Southampton. Please note this paper is subject to Network Rail approval.

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