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ORIGINAL ARTICLE

Life Cycle Cost and Life Cycle Assessment of Composite Bridge with Flat and Corrugated Webs

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Abstract

To satisfy the sustainability criteria, a bridge design must be economically viable during its entire service life with a minimal impact on the environment. While stainless steel is known for its excellent life cycle performance, its high cost prevents it from being used in bridges to a larger extent. This study evaluates a new design solution that takes advantage of using corrugated web in bridge girders to overcome this issue. Three design concepts are evaluated for a three-span case-study bridge. These include a bridge with carbon steel flat web, stainless steel flat web, and stainless-steel corrugated web girders. Each design is optimized using a genetic algorithm. The three optimal solutions are then evaluated in terms of investment costs, life cycle costs (LCC) and life cycle impact. The results show that the investment costs in a flat web girder bridge increase by 27% when stainless steel is used instead of C-Mn (carbon) steel. However, this increase is only 10% when corrugated web girders are used. On the other hand, the LCC savings increase from 6% to 18% for corrugated web girders. Finally, the use of corrugated web in stainless steel leads to a reduction in the climate impacts of up to 32% compared to carbon steel for the studied bridge.

Keywords

Optimization, genetic algorithm, Investment cost, LCC, LCA, Composite bridges, Road bridges, Corrugated web, Duplex, Stainless steel

1 Introduction

Sustainable development is a concept that now guides public and private sector strategies. The United Nations established the 2030 Agenda for Sustainable Development in 2015, along with 17 Sustainable Development Goals [1]. The European Union also prioritizes sustainable development but faces challenges in reducing the environmental impact of buildings and construction sector [2], which accounts for 35% of the greenhouse gas emissions in Europe [3].

Due to the huge economic and environmental impacts, the bridge industry is showing an increased interest in sustainable development [4]. For steel and composite bridges, carbon steel flat web girders, (Figure 1a), are the commonly used design concept for twin I-girders composite road bridges. Carbon steel, despite being the most popular material until recently, is not the most environmentally friendly material. Carbon steel leads to a significant amount of CO2 emissions during manufacturing as well as during the usage phase due to the regular maintenance activities required during the service life.

A new alternative, comprising stainless steel corrugated web girders is evaluated in this study as an alternative design solution to carbon steel flat web girders. While the use of stainless steel may increase the bridge investment costs; the bridge lifecycle may be more cost-efficient. In addition, the use of corrugated web may result in a solution with reduced CO2 footprint, (Figure 1b). The primary reason for choosing stainless steel is the corrosion resistance properties. One of the most prevalent types of stainless steel, which is used in this study, is LDX2101 stainless steel (duplex 1.4162). It is composed of austenite and ferrite. Ferrite possesses a higher strength, whereas austenite is ideal for structural applications because of its ductility, toughness, and excellent corrosion resistance [5]. According to Baddoo et al. [6], the use of stainless steel in bridge construction has a great potential. Karabulut et al. [7] demonstrated in a case study of a continuous road bridge that stainless steel can lower life cycle costs when the design life span is larger than 75 years. However, despite having excellent structural properties and life cycle performance, stainless steel is still not commonly used in bridges because of the high investment cost. Stainless steel costs almost three times as much per kilogram as carbon steel. Therefore, using a corrugated web instead of a flat one can provide the required

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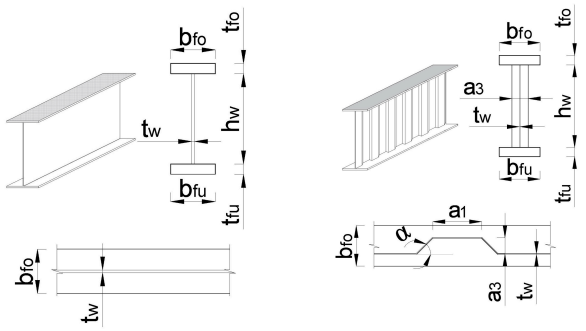
structural capacity while using much less material and thus lower investment cost [8].

This study aims at evaluating the effectiveness of the design concept of stainless-steel corrugated web girders as an alternative for the conventional concept for road bridge girders. A genetic algorithm design and optimization tool is developed and used to optimize the design of the three considered concepts including S355 flat web girders as it is the most used concept for composite bridges in Sweden [9], LDX2101 flat web girders (the conventional concept with stainless steel material), and LDX2101 corrugated web girders for a case study of a three-span bridge. The optimization is done with reference to weight, and the resulting solutions are then evaluated with reference to their life cycle cost (LCC) and climate impact.



(a) (b)

Figure 1 Bridge girder: (a) with flat web, (b) with corrugated web

2 Method

2.1 Optimization routine

The optimization routine established in this work, summarized in Figure 2, begins by inputting relevant design data such as material parameters, environmental inputs (wind speed, relative humidity), and concrete casting sequence. The program then proceeds with designing the concrete deck. Each span is divided into seven segments with the goal of optimizing their dimensions while meeting structural requirements in ultimate limit state (ULS), serviceability limit state (SLS), and fatigue limit state (FLS) while minimizing the total weight of the steel superstructure. The optimization is conducted in several rounds since the bridge is an indeterminate structure and the distribution of the sectional forces is dependent on the distribution of stiffness. The optimization procedure is as follows: In the first step, a system analysis is performed using a randomly generated design vector. A genetic algorithm is then used to optimize the design vector, i.e., steel superstructure. In the second step, the system analysis is updated with the optimized design vector and the process is repeated until the sectional forces converge.

Some design variables, such as the flange thicknesses t_{fo}, t_{fu}, the web height h_w, the corrugation parameters a_1, a_3, α, and the distance between the cross beams in span CCB_{span} and over the supports $CCB_{support}$ are optimized while remaining constant along the bridge's length. Other design variables, such as the top and bottom flange widths b_{fo}, b_{fu} and the web thickness t_w, are allowed to vary at each segment. The optimization vector can be expressed as follows:

$$X = [h_w, t_{w1}, \dots . t_{wn}, a_1, a_3, \alpha, CCB_{span},$$

$$CCB_{support}, b_{fo1}, b_{fu1}, \dots \dots, b_{fon}, b_{fun}, t_{fo}, t_{fu}] \quad (1)$$

Where n denotes the number of segments per half bridge (due to symmetry).

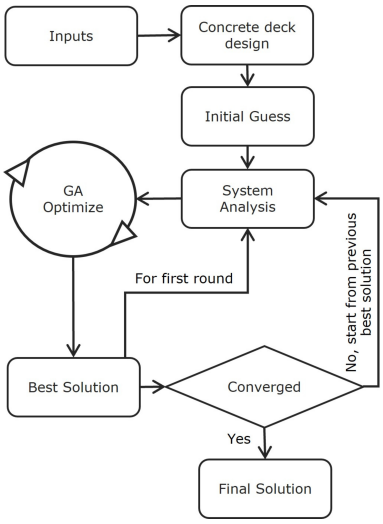


Figure 2 Optimization routine

The considered domains for the design variables based on common available values are the following:

- $t_{w\ (corrugated\ web)}$ $[mm]$: $4, 5, 6, 7, 8, 9, 10, 11, 12$
- $t_{w\ (flat\ web)}$ $[mm]$: $14, 15, 20, 25$
- t_f $[mm]$: $20, 25, 28, 30, 35, 40, 45, 50, 55, 60, 65, 70, 75$
- b_f $[mm]$: 400 to 2500, step $= 100$
- h_w $[mm]$ L/40 to L/20, step $= 100$ (limited to the required 2800 mm for the studied bridge)
- a_1, a_3 $[mm]$: 50 to 400, step 25
- α $[degrees]$: 30 to 45, step$= 5$
- $CCB_{span}, CCB_{support}$ $[mm]$: 4000 to 8000, step$= 500$

The employed genetic algorithm module "geneticalgorithm2" in this work was developed by Demetri Pascal [10] based on Solvi's genetic algorithm module "genetic algorithm" [11]. In the developed module a new function "set function" is added to allow for parallelism. Parallelization is recommended for heavy functions and big populations such as the optimization problem that is tackled in this paper. The genetic algorithm module "geneticalgorithm2" is accessible for free on The Python Package Index website (PyPI.org).

2.2 Life cycle cost (LCC) function

To compare the different concepts from an economic standpoint, a function that estimates overall expenses over the bridge's service life is developed in this work. According to Rossi et al. [12], the classification of life cycle modules that are developed for buildings could also be used for bridges. Therefore, based on this classification the system boundaries considered in this work are defined in Table 1.

Table 1 The life cycle stages included in the system boundary for LCC calculation for a bridge construction (reproduced based on classification of building life cycle modules in EN 15978-2011)

Product stage			Construction stage	Use stage			benefits and loads beyond the system boundaries
A1: Raw material supply	A2: Transport	A3: Manufacturing	A5: Construction/ installation	B1: Use	B2: Maintenance	B4: Replacement	D: Reuse, recovery, and recycling potential

To reflect the differences between stainless steel and conventional carbon steel girders and to improve the accuracy of LCC results, the reference prices should reflect the current market prices; thus, the unit costs and production cost calculations integrated into the Python function for LCC are obtained by interviewing three production companies. Production costs comprise the costs associated with cutting, welding and assembly, web corrugating, painting/pickling, plate edge grinding, shear studs welding, and concrete casting. Prices for welding are determined by the type of the welding, i.e., fillet weld or butt weld. The erection expenses are also included based on the number of splices required for the main girders and cross beams. Other costs (such as earthwork, transportation, and so on) are excluded in these modules, as these are very case-specific. The expenses for the maintenance activities are derived from the maintenance plan operations provided by Swedish Transport Administration (Trafikverket), illustrated in Table 2. The costs for maintenance activities are adopted from the Swedish bridge and tunnel management system (BaTMan) [13]. The expenses connected to the end-of-life (EOL) phase are assumed to have no impact on the results of the design alternative comparison and, therefore, they are excluded from LCC calculations. However, given the higher price of stainless-steel scraps compared to carbon steel, module D is included.

Table 2 Painting plan for a steel bridge in the environmental category C4 for 120 years (provided by Trafikverket)

Activity [m²]	Action time	Reference unit	Relative
Patch up	20 years	Initial painted surface	10%
Overcoating	40 years	Initial painted surface	20%
Remove & replace	60 years	Initial painted surface	100%
Patch up	80 years	Initial painted surface	10%
Overcoating	100 years	Initial painted surface	30%

2.3 Life cycle assessment (LCA) function

In accordance with the European standard EN 15978-2011 [14], a life cycle assessment (LCA) function is developed in Python in this work. The developed LCA function, as for LCC function, takes into consideration the same categorization of building life cycle modules. The modules that have been considered in the LCA function are displayed in Table 3.

Stainless-steel bridges require significantly less maintenance than carbon steel bridges due to their corrosion resistance. Therefore, during the usage stage, the focus is put on the scheduled periodic maintenance B2 and replacement B4 activities. Both the production and transportation of the painting used for the periodic painting are considered.

Table 3 The life cycle stages included in the system boundary for LCA calculation for a bridge construction (reproduced based on classification of building life cycle modules in EN 15978-2011)

Product stage			Construction stage	Use stage		End of Life stage		
A1: Raw material supply	A2: Transport	A3: Manufacturing	A4: Transport	B2: Maintenance	B4: Replacement	C2: Transport	C3: Waste processing	C4: Disposal

According to Du et al. [15] one of the important variables influencing the final LCA outcomes is the EOL plan for bridge demolition waste. The system boundaries therefore include modules C3 and C4. Module D, which addresses the environmental benefits and loads of using recycled materials in bridge construction, such as steel waste and concrete rubble, is optional in the European standards [16], and it is not assessed within the scope of this work.

The unit impacts for the steel materials are based on Environmental Production Declarations (EPDs) provided by two manufacturing companies. The OpenLCA 1.10.3 program is used to extract the environmental impacts for other materials and processes using Ecoinvent 3.8 cut-off system model database [17]. CML2001 is employed as life cycle impact assessment method and the focus is put on the impact category of Global Warming Potential over a 100-year time horizon (GWP 100a), since it is the most common indicator of LCA in bridges [15].

3 Description of the case study

A case study of a three-span continuous bridge with a total length of 190 meters across the Dalälven River in Avesta municipality in Sweden is investigated. The span lengths that are being evaluated are: 55 m, 80 m, and 55 m, see Figure 3. Transversally, the overall required bridge width is 12.8 meters with two traffic lanes. The cross-section of the bridge superstructure is illustrated in Figure 4.

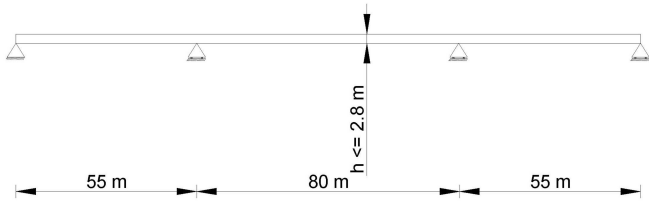


Figure 3 Bridge span configuration

The design requires an average delay traffic of 11,000 vehicles per day, which corresponds to medium flow rates of lorries on roads and motorways, and an indicative number of heavy vehicles per slow lane of around 500 000 according to Collin et al. [18].

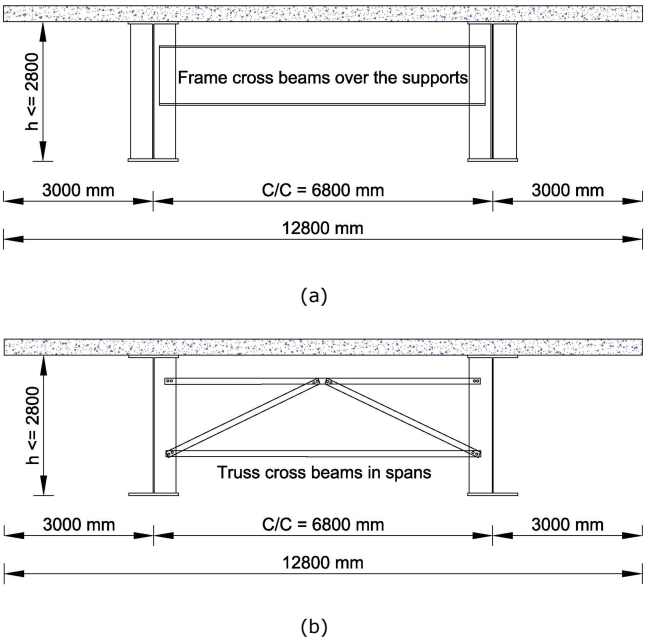


Figure 4 The cross-section of the bridge superstructure: (a) over the supports; (b) in the spans

4 Results and discussion

The Flat S355, Flat LDX2101, and Corrugated LDX2101 design concepts are all optimized using the developed optimization tool. This section presents the optimization results together with a comparison of the three optimal solutions' weights, investment costs, LCCs, and LCAs.

4.1 Optimization results

Table 4 displays the maximum utilization ratio for each bridge segment in Flat S355 optimal design that is obtained from the optimization tool. As can be observed, all utilization ratios are close to 1 meaning that all segments are approximately fully utilized. The design is governed mostly by the bending moment in the middle span and fatigue detail C (Figure 5) in the outer spans. The two further design solutions, i.e., Flat LDX2101 and Corrugated LDX2101, follow the same pattern. However, detail D (Figure 5) controls the fatigue limit state in the Corrugated LDX2101 concept.

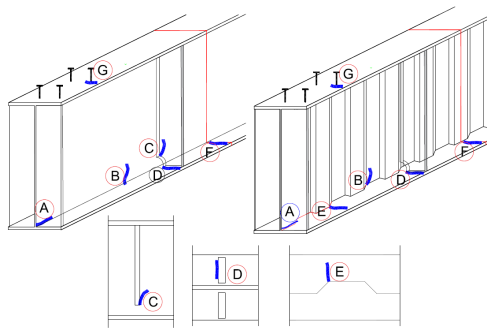
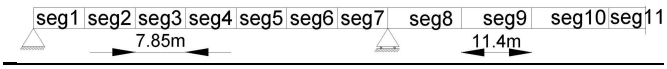


Figure 5 The critical fatigue details in the studied bridge girder.

One of the main benefits of corrugated web beams is the additional support they provide to the lower flange in continuous beams against lateral-torsional buckling due to their high out-of-plane bending stiffness. To account for this, a model, where the flange is treated as a column on elastic supports, provided by Galambos et al. [19] is implemented in the optimization tool for lateral torsional buckling check over mid-supports. It is observed that the optimization tool chooses a larger spacing between the cross beams when using corrugated web (4.5 m for Flat LDX2101 and Flat S355 against 5 m for Corrugated LDX2101), which can be explained by the extra stability the corrugated web provides.

Table 4 Overview of the bridge segments' utilization ratios. Given that the bridge is symmetrical so just one half of it is shown. Segment length is 7.85 m in outer span and 11.4 m in midspan.



	Flat S355
Seg 1	91% shear, service phase
Seg 2	92% moment, service phase
Seg 3	100% fatigue, detail C
Seg 4	96% fatigue, detail C
Seg 5	94% fatigue, detail C
Seg 6	100% fatigue, detail C
Seg 7	100% moment, service phase 98% LT-buckling, service
Seg 8	100% moment, service phase 98% LT-buckling, service
Seg 9	97% moment, service phase
Seg 10	94% moment, service phase
Seg 11	97% moment, service phase

4.2 Total weight

By evaluating the three optimal solutions with reference to the total weight, see Figure 6, it is observed that the overall weight of the Flat S355 option is approximately 386 tons. When the Flat LDX2101 option is used, this weight is reduced to 353 tons. Further reduction is observed when implementing the Corrugated LDX2101 option, resulting in a total weight of 296 tons. Hence, while transitioning from Flat S355 to Flat LDX2101 results in a 9% decrease in weight, transitioning from Flat S355 to Corrugated LDX2101 allows for around 23% reduction in weight.

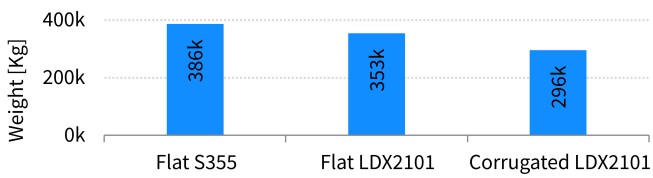


Figure 6 The total weight for the three optimal solutions

A further observation is that the web plate is the primary source of the weight reduction. The web weight for Flat S355 and Flat LDX2101 options is comparable; however, it is reduced by around half when using the Corrugated LDX2101 option. This is due to the high shear strength of the corrugated web, which allows for the provision of the required shear capacity with substantially thinner webs (4

to 10 mm, as opposed to the 14 to 25 mm for the flat webs). Furthermore, while using Flat LDX2101 results in a weight reduction in flanges due to the material's higher strength compared to S355, the same reduction is not observed when using Corrugated LDX2101. Herein, the web height is limited to 2.8 m, however, an additional saving from the flanges is expected when deeper girders are used.

4.3 LCC

When the overall lifecycle costs for the three options are compared, see Figure 7, it is seen that maintenance accounts for a considerable amount of the cost for the carbon steel option (around 24%). The Flat LDX2101 alternative avoids maintenance costs while increasing material costs, resulting in only a 6% savings in overall lifecycle cost. The Corrugated LDX2101 option, on the other hand, removes maintenance costs as well, but the 23% weight reduction yields in a 18% savings in overall lifecycle cost despite the higher material cost.

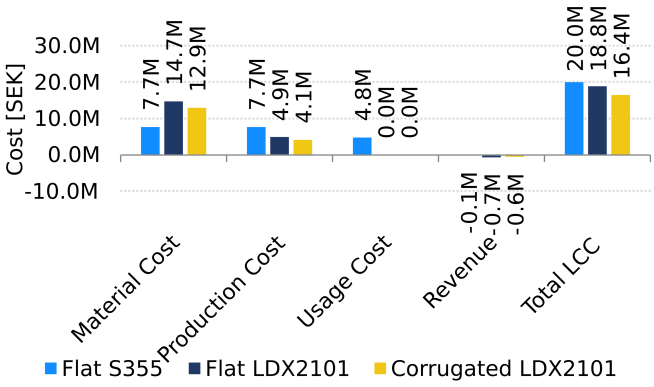


Figure 7 LCC comparison for the three optimal solutions

Furthermore, Flat LDX2101 has a lower production cost than Flat S355 due to the absence of painting and grinding requirements, which are replaced with a less expensive pickling process. The cost of pickling is around a third of the painting cost. Furthermore, the Corrugated LDX2101 option has a lower production cost than Flat LDX2101 due to the absence of painting and a shorter welding length achieved by using fewer cross beams; for Corrugated LDX2101, the algorithm selected 5 m between the cross beams over the support compared to 4.5 m in the case of flat web.

4.4 LCA

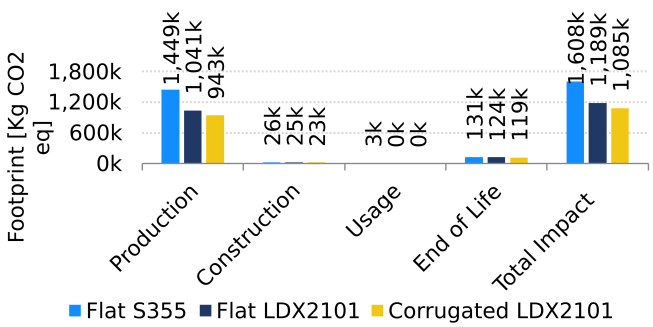


Figure 8 LCA comparison for the three optimal solutions

The LCA results of the three options, illustrated in Figure 8, revealed that the production phase has the largest CO2 footprint, whereas the end-of-life phase (waste processing + disposal) contributes about 10%. The carbon steel option's maintenance work accounts for about 2% of the CO2 footprint. The entire footprint for the Flat S355 option is approximately 1,608,000 kg CO2 eq, see Figure 8.

5 Discussion

Figure 9 summarizes the investment costs, LCC and LCA results for the three obtained optimal solutions. The results are significantly affected by the cost ratio between S355 and LDX2101, which is assumed to be 3 here, i.e., one kilogram of LDX2101 costs three times as much as one kilogram of S355. The saving will drop when this ratio increases.

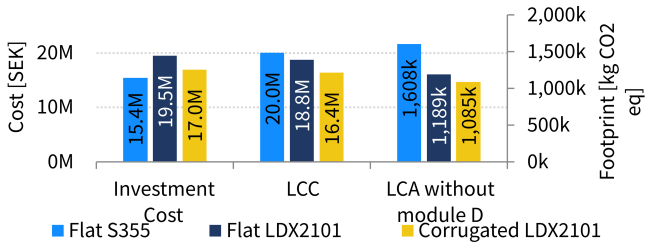


Figure 9 Investment/LCC/LCA comparison for the three optimal solutions

Moreover, the previous conclusions were reached based on certain assumptions, specifically a 1.5% inflation rate and a 3.5% discount rate, both taken from Safi [20] and based on Trafikverket 2013 notations. It is important to recognize that the assumed discount and inflation rates can have a substantial influence on the conclusion of an LCC assessment. A sensitivity of the results to these values are presented in Figure 10. As can be noted, the LCC of the employed concept increases with increasing the discount rate and decreases with increasing the inflation rate. This is opposite for carbon steel concept because considerable part of the LCC comes from the maintenance costs which is not the case for LDX2101 (the future costs for LDX2101 is just the reselling at the end of life). Therefore, the Corrugated LDX2101concept becomes more competitive for low discount rates and high inflation rates.

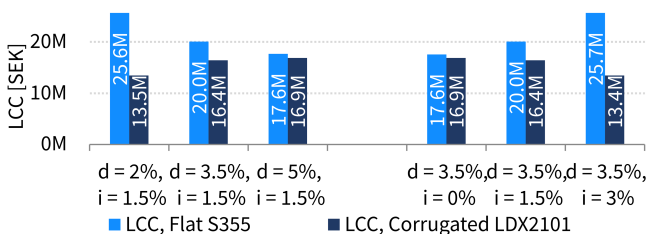


Figure 10 Sensitivity analysis of LCC potential savings to discount (d) and inflation rates (i)

Furthermore, the corrugated web solution demonstrated an 18% lower LCC with the maintenance schedule utilized in this study (Figure 10). It is noteworthy that this painting schedule only requires one repaint during the entire service life. However, the benefits of using stainless steel will become more pronounced with a more intensive maintenance schedule, such as the one proposed by Rossi et al.

[12]. Thus, using a corrugated web makes more sense for stainless steel material, as it doesn't add painting costs.

Finally, previous studies have highlighted the potential advantages of stainless steel in terms of LCC. However, the high initial investment costs have hindered its prevalent use. Nevertheless, the results in Figure 9 demonstrate that the investment costs for stainless steel can be significantly reduced with the implementation of a corrugated web design resulting in a mere 10% higher investment cost compared to S355.

Employing a corrugated web in bridge construction reduces material but increases painting area. Painting and re-painting work account for a considerable amount of the investment and LCC expenses (around 23% and 40%, respectively). Therefore, the use of corrugated webs becomes of particular interest when stainless steel is the material selected for the bridge.

6 Summary and Conclusion

This study proposes a more climate-friendly design solution for stainless steel-concrete composite bridges that comprises corrugated web girders. Three design solutions, namely, Flat S355, Flat LDX2101, and Corrugated LDX2101 are optimized and compared in terms of weight, investment cost, LCC, and LCA. The results show that the Flat LDX2101 solution has a 27% investment cost premium over the Flat S355 alternative for a price ratio of three, whilst LDX2101 Corrugated option has a comparatively minor investment cost increase of roughly 10%.

Regarding LCC, the Flat LDX2101 concept shows limited benefits, with only a 6% decrease compared to S355. Corrugated web, however, offered an 18% reduction in LCC.

Furthermore, the LCA results show that LDX2101 solutions have a continuously lower climate impact with the corrugated web solution performing better than the flat web alternative due to less material usage.

It is important to keep in mind that factors affecting LCC, such as discount and inflation rates, as well as painting schedules, have a large effect on the total LCC results. Regardless of these factors, the conclusion—that using a corrugated web design can substantially lower investment costs for stainless steel to just 10% higher than S355—remains valid.

Research conclusions are based on limited three-span case study with predefined conditions. A detailed study of various conditions is needed.

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