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STEEL SOIL COMPOSITE BRIDGE: AN ALTERNATIVE DESIGN SOLUTION FOR SHORT-SPAN BRIDGE TOWARDS SUSTAINABILITY

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SUMMARY

The construction sector is a major source of greenhouse gases. Under the increasing concern in climate change and growing construction activities, the whole sector is challenged to shift focus toward sustainable solutions. The traditional procurement often prioritizes the technical and economic viability, while their environmental performance is overlooked. Today's designers are urged to seek new design options to reduce the environmental burdens. Sweden owns more than 24574 bridges and most of them are short spans. Among them, the slab frame bridge (CFB) is a common solution. Soil steel composite bridge (SSCB), alternatively, is a functional equivalent solution to CFB and shows advantages in low cost and easy construction. This paper compares the environmental performance between these two bridge types based on life cycle assessment (LCA). The analysis and result shows that, the SSCB is preferable over CFB in most of the examined environmental indicators.

Key words: concrete slab frame bridge; soil steel composite bridge; soil steel flexible culverts; LCA; CO_2 emission; sustainable construction; life cycle assessment; global warming; climate change

1. INTRODUCTION

Bridges are vital infrastructure in a country's economic development, and responsible for considerable environmental burdens due to their large consumption in raw materials and energy. According to Swedish Transport Administration [1], there are more than 24574 bridges in Sweden and most of them are short spans [2]. Among these, the concrete slab frame bridge (CFB) is a common solution. However, due to the challenge of climate change, designers are concerned to seek new design solutions to mitigate the environmental impact. Soil steel composite bridge (SSCB), alternatively, is a technical solution functionally equivalent to the CFB. Earlier studies [3, 4] showed SSCB is favourable due to its ease constructability, low maintenance as well as competitive cost. However, their environmental performance had never been examined.

Life Cycle Assessment (LCA) is a standardized and internationally recognized approach for quantifying the resource consumption, environmental impacts, emissions as well as the health impacts linked to a product or service [5-8]. LCA only started to be applied in the construction sector in recent years. Comparing to the building sector, its implementation on bridges is very rare [9, 10]. According to the literature review in [11], the pilot study of LCA on bridges was first performed in 1998 by [12] and [13]. Since then, a broader LCA implementation is more focused on buildings other than bridges. This paper intends to presents a generalized LCA framework for bridges, aiming to demonstrate bridge LCA approach in practice for the decision-maker. Furthermore, a comparative LCA study is conducted on two selected short span bridge cases in Sweden: one CFB and one SSCB. The life cycle impact assessment method (LCIA) of ReCiPe (H) [14] is implemented on case studies, with the life cycle inventory (LCI) data collected from industrial sectors. ReCiPe (H) is a combined method of Eco-indicator 99' and CML 2002 with up-to-date impact categories. This study covers a comprehensive set of indicators including 12 mid-point categories, namely Global warming potential (GWP), Ozone depletion potential (ODP), Human toxicity potential (HTP), Photochemical oxidant formation potential (POFP), Particulate matter formation potential (PMFP), Ionizing radiation potential (IRP), Terrestrial acidification potential (TAP), Freshwater eutrophication potential (FEP), Marine eutrophication potential (MEP), Terrestrial ecotoxicity potential (TETP), Freshwater ecotoxicity potential (FETP), Marine ecotoxicity potential (METP). Besides, the cumulative energy demand (CED) and four selected impacts of GWP, ODP, POFP and PMF are further detailed. The result assists the decision makers in selecting the short-span bridge types due to their environmental performance at the early stage.

2. LCA METHODOLOGY

This paper applies the LCA framework presented in [11, 15]. The framework enables a detailed quantification of the CED and a list of potential environmental impacts through a bridge whole life cycle span, from raw material acquisition, though construction, maintenance and operation until the end of life (EOL). The dominant structural components and critical activities that contribute to the most environmental burdens are spotted and tracked. The analysis is performed with the aid of the calculation tool GreenBridge developed by [16].

The reliability of LCA is primarily determined by the quality of the LCI database and the accuracy of input. The same material may have different LCI profile due to the variation of regional production technology. This paper has adopted the European data from Ecoinvent v2.2 database to represent the Swedish condition. Thousands of materials and production processes from the construction sector are provided by Ecoinvent. Fifteen types of process and material datasets are retrieved to quantify the energy consumption and the emission of the bridge related scenarios. Each type of the data includes over thousands of air, liquid and solid substances.

Figure 1. A concrete slab frame bridge [18]

3. CFB AND SSCB

In Sweden, both of the CFB and SSCB are commonly used for short-span bridges, serving the same technical function, often for a designed life span of 80 years. By 2006, the Swedish Transport Administration owns approximately 2270 corrugated steel culverts [17]. CFB, as presented in Figure 1, mainly consists of a reinforced concrete frame as the load bearing structure. The superstructure and substructure are continuously connected. In comparison, SSCB is a very simple structure type and is functionally equivalent to CFB. It consists of the corrugated pipe surrounded with the compacted frictional soil, see Figure 2 as an example. This structure type is typically on a concrete foundation, which is not included in the analysis.

Figure 2. A steel soil composite bridge [19]

Building a small CFB normally requires 2 to 3 months, without counting the foundation preparation or the backfilling. The involved machinery usage covers the earthwork excavators for formwork foundation preparation, soil compactor, dumpers and cranes. Forming, reinforcement installation and concreting are the main activities in CFB construction. These three activities need to be repeated several times in separate processes, because the full structure cannot be built at the same time. The foundation slabs are built first, followed by the front walls, wing walls and the bridge deck.

In comparison, SSCB is simple to build, with a rapid construction process and minimum temporary equipment needed. The curved corrugated steel plates can be easily bolted together on-site. Bolting the curved corrugated steel plates is carried out close to the final location of the bridge. This would even reduce more construction time, transportation and the steel plate can be installed immediately after the preparation work of ground. Once being bolted, the conduit can be backfilled using frictional soil which is carefully compacted. The decreased construction time for SSCB can substantially reduce the traffic disturbances, thus further mitigate the associated environmental impact.

4. CASE STUDY

The selected case study intends to compare the life-cycle environmental performance between two short span bridge types in Sweden. For this reason, 2 recently built bridges representing CFB and SSCB are chosen for the analysis. Table 1 details the dimensions and bridge specifications which was provided by contractors. The selected CFB is from the Katrineholm project, a new bypass Road 55/56 serving as a dual carriageway between Strångsjö and Uppsala-Södertälje. The SSCB bridge belongs to the newly built E4 Sundsvall project. Both bridges are registered in the Swedish Bridge Management System with the series number, as shown in Table 1. For a fair comparison, the functional unit is defined as: one square meter of bridge effective area in one year through the life span of 80 years. The effective area of a bridge is defined geometrically as the free width × the length. The study scope covers the whole bridge through the entire life cycle from cradle to grave.

Table 1 General data for the selected bridges

Bridge Registration	**-**	**4-824-1**	**22-1625-1**
Notation in this paper	**-**	CFB1	SSCB1
Item	**Unit**	**-**	**-**
Bridge free width	(m)	16,0	18,5
Bridge length	(m)	8,3	6,9
Bridge effective area	(m^2)	133	128
Intended life span	(years)	80	80

4.1 BRIDGE LIFE CYCLE

4.1.1 THE MATERIAL MANUFACTURE PHASE

The material manufacture phase encompasses all the upstream processes of each material used to construct the bridge, from the extraction of raw materials from ground until products are ready for use at the factory gate. A life cycle inventory (LCI) database with unit environmental profiles for each relevant material is used. This provides data on the associated release of thousands of substances that are then aggregated into mid-point impact categories. With the adjustment of considered structural components, the summarized bills of material quantities are presented in Table 2. The items listed are the amount of concrete, reinforcement, bitumen sealing for the bridge deck waterproofing and the steel railings.

4.1.2 THE CONSTRUCTION PHASE

The environmental impact of the construction phase is dominated by the usage of construction machines, site-preparation, materials and workers transportation to and at the site. This study has thoroughly collected information on material transportation, which is further presented in Table 3.

Table 2 Permanent materials quantity

Item	**Unit**	**CFB1**	**SSCB1**
Concrete	(m^3)	391	0
Reinforcement	(ton)	27	0
Structural steel[a)]	(ton)	-	46
Structural steel plate thickness	(mm)	-	6
Corrugation wave length	(mm)	0	200×55
Painted area	(m^2)	0	111
Bitumen sealing	(kg)	750	-
Steel railings	(ton)	7,7	7,8

a): Hot dip galvanized

4.1.3 THE MAINTENANCE AND OPERATION PHASE

This phase predicts the future maintenance and operation scenarios, which is regarded as the longest stage for bridges under the expected design life [10]. A well planned maintenance schedule can extend the bridge service life and minimize the environmental burden from the whole life cycle perspective. Based on the historical data and personal communication with experts on site, a list of general scheduled maintenance and repair plans are presented in Table 4. As stated above, this study covers the periodic maintenance schedules related to the concrete and reinforcement repair, bitumen sealing for waterproofing and steel for railing replacement. All of the upstream processes involved in manufacturing these materials were obtained from Ecoinvent database, covering from the raw material extraction until the ready-made products at the factory gate.

4.1.4 THE END OF LIFE

Recycling in this stage is environmentally beneficial due to the contribution to the reduction of original material usage and associated emissions. The steel used in SSCB is fully recyclable. The simple “cut-off” method detailed in [20, 21], which recommends that each product should only be assigned from the environmental impacts directly caused by that product, is applied for the allocation issues in this study, thus to avoid including the indirect impacts related to other concerned products. Therefore, the saved energy and raw material due to steel recycling are already counted in the initial material manufacture phase through using the ready-made LCI data by Ecoinvent v2.2, which represents the average manufacture situation in Europe by a mixture of 63% primary steel and 37% of secondary steel from the electric furnace. After demolition, the waste concrete is assumed to be crushed into aggregate for further usage in the road construction. Under the Swedish condition, it is assumed to consume 16.99 MJ diesel and 21.19 MJ electricity when producing a ton of aggregate from crushing waste concrete [22].

Table 3 Summary of transportation

Item	**Unit**	**CFB1**	**SSCB1**
Transportation by	-	-	-
Scaffolding	(ton×km)	266	-
Reinforcement	(ton×km)	4 266	-
Concrete	(ton×km)	9 372	-
Structural steel	(ton×km)	-	9 694
Transportation by	-	-	-
Reinforcement	(ton×km)	18 550	-

Table 4 Maintenance activities

Item	**Unit**	**CFB1**	**SSCB1**
Edge beam repair/replacement	(m^3)	12,45	0
Waterproofing replacement	(kg)	750	0
Steel railings	(ton)	7,7	7,8

4.2 RESULTS

This study covers a comprehensive set of indicators including 12 mid-point categories, namely Global warming potential (GWP), Ozone depletion potential (ODP), Human toxicity potential (HTP), Photochemical oxidant formation potential (POFP), Particulate matter formation potential (PMFP), Ionizing radiation potential (IRP), Terrestrial acidification potential (TAP), Freshwater eutrophication potential (FEP), Marine eutrophication potential (MEP), Terrestrial ecotoxicity potential (TETP), Freshwater ecotoxicity potential (FETP), Marine ecotoxicity potential (METP), as presented in Table 5. Furthermore, the cumulative energy demand (CED) and 4 types of impact categories, in terms of tracking each structural components and life cycle scenario activities are displayed in

Figure 3 to Figure 7. It has been noted that, for a fair comparison, the results are normalized by the bridge area and the bridge life span of 80 years. More specifically, each result is normalized into per square meter per year.

Table 5 Characterized mid-point indicators

Impact category	Unit	CFB1	SSCB1
GWP	kg CO2 eq.	18,1	9,3
ODP	kg CFC-11 eq.	8,6E-07	4,9E-07
HTTP	kg 1,4-DB eq.	3,7E+00	5,0E+00
POFP	kg NMVOC	5,8E-02	3,7E-02
PMFP	kg PM10 eq.	2,6E-02	3,3E-02
IRP	kg U235 eq.	1,1E+00	5,8E-01
TAP	kg SO2 eq.	4,6E-02	3,8E-02
FEP	kg P eq.	3,2E-04	6,8E-04
MEP	kg N eq.	2,0E-03	1,2E-03
TETP	kg 1,4-DB eq.	1,4E-03	1,5E-03
FETP	kg 1,4-DB eq.	4,0E-03	3,9E-03
METP	kg 1,4-DB eq.	1,1E-02	2,0E-02

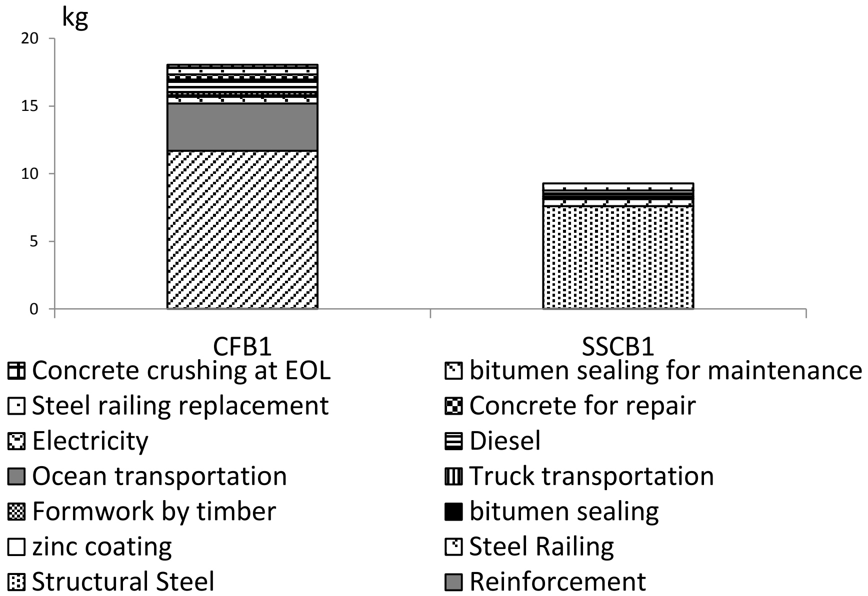

Figure 3 Global warming potential (kg CO_2 eq. per m^2 per year)

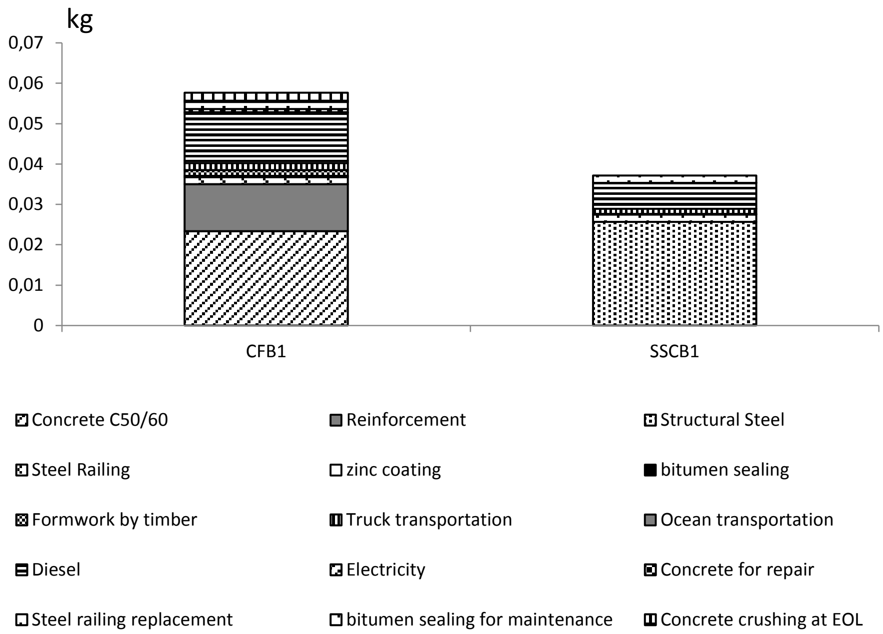

Figure 4 Photochemical oxidant formation (kg NMVOC per m^2 per year)

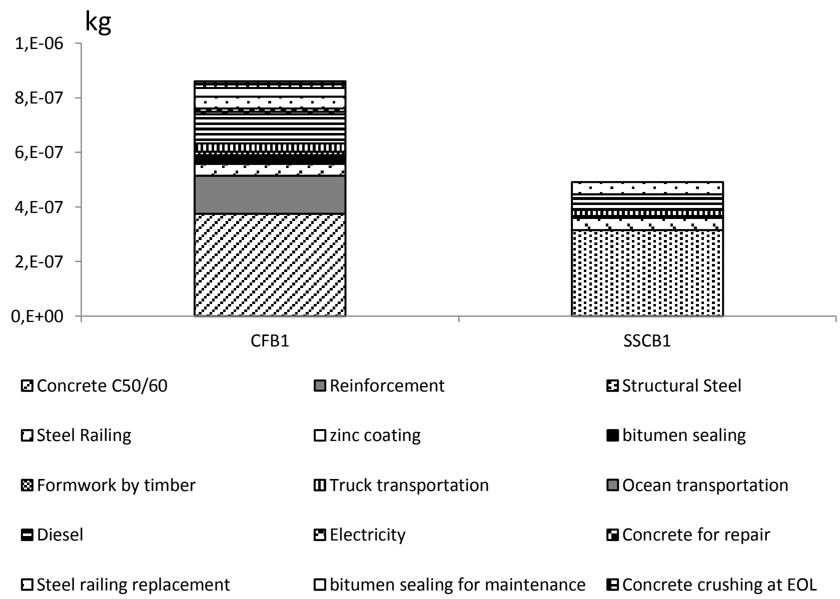

Figure 5 Ozone depletion potential (kg CFC-11 eq. per m^2 per year)

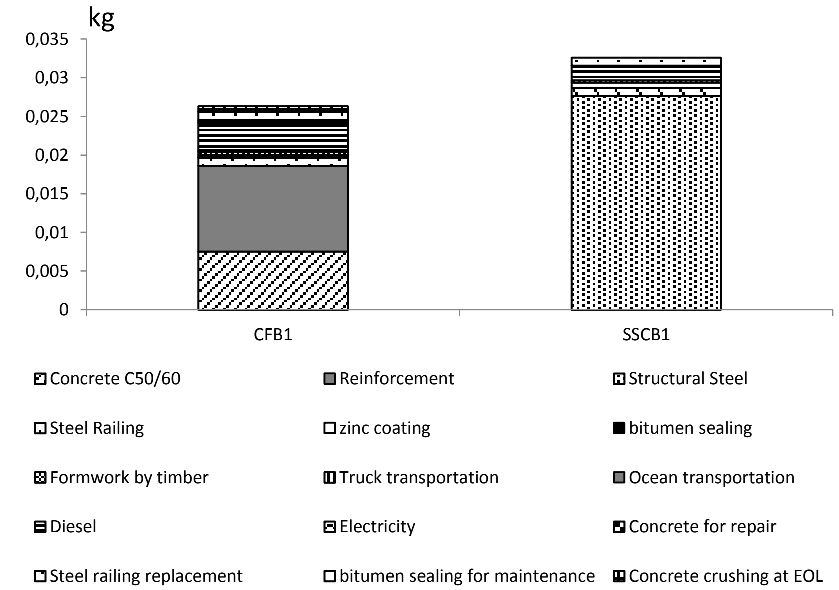

Figure 6 Particulate matter formation (kg PM_{10} per m^2 per year)

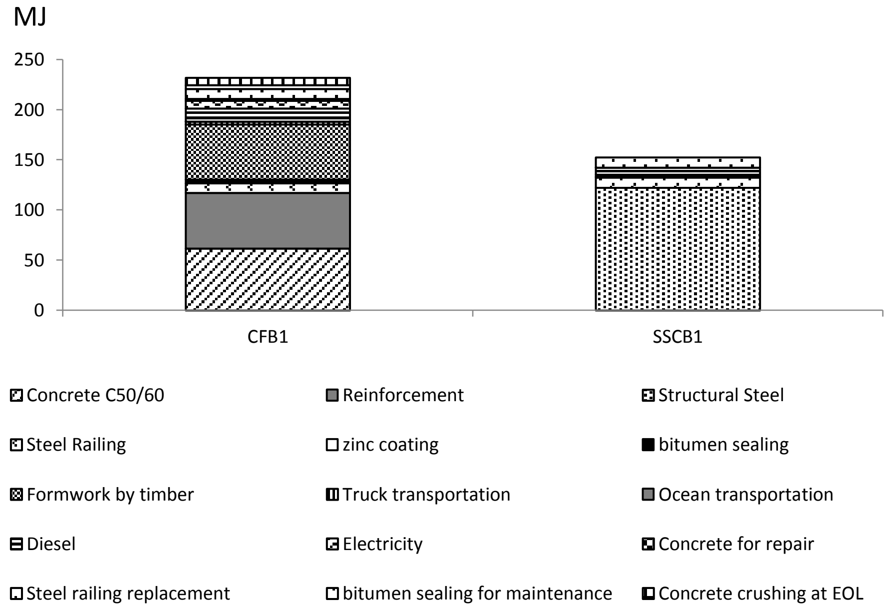

Figure 7 Cumulative Energy demand (MJ per m^2 per year)

5 CONCLUSIONS

This paper compared two types of commonly used short span bridges in Sweden: SSCB and CFB. A detailed procedure of LCA implementation on bridges was presented to the practitioners. The environmental burden of bridges was comprehensively evaluated from cradle to grave, including 12 sets of mid-point indicators and CED. The results showed that, the case of SSCB is preferable over CFB in most of the examined environmental indicators through the whole life cycle, mainly due to the ease construction and maintenance of SSCB. The initial material stage was found to be dominant in the total environmental impact.

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