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Citation for the original published paper (version of record):

Hlal, F., Amani, M., al-Emrani, M. (2023). Stainless steel corrugated web girders for composite road bridges: Optimization and parametric studies. Engineering Structures, 302. http://dx.doi.org/10.1016/j.engstruct.2023.117366

Engineering Structures 302 (2024) 117366

Contents lists available at ScienceDirect

Engineering Structures

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

Stainless steel corrugated web girders for composite road bridges: Optimization and parametric studies

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ARTICLE INFO

Keywords:
Optimization
Genetic algorithm
Investment cost
LCC
LCA
Composite bridges
Road bridges
Corrugated web
Duplex
Stainless steel

ABSTRACT

To achieve sustainability in bridge design, it is critical to ensure both economic viability and low environmental impact. While stainless steel has great mechanical properties and life cycle performance, the material is expensive, which has limited its use in bridges. This research aims at exploring the benefits of using stainless steel corrugated web girders as an alternative to carbon steel flat web girders in composite road bridges. This concept is expected to lower the investment cost, which enables a broader utilization of the good properties offered by stainless steel. A genetic algorithm optimization routine has been developed to produce bridge designs with minimum weight, investment cost, life cycle cost (LCC), or life cycle impact. Multiple parametric studies are conducted using a simply supported reference bridge. The optimal design solutions are compared for two main design alternatives: conventional S355 flat web girders and duplex (EN 1.4162) corrugated web girders. The parametric studies consider the effects of different design parameters, including the span length, available girder depth, average daily traffic (ADT) with the corresponding indicated number of heavy vehicles in the slow lane (N_{obs}), and the paint maintenance schedule, on the optimal solutions. Furthermore, a sensitivity analysis is carried out to analyse the impact of inflation and discount rates on the obtained results. The results show that the concept of stainless steel corrugated web girders offers significant potential LCC and environmental impact saving for the examined span lengths, particularly in the case of deeper girders, high ADTs, and more intensive maintenance activities. Also, despite the influence of inflation and discount rates on LCC results, the studied concept consistently demonstrated favorable results.

1. Introduction

Nowadays, sustainability is a priority in the design, construction, and maintenance of civil engineering structures [1]. The United Nations established the 2030 Agenda for Sustainable Development in 2015, along with 17 Sustainable Development Goals (SDGs) [2]. The SDGs address urgent and crucial concerns that humans are currently confronted with, such as climate change and resource depletion [2]. The Communication "Next Steps for a Sustainable European Future" makes it clear that the European Union (EU) prioritizes the transition to a sustainable society [3]. One of the biggest obstacles for the EU in achieving its aim of reducing climate change is mitigating the environmental impacts of buildings and construction. The construction and building sector in the EU accounts for around 40% of total energy final consumption, 35% of greenhouse gas emissions (GHG), and more than 50% of all extracted materials [4]. Furthermore, the construction industry generates a large amount of waste, accounting for one-third of the EU's yearly waste creation [5].

The bridge industry has shown growing interest in sustainable development, particularly in light of its huge potential impacts on the economy and environment [6]. Composite bridges are well-known bridge types, usually designed with steel girders having flat webs (Fig. 1a) and connected to a concrete deck using shear studs. The shear studs allow composite action and enable the best possible utilization of the two materials [7]. The steel girders are typically made of conventional carbon steel, which is prone to corrosion and necessitates frequent maintenance in the form of inspection, repainting, and replacement throughout its service life. In addition to the costs of these activities, the impact on the environment and the disruption of traffic during the maintenance work are considerable [8].

To mitigate the problems associated with maintenance activities, stainless steel is a good solution. Corrosion resistance is the main

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https://doi.org/10.1016/j.engstruct.2023.117366
Received 3 July 2023; Received in revised form 20 October 2023; Accepted 13 December 2023

justification for using stainless steel [9]. The high durability and corrosion resistance of stainless steel can be utilized to minimize the need for maintenance during the bridge's design life, leading to a lower life cycle cost. The term "stainless steel" refers to a group of alloys with at least 10.5% chromium that, when exposed to water and oxygen, forms a protective layer against corrosion. Duplex stainless steels are the most commonly used type in bridge applications because of their excellent strength and corrosion resistance [1]. Duplex stainless steel is composed of austenite and ferrite. Ferrite increases strength, whereas austenite is ideal for structural applications because of its ductility, toughness, and excellent corrosion resistance [10]. Not only that but also duplex stainless steel has a comparable or higher strength-to-weight ratio compared to carbon steel. In addition, stainless steel's improved fire resistance makes it useful for civil engineering applications [11].

Previous studies have shown a great potential for stainless steel in bridge construction [1,9]. Karabulut et al. [12] 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. Moreover, many other case studies have demonstrated the potential life cycle cost saving of using stainless steel [8, 13–15]. However, despite having excellent structural properties and life cycle performance, stainless steel is still not commonly used in bridges because of the high initial investment cost; per kilogram, stainless steel costs almost three times as much as carbon steel [8].

Steel girders are typically made of flat plates, e.g., webs and flanges. A deeper web plate can contribute to higher bending and shear resistance. However, to ensure stability for deeper girders, the web must either be made thicker or stiffened with longitudinal and/or transverse stiffeners. Generally speaking, this will result in increased production costs and additional welded details that will in turn affect the design due to fatigue consideration. A corrugated web girder (Fig. 1b) may well be employed to achieve the required bending and shear capacity by increasing the depth with much thinner plates and fewer stiffeners, resulting in considerable material saving [16]. Based on this, corrugating the web in steel-concrete composite bridges seems like a highly interesting design solution to minimize material and manufacturing costs, which has the potential to lower the investment cost in the case of employing stainless steel.

Corrugated web girders in combination with stainless steel material were studied in preliminary work by Wahlsten et al. [8] as a new design solution for both road and railway bridge girders. The study showed a considerable potential saving from using the new concept in terms of both material and life cycle costs. However, the study, as well as previous studies [8, 13–15], was conducted on a specific case study, and the comparison was made by merely changing the material of the carbon steel to stainless steel while all other design parameters (e.g., the number and locations of changes in the cross-section) remained the same as in the original design. However, due to the difference in material price between C-Mn steel and stainless steel and as the behavior and design of corrugated web girders differ in comparison to conventional flat web girders, a direct transfer of the design parameters from the latter to the former will not reflect the real potential the studied concept has. In addition, there is a need to explore the design space of the new concept, e.g., the effects of changing several design inputs, such as the average daily traffic (ADT), height limitations, and span length. This is significant because the most feasible design solution may differ based on the different inputs, and a more informed decision-making process can be obtained by a thorough investigation of the design space.

The primary goal of this work is to study the feasibility of this new concept and examine its competitiveness compared to the conventional concept. Some important design parameters are investigated to give the study a broader application area and to explore the design space of road bridges in more detail. Evaluation is done with reference to weight, investment cost, LCC (Life Cycle Cost), and LCA (Life Cycle Assessment). An optimization routine based on a genetic algorithm is first developed. The routine can produce the optimal design solution given a set of design input parameters. The optimization objective can be set to minimize the total weight, investment cost, life cycle cost, or life cycle impact. An existing simply supported bridge located in Böle, Sweden, is redesigned through the developed design and optimization tool, employing the two design concepts of flat web carbon steel girders and corrugated web stainless steel girders separately. The optimization of the two design concepts is done with reference to weight, investment cost, life cycle cost, and life cycle impacts separately, and the obtained optimal solutions are then evaluated and compared. Following that, the benefit of using the stainless-steel corrugated web solution is studied under the effects of changing influencing design parameters that are believed to have a high impact on the design. These include the cost and intervals of painting activities, the average daily traffic, the number of heavy vehicles per slow lane, the girder's height limitation, and span length. Additionally, the effects of changes in the assumed inflation and discount rates on the results are assessed.

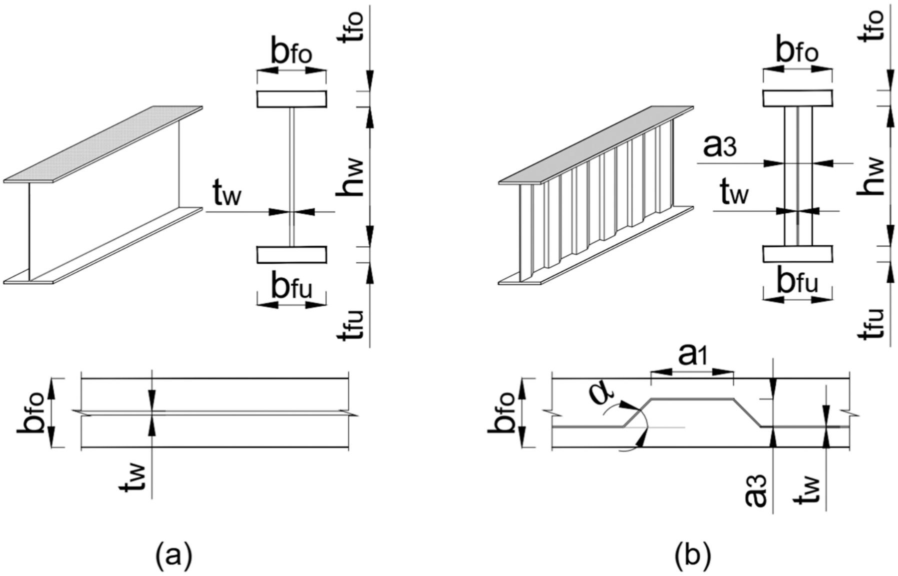


Fig. 1. A bridge girder with (a) flat web (b) corrugated web.

2. Design and optimization tool

2.1. Optimization tool

The primary goal of many engineering optimizations is to maximize or minimize a specified objective. Herein, the developed optimization routine is designed to allow flexibility to choose the objective, whether it is to minimize material usage, investment cost, life cycle cost (LCC), or life cycle impact. The resulting design solutions should satisfy the structural requirements in the ultimate limit state (ULS), serviceability limit state (SLS), and fatigue limit state (FLS). To ensure that these structural requirements are met, several constraints are imposed on the optimization process. One essential set of constraints is the utilization ratio of the structural elements. In this case, the main girders, and the cross-beam utilization ratios are constrained to be less than one. Other functional constraints are introduced, such as the top flange being compressed (as this assumption is used when calculating cross-sectional properties).

Based on Solgi's genetic algorithm module "geneticalgorithm" [17], Demetry Pascal [18] developed the genetic algorithm module "geneticalgorithm2" which is employed in this work. To enable parallelism, a new function called "set function" is included in the developed module. Parallelization is recommended for demanding functions and large populations, such as the optimization problem that is tackled in this study. The genetic algorithm module "geneticalgorithm2" is available as open source on the Python Package Index website (PyPI.org).

Fig. 2 provides a summary and description of the optimization tool developed in this work. The tool begins with a few inputs that are already known and necessary to run the structural design, such as material grades, environmental inputs like wind speed and relative humidity, concrete casting sequence, design service life, average daily traffic (ADT), indicated number of heavy vehicles per slow lane (N_{obs}), and geometric inputs like span lengths, c/c distance between the main girders, number of lanes, lane width, and total bridge width. The optimization tool divides each span into seven segments and aims to find the optimal dimensions for each segment, as well as the distances between cross beams in the span and over the supports, in order to minimize a specific objective such as weight, investment cost, life cycle cost, or life cycle impact. The optimization vector is defined as follows:

$$X = [h_w, t_{w1}, \ldots .t_{wn}, a_1, a_3, \alpha, CCB_{span}, CCB_{support}, b_{fo1}, b_{fu1}, \ldots .., b_{fon}, b_{fun}, t_{fo}, t_{fu}] \quad (2\ \text{-1})$$

Where h_w represents the web height that is constant along the bridge. $t_{w1}, \ldots .t_{wn}$ represents the web thickness, which can vary for each segment. a_1, a_3, and α represent the corrugation parameters, ref. Fig. 1b, which is constant along the bridge. $CCB_{span}, CCB_{support}$ represent the distances between the cross beams over the supports and in the span, respectively. For a simply supported bridge, $CCB_{span} = CCB_{support}$. b_{fo1}, $b_{fu1}, \ldots .., b_{fon}, b_{fun}$ represent the flange widths of the top and bottom flanges that can vary between the segments. t_{fo}, t_{fu} represent the thicknesses of the top and bottom flanges, respectively, which are kept constant along the bridge. When the bridge under consideration is symmetric, the length of the optimization vector is 20. The common domains considered for the design variables are presented in Table 1.

The tool starts by designing the concrete deck. The concrete deck thickness, as well as the transverse and longitudinal reinforcement, are not included as optimization parameters but are calculated based on the distance between the two main steel girders and the crack width

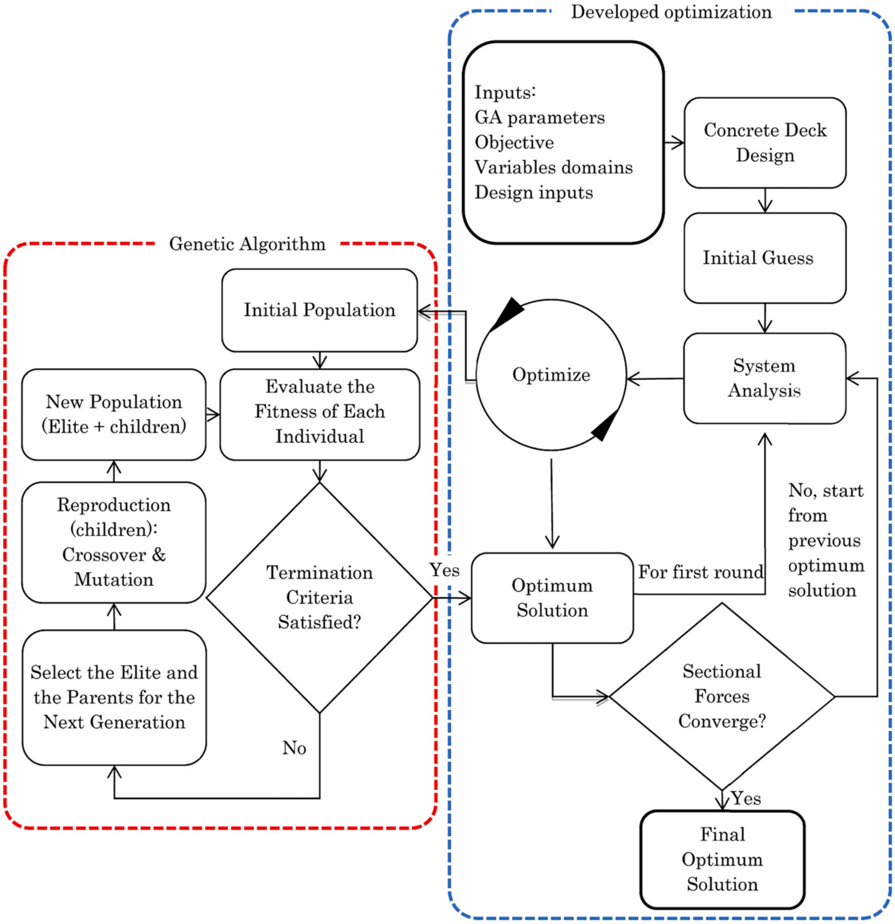


Fig. 2. Diagram depicting the relationship between the developed routine and the genetic optimization algorithm.

Table 1
Variables domains evaluated in the optimization routine.

Parameter	Domain
$t_{w(corrugated\ web)}\ [mm]$	4, 5, 6, 7, 8, 9, 10, 11, 12
$t_{w(flat\ web)}\ [mm]$	14, 15, 16, 18, 20, 22, 25
$t_f\quad [mm]$	20, 25, 28, 30, 35, 40, 45, 50, 55, 60, 65, 70, 75
$b_f\quad [mm]$	400to2500, step = 100
$h_w\ [mm]$	1000 to 3000, step = 100 for span 52 m 600 to 2000, step = 100 for span 30 m
$a_1, a_3\quad [mm]$	50 to 400, step 25
$\alpha\ [degrees]$	30 to 45, step= 5
$CCB_{span}, CCB_{support}\quad [mm]$	4000 to 8000, step= 500

limitations according to EN1994–2 [19]. After the deck design, the tool employs an initial guess for the design vector (2−1) to conduct the initial system analysis. As the optimization routine is developed to incorporate continuous bridges, which are indeterminate structures, and the distribution of sectional forces is determined by the stiffness of the structure, the optimization routine needs to be executed in several rounds until convergence of the solution is reached. Within each round, a genetic algorithm function is executed by the program to determine the optimal design vector that meets the structural requirements for the ultimate limit state (ULS), serviceability limit state (SLS), and fatigue limit state (FLS) based on the sectional forces calculated from the previous design vector. The resulting optimal design vector is then used to update the system analysis. This process is repeated until convergence in sectional forces between two rounds is achieved, i.e., the difference between the sectional forces in two rounds is less than a given threshold, taken as 5% in this study. At this point, the optimal solution is considered to have been attained.

2.2. LCA system boundaries

The European Standard EN 15978:2011 [20] specifies the calculation methodology for assessing a building's environmental performance based on Life Cycle Assessment (LCA) and other quantitative environmental data. The method used for the assessment includes all stages of the building life cycle and is based on data obtained from Environmental Product Declarations (EPD), their "information modules" (EN 15804 [21]), and other information required and relevant for carrying out the assessment. The assessment covers all building-related construction products, processes, and services used throughout the building's life cycle. As the classification of life cycle modules that are developed for buildings could also be used for bridges [22], the established Python function for life cycle assessment (LCA) follows the same classification as building life-cycle modules. Table 2 displays the modules that have been considered in the calculation.

Modules A1, A2, and A3, which cover the production stage, including the 'cradle to factory gate' activities for the materials and services used in the production stage, are considered. This stage might reflect the entire material manufacturing life cycle, including different additional activities such as material transportation, initial energy usage, and waste treatment.

Modules A4 and A5, which represent the environmental impacts of material transportation and the construction-installation process, are, according to Du and Karoumi [23], ignorable. Herein, the installation processes, including the machinery work (A5), are neglected, while module (A4), which considers the material transportation, e.g., steel plates imported from abroad by railway and transferred to the bridge site by trucks, is considered. The transportation distances are obtained from the tool developed by Trafikverket to estimate the climate impact [24]. For example, this tool provides structural steel transportation distances of 1000 km railway, 200 km national transport, and 40 km local transport [24]. The main difference between stainless steel and carbon steel bridges is that stainless steel bridges require significantly less maintenance than carbon steel bridges due to their corrosion resistance, i.e., no painting is required. 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. A bridge, unlike a building, is often operated with minimal energy and water use. Accordingly, modules B6 (operational energy use) and B7 (operational water use) do not need to be considered for the system boundaries.

Table 2
The life cycle stages included in the system boundary for LCA calculation for bridge construction (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

The deconstruction or demolition module (C1) is not considered in the LCA function. However, module C2, which estimates the environmental impact of waste transportation, is considered. This is because bridge destruction can generate large amounts of waste, which must be carried from the site to treatment plants or landfills. According to Du et al. [23], one of the important variables influencing the final LCA outcomes is the end-of-life (EOL) plan for bridge demolition waste. Therefore, modules C3 and C4, which according to EN 15978:2011 include waste treatment processes such as sorting, pre-recycling, and energy recovery, as well as potential pre-disposal treatments such as incineration and emissions from final disposal, are considered. The border between module C4 and module D is set where the processed material or product reaches the end-of-waste state. 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 [9], and it is not assessed within the scope of this work.

2.3. LCC system boundaries

To compare the different design concepts from an economic standpoint, a Python function that calculates the overall expenses over the bridge's service life is developed in this work. Similar to LCA, based on the classification of life cycle modules that are developed for buildings, the system boundaries considered in this work are defined in Table 3.

The first module considered is module A, series A1 to A5, which reflects the phases preceding the use phase of a bridge. This category focuses on the material costs associated with the construction materials needed for the different design alternatives. To reflect the differences between stainless steel and standard carbon steel girders and to improve the accuracy of LCC results, the reference prices should reflect the current market prices. The unit costs and production cost calculations integrated into the Python function for LCC are obtained from two manufacturing companies. This comprises the costs associated with

Table 3
The life cycle stages included in the system boundary for LCC calculation for bridge construction (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

cutting plates, welding, assembly, corrugating in the case of the corrugated web, painting or pickling, edge grinding, shear studs and their welding, and finally concrete and concrete casting. Welding costs are determined based on the type of connection, i.e., fillet or butt welds. The erection expenses are also included based on the number of splices required for the main girders and cross-beam assemblies. Other costs (such as earthwork, transportation, and so on) are ignored in these modules.

Regarding the usage phase (modules B1 to B5), the costs associated with the periodic maintenance of the steel girders are considered. The costs of maintenance activities are provided by the Swedish Transportation Administration (Trafikverket) [25] and are adopted from the Swedish Bridge and Tunnel Management System (BaTMan) [26]. Temporary traffic restrictions due to maintenance activities result in user costs such as traffic delay costs and vehicle operation costs [8]. Traffic delay cost is the only user cost considered in the LCC analysis performed in this work. The costs at the end-of-life (EOL) phase, module C, are assumed to have no impact on the comparative studies conducted on the two considered design alternatives. As a result, all costs associated with the EOL stage are excluded. Module D is considered given the higher price of stainless-steel scraps compared to carbon steel. Section 4.2 provides further information on different pricing details.

3. Description of the reference case study bridge

A simply supported bridge situated in Böle, Sweden, serves as a reference case study bridge in this research. The parametric studies are designed based on variations made to the parameters of the reference bridge. The reference bridge is a 52-meter-long, one-span steel-concrete composite bridge made up of twin flat-web carbon steel I-girders. The width of the bridge is 9.5 m, including two traffic lanes. The distance between the two main girders is 5.6 m, and the length of the deck cantilevers on each side is 1.95 m. The geometry and cross-section of the bridge are presented in Fig. 3. The flanges of the original bridge are made of carbon steel grade S420ML, while the web, stiffeners, and cross beams are made of carbon steel grade S355. However, for this study, it is assumed – for the reference case of carbon steel – that the flanges, web, cross beams, and stiffeners are all made of the same steel grade, S355.

4. Principles and assumptions

4.1. *Structural design assumptions*

The design process follows the Eurocode standards and the national standards in Sweden. The structural analysis and design are performed during both the construction phase, where there is no composite action and the steel girders carry the loads, and the service phase, where composite action is achieved. The loads considered are the self-weight of the superstructure, traffic loads (both vertical loads and braking and acceleration loads), temperature loads, creep, and shrinkage. The traffic loads are according to EN 1991–2 [27]. Temperature variations are according to the Swedish national annex TSFS 2018:57 [28]. The creep and shrinkage effects are considered according to EN1992–1-1 [29]. Shrinkage and temperature loads are applied as axial loads and moments at the supports, as described by Jean-Paul et al. [30]. The loads are combined in accordance with EN 1990 [31].

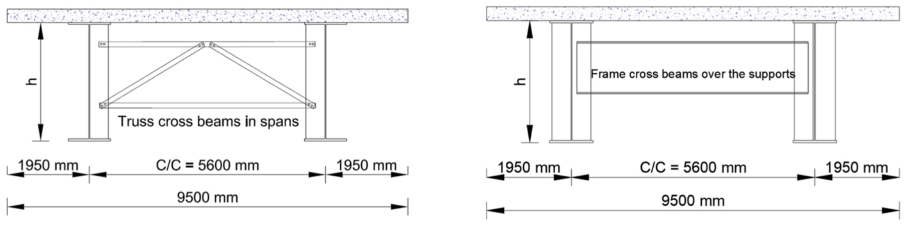
The design considers the ultimate limit state, serviceability limit state, and fatigue limit state. In the ultimate limit state, the Eurocode Load Model 1 (LM1) [27] is employed to assess the effects of traffic loads, and Load Model 3 (LM3) [27] is employed for the fatigue limit state. In the serviceability limit state, the deflection of the structure is checked to remain within acceptable limits. Specifically, the deflection induced by traffic loads should be less than L/400 (where L indicates the bridge length), as defined in Krav brobyggande (Bridge construction requirements in Sweden) [32]. The secant modulus of elasticity is used here for stainless steel, as specified in EN 1993–1-4 [33].

The mechanical properties of S355 have been derived from the EN 1993–1-1 [34] standard, whereas the properties of the duplex material EN 1.4162 have been derived from the EN 1993–1-4:2006/A1:2015 [35] standard.

The design of corrugated web beams follows the guidelines outlined in Annex D of EN1993–1-5. It's important to note that these models were originally developed for carbon steel. However, for the sake of this study and to evaluate the potential benefits of this concept, these models are applied to stainless steel based on the studies conducted by Hlal et al. [36] and Amani et al. [37].

The cross beams are designed as frames at the two end supports and as trusses made of VKR profiles (Hot-formed structural tubes) in the span, as illustrated in Fig. 3. Butt welds are assumed for the top flange-web connection along the bridge and the bottom flange-web connection above the supports. The connection between the bottom flange and the web along the span is made by a fillet weld. Also, the connection between the transverse stiffeners and the web is assumed to be made using a fillet weld. The connection between plates at the location of changing the width of the flanges is made with butt welds. Likewise, a butt weld is assumed for the bridge splices that are assembled on-site. In terms of welding location, it is assumed that all welding takes place in the workshop, except for the bridge splices, which are assumed to be done on-site.

As to the fatigue design, the welded details evaluated in the bridge are categorized based on EN 1993–1-9 [38] which assumes the same detail categories for carbon steel and stainless steel. Fig. 4 provides visual illustrations of these details. Detail A [$80MPa$]: longitudinal welds between the web and flange of the main girder under shear. Detail B [$100/125MPa\ for\ shear/normal\ sress$]: longitudinal welds between the web and flange of the main girder. Detail C [$80MPa$]: welds between transverse stiffeners and the web of the main girder. Detail D [$80MPa$]: weld between transverse stiffeners and flanges of the main girders. Detail E [$100MPa$]: the welds between web and flange for the corrugated web. Detail F [$112MPa * k_s$]: flange splice. The size-effect factor $k_s = \left(\frac{25}{t_f}\right)^{0.2} for\ \ t_f > 25mm$. Detail G [$80MPa$]: shear studs for composite action between steel girders and concrete bridge deck.



(a) (b)

Fig. 3. Bridge superstructure cross-sections: (a) over the supports; (b) in spans.

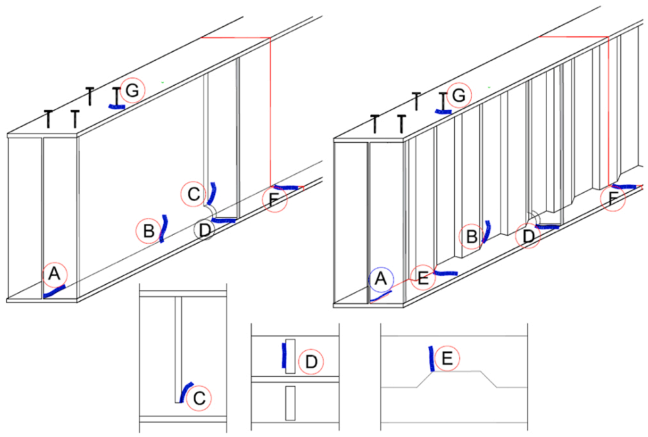


Fig. 4. The considered fatigue details in the studied bridge.

4.2. *Life cycle costs assumptions*

Steel unit pricing was collected from two companies in Sweden for the fourth quarter of 2022 (Personal communication). The unit price for steel plates of grade S355 was 10 SEK/kg, while hot-rolled and hollow-section profiles of the same grade cost 16 SEK/kg. The unit price for duplex material EN1.4162 was 30 SEK/kg for steel plates and 48 SEK/kg for hot-rolled and hollow-section profiles. The reselling costs for S355 and EN1.4162 were 3 SEK/kg and 22.5 SEK/kg, respectively. It should be noted that these prices are only valid for the specified quarter and are subject to change. The other costs implemented in the production cost calculation model associated with cutting plate edges, welding, painting, corrugating, grinding, pickling, shear studs, concreting, and erection were all obtained from interviews with two manufacturing companies in Sweden. The detailed costs can be found in Hlal [39].

The net present value (NPV) approach, which approximates the present value of all predicted cash inflows and outflows for a project, is used to estimate life cycle costs with the assumption of an inflation rate of 1.5% and a nominal discount rate of 3.5%, both adopted from Safi [40] and based on Trafikverket 2013 notations.

4.3. *Life cycle impact assessment assumptions*

The considered impacts per kg for carbon steel and stainless steel plate materials are $2.63kg\ CO2eq/kg$ and $1.7kg\ CO2eq/kg$, respectively, which are obtained from EPDs provided by two major producers of these two materials in Sweden. The environmental impacts of other various materials and processes employed in the design of the case studies in the current research are obtained from the Ecoinvent v3.8 database in the OpenLCA 1.10.3 program [41]. The CML 2001 is used as the life cycle assessment method, and the focus is put on the impact category of Global Warming Potential over a 100-year time horizon (GWP 100a), as it is the most commonly used indicator of LCA in bridges [42].

5. Parametric studies

This research investigates the influence of several parameters on the potential cost saving associated with employing stainless steel corrugated web girders in composite road bridges. Two painting maintenance schedules are considered according to

Table 5 and Table 6. The first schedule is provided by the Swedish Transport Administration (Trafikverket) [25], while the second one is obtained from Rossi et al. [22]. Section 6.2 provides detailed descriptions of these schedules. In addition, Average Daily Traffic (ADT) and the indicated number of heavy vehicles per slow lane (N_{obs}) are among the investigated parameters. Three scenarios based on low, moderate, and high ADT with associated values of N_{obs} are taken into account in the studies according to the information provided in Section 6.4. The other studied parameter is the maximum allowed height of the bridge girder, for which the limits of L/35, L/28, and L/17, where L denotes the bridge's span length, have been taken into account. The last studied parameter is the span length, for which two values of 52 m and 30 m are considered.

Table 5
Painting plan for the structural steelwork of a bridge in the environmental category C4 for 120 years (provided by Trafikverket [25]).

Activity	System age	Reference unit	Unit	Relative
Patch up	20 years	Initial painted surface	m^2	10%
Overcoating	40 years	Initial painted surface	m^2	20%
Remove & replace	60 years	Initial painted surface	m^2	100%
Patch up	80 years	Initial painted surface	m^2	10%
Overcoating	100 years	Initial painted surface	m^2	30%

Table 6
Painting plan for the structural steelwork of a bridge in the environmental category C4 for 120 years (adopted from Rossi et. al [22]).

Activity	System age	Reference unit	Unit	Relative
Patch up	12.8 years	Initial painted surface	m^2	5%
Overcoating	18.5 years	Initial painted surface	m^2	90%
Remove & replace	31 years	Initial painted surface	m^2	90%

As the first step in the parametric studies, the reference case study bridge, which is described in Section 3, is optimized for different optimization objectives of weight, investment cost, life cycle cost (LCC), and life cycle impact. This is done to find out how different optimization objectives affect the optimal design of both concepts with flat-web carbon steel and corrugated-web stainless steel girders. Then, based on the results, the optimization objective is set to LCC, and the two design solutions are reoptimized while the input values for the above-mentioned studied parameters are changed. Table 4 summarizes the studied parametric models, in which the optimum design solutions are labelled ID1 through ID25.

6. Results and discussion

The design of all bridges in the parametric study was governed by either ULS or FLS criteria, specifically related to welded vertical stiffeners (detail C for flat web and detail D for corrugated web, Fig. 4). SLS criteria only governed in cases with limited height (ID14 and ID16). The following sections will present the results of the parametric study, focusing on the examined parameters.

6.1. *Optimization objective*

As mentioned in Section 5, as the first step in the parametric studies, the influence of the optimization objective on the design solution is studied. This is done on the reference case study bridge made of flat-web S355 girders, ID 1–4, and corrugated-web duplex girders, ID 5–8. The results are presented in Fig. 5.

The weight, life cycle cost, life cycle impact, and investment cost of the optimized designs with the different objectives are compared in Fig. 5a to d, respectively. In Fig. 5a, it is observed, as expected, that, for the flat web concept, when the optimization objective is weight, the design tool produces a solution with the minimum weight (75 tons), which is attained by promoting solutions with deeper girders and thinner plates with the maximum number of sectional changes. However, when the objective is set to minimize LCC or investment cost, the optimization algorithm prioritizes reducing the cost by reducing the number of sectional changes and decreasing the painting area to reduce the cost of painting during the production and usage phases, even though this can result in heavier solutions, 84 and 80 tons (7 to 12%

Table 4
Parametric models of flat web carbon steel (S355) and corrugated web stainless steel (EN1.4162) girders. Painting schedules are adopted from Trafikverket [25] and Rossi et al. [22].

ID	Optimization objective	Material grade, concept	Span length [m]	N_{obs}	ADT	Allowable height [m]	Painting schedule
ID1	LCC	S355, Flat	52	50,000	200	3	Trafikverket
ID2	Weight	S355, Flat	52	50,000	200	3	Trafikverket
ID3	LCA	S355, Flat	52	50,000	200	3	Trafikverket
ID4	Investment	S355, Flat	52	50,000	200	3	Trafikverket
ID5	LCC	Duplex, corrugated	52	50,000	200	3	-
ID6	Weight	Duplex, corrugated	52	50,000	200	3	-
ID7	LCA	Duplex, corrugated	52	50,000	200	3	-
ID8	Investment	Duplex, corrugated	52	50,000	200	3	-
ID9	LCC	S355, Flat	52	50,000	200	3	Rossi et al.
ID10	LCC	Duplex, corrugated	52	500,000	11,000	3	-
ID11	LCC	S355, Flat	52	500,000	11,000	3	Rossi et al.
ID12	LCC	S355, Flat	52	500,000	50,000	3	Rossi et al.
ID13	LCC	S355, Flat	52	500,000	11,000	3	Trafikverket
ID14	LCC	S355, Flat	52	500,000	11,000	1.5	Trafikverket
ID15	LCC	S355, Flat	52	500,000	11,000	1.8	Trafikverket
ID16	LCC	Duplex, corrugated	52	500,000	11,000	1.5	-
ID17	LCC	Duplex, corrugated	52	500,000	11,000	1.8	-
ID18	LCC	S355, Flat	52	125,000	5,000	3	Trafikverket
ID19	LCC	Duplex, corrugated	52	125,000	5,000	3	-
ID20	LCC	S355, Flat	30	50,000	200	2	Trafikverket
ID21	LCC	S355, Flat	30	125000	5000	2	Trafikverket
ID22	LCC	S355, Flat	30	500,000	11,000	2	Trafikverket
ID23	LCC	Duplex, corrugated	30	50,000	200	2	-
ID24	LCC	Duplex, corrugated	30	125000	5000	2	-
ID25	LCC	Duplex, corrugated	30	500,000	11,000	2	-

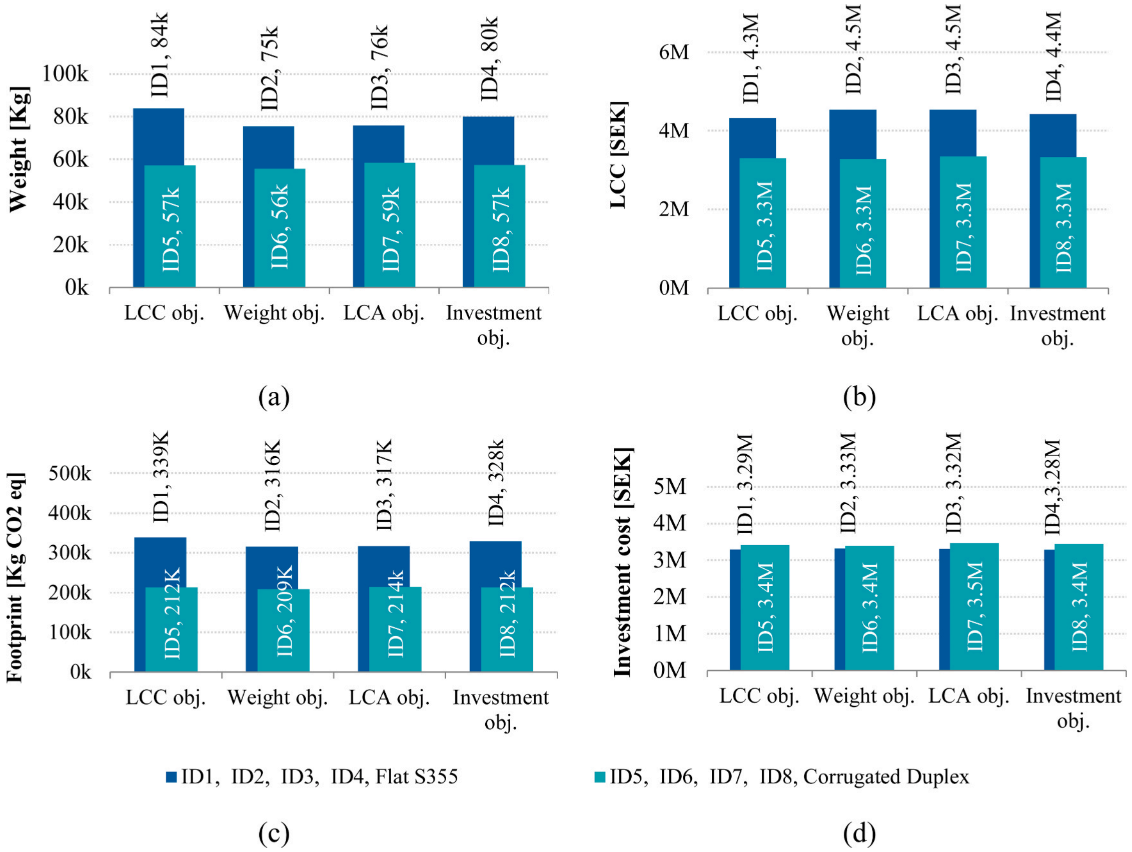


Fig. 5. The influence of optimization objectives on weight, life cycle cost, life cycle impact, and investment cost in optimal solutions.

more weight or material). When optimizing with respect to LCA, the optimization process is the same as optimizing with respect to weight since the main environmental impact comes from material production. Therefore, the algorithm focuses on reducing the weight (76 tons in Fig. 5a), which results in a minimum environmental impact as seen in Fig. 5c. On the other hand, for the stainless-steel alternative, the optimization tool always produces solutions with minimized weight or material, irrespective of the objective function, Fig. 5a. This is simply due to the lack of painting needs (during production and maintenance) for stainless steel, contrary to carbon steel, which leads the optimization tool to always search for design solutions with the minimum weight.

Based on an understanding of how changing the optimization objective affects the design outcome and because the goal of this work is to investigate potential saving in terms of life cycle costs, the optimization objective is set to LCC in the remaining parametric studies in the present study.

Given the results obtained in Fig. 5, several conclusions can be drawn regarding the saving that can be achieved by employing the new design concept of corrugated web stainless steel girder bridges. In comparison to flat web carbon steel girders, the design concept of corrugated web stainless steel girders shows a reduction ranging from 24% to 28% in life cycle costs and a reduction of 32% to 37% in life cycle impact. It is also observed that there is a reduction in the weight of the stainless-steel design solutions in comparison to the carbon steel ones in the range of 23% to 32%. Despite the high difference in material costs, the increase in investment costs of using stainless steel is only within the range of 2% to 5%.

With a detailed look at the costs of ID1 and ID5, as shown in Fig. 6a, it is observed that the removal of the requirements for painting during maintenance of the stainless steel design solution results in substantial saving in LCC. Moreover, the corrugated web design solution lowers both material consumption and production costs, which helps to compensate for the higher material cost of stainless steel. The production cost of the stainless-steel corrugated web design concept is lowered by 46% due to the elimination of grinding and painting during production as well as lower cutting costs. The welding costs are also decreased due to the incorporation of fewer cross beams and thinner welded plates. In Fig. 5a, it is shown that the corrugation concept leads to a reduction in the steel weight of around 32%. This reduction is coming partly from the flanges and partly from the web. The reduction in flange material, 25%, is the result of the algorithm choosing a deeper girder for the corrugated web (3 m against 2.2 m for the flat web), and the reduction in web material, 49%, is due to the higher shear capacity of the corrugated web.

Regarding the saving in life cycle impact, a clear link between the amount of material utilized and the total life cycle impact is observed. Fig. 6b shows that the main environmental impact comes from material production. Notably, the assumed unit impact of stainless steel $(1.7kg\ CO2eq/kg)$ is substantially lower than that of S355 $(2.63kg\ CO2eq/kg)$. This difference explains the significant reduction in environmental impact noticed with the new concept. Note here that even if the unit impact for both materials were the same, the new design would have a lower environmental impact due to the reduced amount of material utilized.

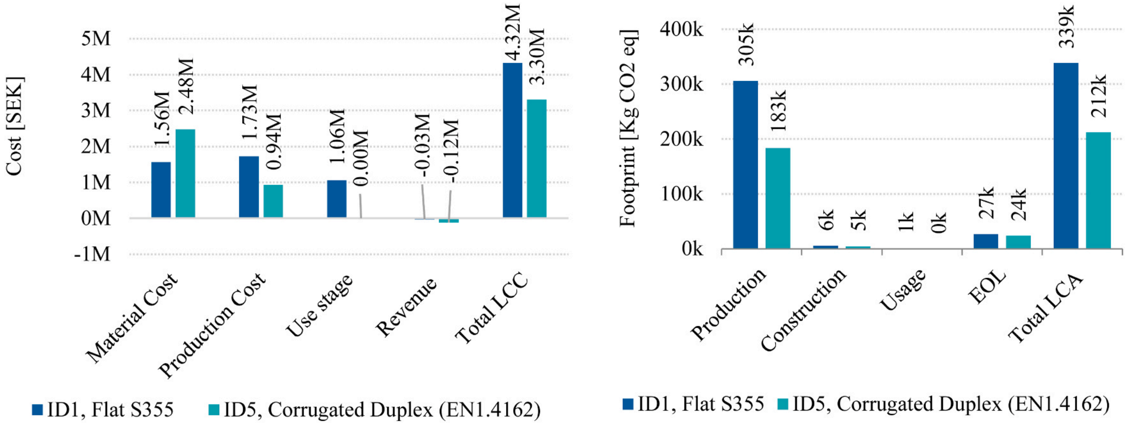
6.2. The effects of the painting schedule

One of the fundamental distinctions between carbon steel and stainless steel pertains to their surface treatment, particularly in relation to painting. In the case of carbon steel bridge girders, the initial application of paint is crucial during production to prevent corrosion, and periodic repainting and paint repair are necessary throughout their service life. In contrast, stainless steel girders require pickling after welding but do not necessitate any additional corrosion protection.

The maintenance activities related to painting carbon steel bridge girders can be generally categorized into three types: patching up, overcoating, and repainting. Evaluation of the economic feasibility of using stainless steel in bridge superstructures is highly dependent on the intensity of these activities and the associated costs that are reflected in the net present value (NPV) of the life cycle costs (LCC).

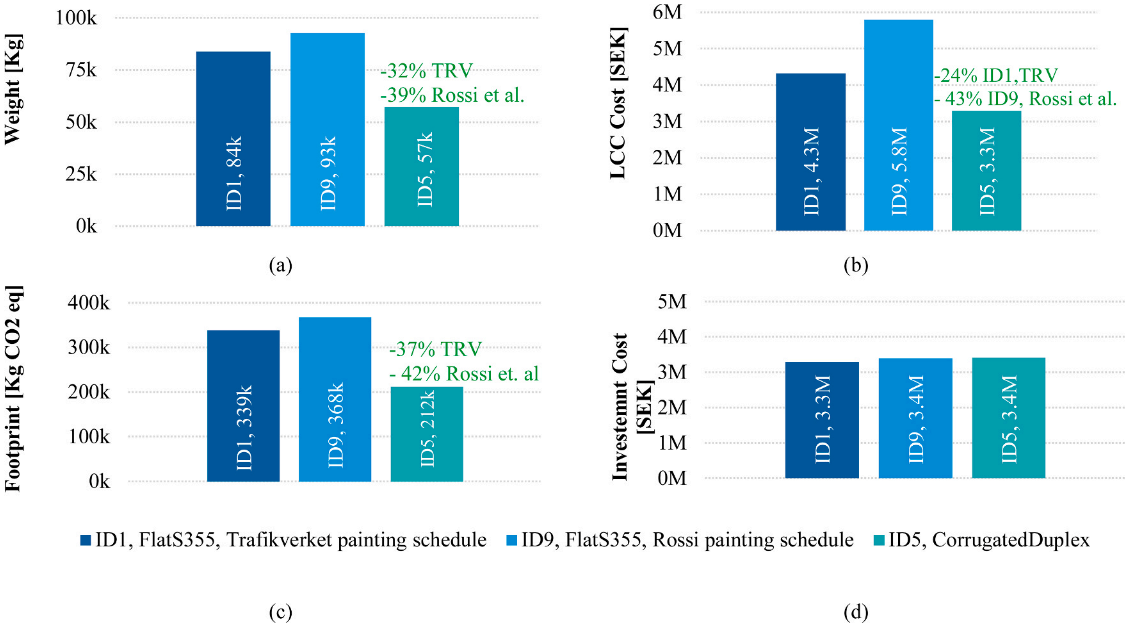
In the current study, the impact of the maintenance activities time intervals and costs on the efficiency of using corrugated web stainless steel girders is assessed by evaluating two distinct painting schedules. These schedules vary considerably in terms of both the processed painting area during each activity and the time intervals between each successive activity. The first schedule, presented in Table 5, is used by the Swedish Transport Administration (Trafikverket) [25] and is supported by corresponding painting costs obtained from the Swedish bridge and tunnel management system (BatMan) [26]. The second painting schedule is based on a comprehensive review of relevant sources, including a range of scholarly literature, expert opinions, scientific papers, and feedback from various European companies. This information was compiled and analysed by Rossi et al. [22], and their resulting recommendations for the painting maintenance schedule are reflected in Table 6. The corresponding painting costs were obtained from Rossi et al. [22], with cost conversion at the exchange rate of 1 USD = 10.37 SEK.

The optimized corrugated web stainless steel concept, ID5, demonstrates a reduction in weight of 32% and 39% when compared to the traditional carbon steel concept optimized based on the two painting schedules, ID1 and ID9, respectively; see Fig. 7a. Additionally, when considering life cycle costs (LCC), ID5 shows a decrease in LCC of 24% and 43% when compared to ID1 and ID9, respectively; see Fig. 7b. This means the saving in LCC increased by 19% when the paint maintenance schedule proposed by Rossi et al. [22] was used. Similarly, when comparing ID5 to ID1 and ID9 in terms of life cycle assessment (LCA), a reduction of 37% and 42% is observed, respectively; see Fig. 7c. This is, of course, due to the heavier solution produced by the optimization tool when the painting is needed for maintenance, as discussed before. It is concluded that the new concept has a considerably lower life cycle cost



(a) (b)

Fig. 6. Breakdown of costs and footprint for ID1 and ID5.



(a) (b)

(c) (d)

Fig. 7. Effect of different paint maintenance schedules on the optimal design solution and LCC saving.

and footprint with a comparable investment cost (Fig. 7d) when compared to the conventional concept.

6.3. The effects of assumed discount and inflation rates

The results shown in Fig. 7 are obtained assuming a 1.5% inflation rate and a 3.5% discount rate, both obtained from Safi [40] and based on Trafikverket 2013 notations. However, changes in the assumed discount rate and inflation rate can have a substantial influence on the results of the life cycle cost (LCC) calculations. Previous research typically addresses this by conducting sensitivity analyses on these rates [22,40]. Since road bridges in Sweden usually have a design life of 120 years, this parameter is kept constant, and a sensitivity analysis is conducted to examine the impact of changes in the discount and inflation rates on the conclusions drawn. Based on recommendations from Trafikverket's LCC experts (Personal communication, February 02, 2022), two additional discount rates, namely 2% and 5%, are investigated. Furthermore, two additional inflation rates of 0% and 3% were considered. The results, in terms of potential saving in Life cycle costs (LCC), are summarized in Fig. 8. It is observed that the saving is very dependent on inflation and discount rates. However, regardless of what values these rates take, the new concept generates a considerable LCC saving (28% to 68%).

6.4. The effects of average daily traffic (ADT) and indicated number of heavy vehicles per slow lane (N_{obs})

The average daily traffic (ADT) for a bridge depends on its location, i.e., whether it is situated in an urban or rural area with varying traffic flow rates. The value of ADT is linked to the indicated number of heavy vehicles per slow lane, denoted as N_{obs} [27], which significantly impacts the fatigue design of the bridge structure [43]. As N_{obs} increase, the traffic volume factor λ_2 increases, and if the fatigue limit state governs the design, the permissible stress decreases, necessitating bigger sections (i.e., more material) to meet the design criteria.

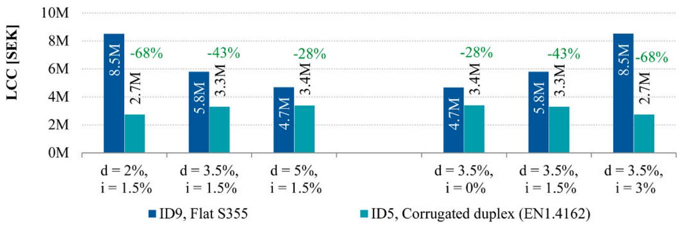


Fig. 8. Sensitivity analysis of LCC calculations to discount and inflation rates. ID9 is Flat S355 and ID5 is Corrugated uplex.

In the context of life cycle cost analysis, the average daily traffic (ADT) is an influential parameter as it affects the user cost resulting from the traffic delay time. In the parametric studies of the current research, low, medium, and high ADT values are considered, namely 200, 11 000, and 50 000 vehicles per day, which correspond to N_{obs} values of 50 000, 500 000, and 500 000 vehicles per year, respectively. The third ADT value of 50 000, in conjunction with N_{obs} of 500 000, is studied to examine the impact of the user cost (separately from fatigue) on the outcomes. The design optimization results for flat web carbon steel girders are designated by ID9, ID11, and ID12 for ADT and N_{obs} of 200 and 50 000, 11 000 and 500 000, and 50 000 and 500 000, respectively. When using corrugated web stainless steel girders, the results are designated by ID5 and ID10 for ADT and N_{obs} of 200 and 50 000 and 11 000 and 500 000, respectively. It is worth mentioning that the third case (ADT value of 50 000, in conjunction with N_{obs} of 500 000) is not optimized for the stainless-steel solution since it only impacts the user cost, which does not exist in the case of stainless steel.

The life cycle costs of the optimized designs with different ADT and N_{obs} are compared in Fig. 9, and the details of the total life cycle costs and weight in the cases of ID5 and ID9 are compared in Fig. 10. Fig. 9 depicts a potential saving of 43% (comparing ID9 and ID5) in the total

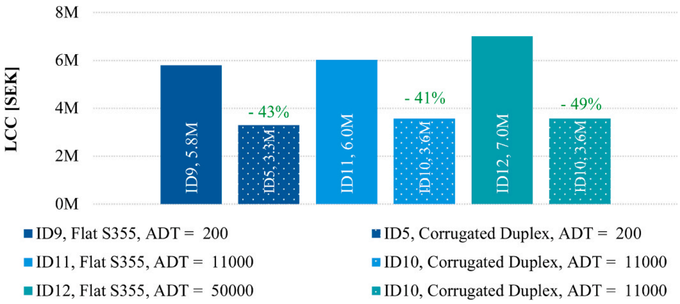


Fig. 9. Sensitivity of Life Cycle Cost saving to average daily traffic ADT and number of heavy vehicles in the slow lane N_{obs}.

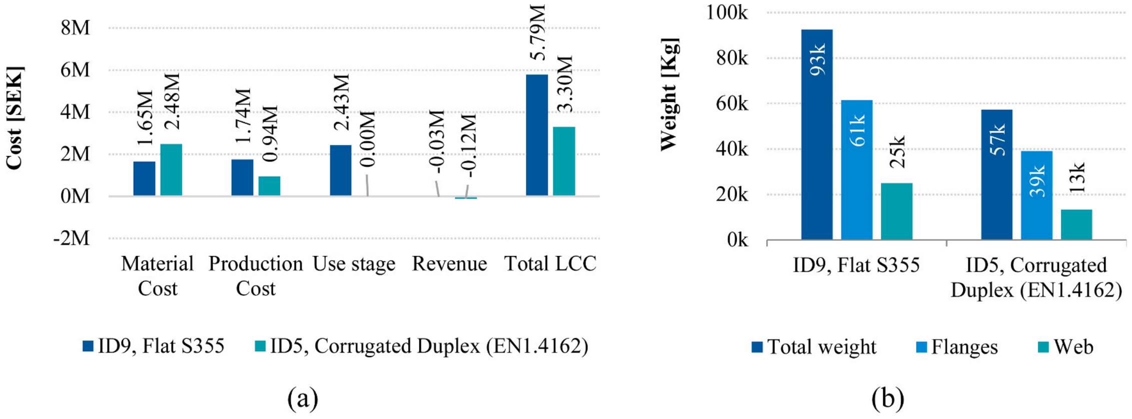


Fig. 10. Breakdown of costs and weight for ID5 and ID9.

LCC from using the corrugated web stainless-steel design solution for a low ADT. The cost details shown in Fig. 10a reveal that in addition to the saving in maintenance costs (100%), the stainless-steel solution (ID5) reduces production costs by 46%. This reduction is due to three factors: firstly, the elimination of the need for edge grinding and painting; secondly, a reduction in the cost of cutting; and lastly, a reduction in the cost of welding due to the use of thinner flanges and webs. Fig. 10b shows that the weight decrease in the case of ID5 (corrugated web stainless steel girders) is due in part (36%) to the use of smaller flanges for the stainless-steel solution because the optimization tool chooses a deeper web for a corrugated web girder and thus a lower flange area, and in part (47%) to thinner webs due to the higher shear capacity of the corrugated webs, as discussed before.

For the second scenario, considering bridges with increased ADT and N_{obs}, namely 11 000 and 500 000, the LCC saving is around 41% compared to 43% in the first scenario, ref. Fig. 9. The chosen optimal solutions weigh 99 tons and 63 tons for S355 and duplex, respectively, in the second scenario (High ADT and N_{obs}), compared to 93 tons and 57 tons in the first scenario (low ADT and N_{obs}). Despite the increase in weight for both concepts because fatigue is governing the design in the second scenario, the saving achieved is still significant.

For the third studied value of ADT and N_{obs}, when the ADT is even higher, the saving in LCC increase again to 49% (ref. Fig. 9). This is due to the higher user cost associated with the increased traffic, which results in a user cost of 1 172 001 SEK for ID12 with an ADT of 50 000 compared to 257 840 SEK for ID11 with an ADT of 11 000 (around 4.5 times). Herein, the user cost assumes a time delay of 2 days, 5 days, and 5 days for patch-up, overcoating, and repainting activities, respectively. It should be emphasized that these time delays are case-specific and may be longer, ranging from a few weeks to a few months, where the benefits of employing stainless steel in such instances become much more pronounced. On the other side, the maintenance activities can be done without any traffic delays, a scenario with negligible user cost that is close to what has been considered in this study.

In conclusion, it is observed that the studied concept can produce considerable saving in LCC compared to the traditional concept, irrespective of the design values of ADT and N_{obs}. As expected, however, this saving is slightly higher for bridges with high ADT due to higher user costs. It should also be emphasized here that the assumptions made for user costs are very conservative.

6.5. Height limitations

In bridge design, the available free height under the bridge sometimes limits the girder depth. Moreover, one of the main constraints to using deep girders for flat web designs is web buckling as the web height increases. This may necessitate the addition of longitudinal and transversal stiffeners or the use of a thicker web, resulting in increased material usage and production costs. Nevertheless, because of the high shear buckling strength of corrugated web plates, they do not pose such a challenge, making deeper girders a more viable option. To investigate the potential material saving associated with the use of deeper webs, an optimization study is conducted on three cases where the upper bound for the web height in the optimization is set to three different values of 3.0, 1.8, and 1.5 m. The resulting web height for the optimum solutions produced by the optimization tool is given in Table 7.

The results in Table 7 show that the optimization tool chooses comparable depths for stainless steel and carbon steel girders at the height limitations of 1.5 m and 1.8 m. However, with a height limitation of 3 m, the tool attempts to reduce the LCC by minimizing the painting area for the S355 option. As a result, the algorithm selects a 2.3 m web height with a flat web, which results in a smaller painting surface at the expense of a somewhat heavy solution (82 tons), ref. Fig. 11a. It is worth mentioning that when the optimization procedure for ID13 is repeated with the objective to minimize the weight, the algorithm selects a height of 2.9 m for the S355 choice, which results in the lowest weight (74 tons).

Furthermore, Fig. 11b shows that the LCC saving increases as the allowable web depth increases. While the weight saving stays constant for height limitations of 1.5 m, 1.8 m, and 3 m (20%, 24%, and 24%, respectively), the LCC saving increases from 5% to 14% and 20%. The reason for this, as discussed earlier, is that increasing the web height to reduce weight increases the painting area for carbon steel solutions but has no such consequence for stainless steel girders. This leads to the conclusion that it is more beneficial to use deeper girders for stainless steel, as increasing the web height does not affect the painting area.

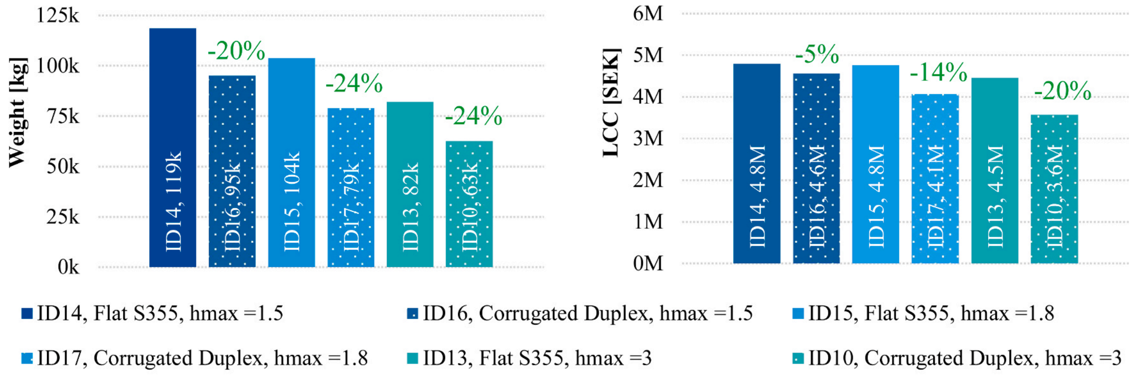
6.6. Span length

To evaluate the effects of the span length on the potential cost saving, a sensitivity study is carried out, examining two specific span lengths: 52 m and 30 m. For each span, the optimization is performed across three different levels of Average Daily Traffic (ADT): low, medium, and high, namely, 200, 5000, and 11 000, which correspond to N_{obs} of 50 000, 125 000, and 500 000. To allow for a logical comparison between the two span lengths, the same set of input parameters representing different materials and ADT levels is employed.

The life cycle cost and the total weight of the optimized designs with different ADTs are compared in Fig. 12. It is observed that the results from the shorter-span cases (30 m) are rather consistent with those from the longer-span cases (52 m) for all ADT and N_{obs} combinations. Weight saving range from 24% to 32% for the long-span bridge cases (Fig. 12a) and from 20% to 31% for the short-span bridge cases (Fig. 12b). Similarly, the reduction in life cycle cost (LCC) ranges from 20% to 26% for long-span bridges (Fig. 12c) and from 18% to 22% for short-span bridges (Fig. 12d). These results show that the saving in all cases is comparable

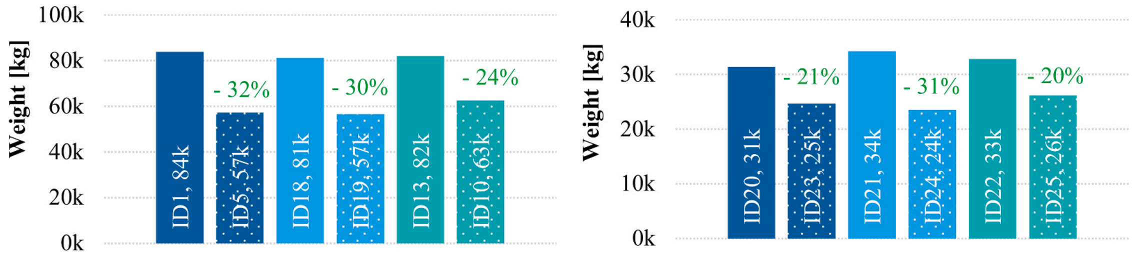
Table 7
The optimal web heights with the allowable maximum web height (TRV schedule is used for Flat S355).

ID	ID14	ID16	ID15	ID17	ID13	ID10
Concept	Flat S355	Corrugated Duplex	Flat S355	Corrugated Duplex	Flat S355	Corrugated Duplex
Allowable web height [m]	1.5	1.5	1.8	1.8	3	3
Web height in the optimum design [m]	1.4	1.5	1.7	1.8	2.3	2.9

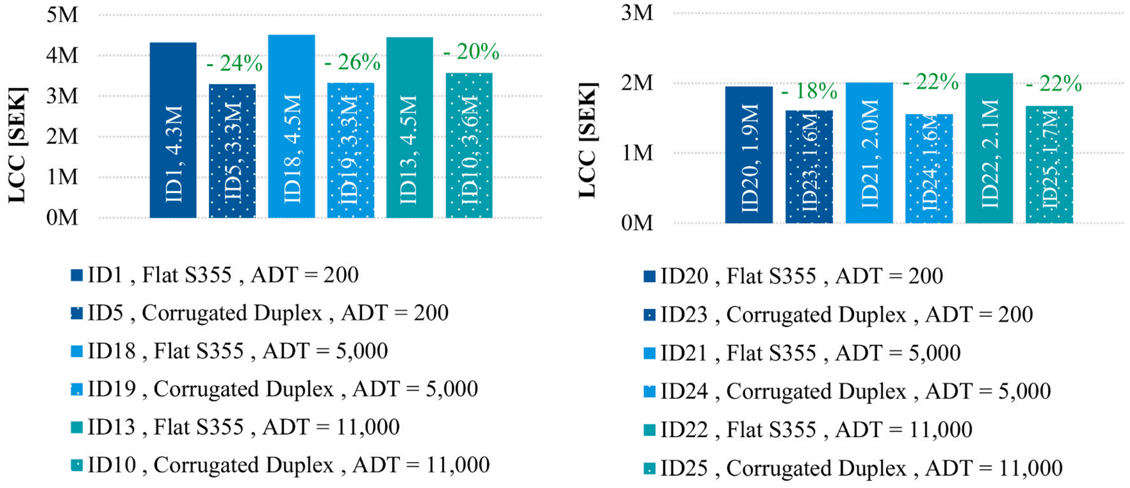


(a) (b)

Fig. 11. Sensitivity of Life Cycle Cost saving to bridge girder allowable height. (a) weight comparison (b) LCC comparison.



(a) Weight comparison, span = 52m
(b) Weight comparison, span = 30 m



(c) LCC comparison, span = 52m
(d) LCC comparison, span = 30 m

Fig. 12. Evaluation of weight and LCC potential saving for different bridge span lengths.

irrespective of span, ADT, and N_{obs}; in other words, they indicate that the saving is achievable within a wide range of span length.

7. Summary and conclusion

Using stainless steel in bridge construction can have large benefits from a life cycle performance point of view. However, the initial investment cost of using stainless steel in bridges is rather high, and this hinders its widespread usage in the bridge industry. In this paper, a new concept for twin-girder composite road bridges is evaluated with respect to investment costs, life cycle costs, and life cycle impact. The concept incorporates stainless steel girders with corrugated webs and aims at reducing investment costs and enhancing the life cycle performance of composite road bridges. The new concept is compared to the conventional design concept of flat web carbon steel girders in terms of weight, investment cost, life cycle cost, and life cycle impact. All designs are generated using a design and optimization tool to ensure proper designs and optimized solutions in all cases. A detailed parametric study is also performed to explore the sensitivity of the results obtained to various design parameters. The results of the study can be summarized as follows:

a. By employing a corrugated web design, the substantial disparity in investment costs between carbon steel and stainless steel options can be significantly reduced. For instance, in one case, the study showed that the stainless-steel alternative could be achieved with just a 4% higher investment cost. This reduction in investment costs comes from the use of less materials and decreased production costs. The reduction in material usage primarily arises from the implementation of thinner webs in the corrugated web design. When the maximum allowable girder height limit in the optimization is set generously, additional saving in girder flanges can also be realized. In addition to the reduction in material, the production costs for the steel superstructure are lowered by eliminating the need for painting and grinding processes and also lowering cutting and welding costs through the use of less material and thinner plates.

b. The optimization process acts differently depending on the optimization target, such as weight, investment cost, life cycle cost (LCC), or life cycle impact (LCA). When it comes to carbon steel, the painting cost makes up a major component of the total cost; for example, painting during production accounts for about 25% of the investment cost in one of the studied cases (ID1), and the total cost of painting in production and maintenance reaches 43% of the total LCC. When the objective is cost (investment or LCC), the optimization procedure prioritizes reducing the painting area of carbon steel girders, whereas when the objective is life cycle impact, it promotes solutions that lower the weight (material usage). In the case of stainless steel, however, both the cost and the life cycle impact are mostly determined by the amount of material used. Regardless of the objective function used, the optimization constantly seeks to reduce the material with minimal difference in the obtained optimal solutions.

c. In LCC analysis, the assumed paint maintenance schedule affects the results. However, even with the more conservative of the two maintenance schedules considered in this study, the concept produced a substantial improvement in life cycle cost (24% to 43% reduction) compared to the conventional C-Mn steel concept.

d. One source of uncertainty in LCC analysis is inflation and discount rates. These factors can influence the projected life cycle costs and thus the conclusions of comparative LCC studies such as the one produced in this paper. Nonetheless, despite the uncertainties caused by these rates, all scenarios analyzed in the study consistently revealed considerable benefits associated with the implementation of the new concept.

e. The ADT, in combination with N_{obs}, can affect the optimal design solution in two ways. Firstly, increasing N_{obs} may shift the governing design limit state from the ultimate limit state (ULS) to the fatigue limit state (FLS), limiting the benefit of employing a higher-strength material such as duplex EN1.4162, which decreases the potential saving. On the other hand, increasing the ADT results in higher user costs due to traffic detours, making the use of stainless steel more rewarding. In all the combinations of ADT and N_{obs} that were studied in this work, the new concept showed a good potential LCC saving, even though this saving was slightly lower when the fatigue limit state was governing the design. Furthermore, the study's conservative assumptions regarding repair and maintenance activities mitigate the influence of higher average daily traffic (ADT) on user costs, which was only 2% of maintenance costs for one of the studied cases. Therefore, if maintenance repairs take longer than what is assumed here, bridges with higher ADT will incur higher user costs, resulting in even greater saving in life cycle costs.

Acknowledgement

This research was conducted as part of the "Sustainable and Maintenane free bridges" project, which was funded by the Swedish Transport Administration [Project No. TRV 2020/117504]. The financial assistance is much appreciated.

CRediT authorship contribution statement

Hlal Fatima: Data curation, Formal analysis, Methodology, Software, Validation, Visualization, Writing – original draft. **Amani Mozhdeh:** Supervision, Writing – review & editing. **AL-Emrani Mohammad:** Data curation, Funding acquisition, Methodology, Supervision, Validation, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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