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STEEL SOIL COMPOSITE BRIDGE: AN ALTERNATIVE DESIGN SOLUTION FOR SHORT-SPAN BRIDGE TOWARDS SUSTAINABILITY[1]

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The construction sector is a major source of greenhouse gases. Under the increasing concern about climate change and growing construction activities, the whole sector is challenged to shift focus toward sustainable solutions. The traditional procurement often prioritizes technical and economic viability, while their environmental performance is overlooked. Today's designers are urged to seek new design options to reduce environmental burdens. Sweden owns more than 24574 bridges, most of which 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 its results show 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; simultaneously, they are responsible for considerable environmental burdens due to large consumption of raw materials and energy. According to the Swedish Transport Administration [1], there are more than 24574 bridges in Sweden,

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most of which are short spans [2]. Among these, the concrete slab frame bridge (CFB) is a common solution. However, due to the challenges posed by climate change, designers are urged 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 that SSCB is favourable due to its easy constructability, low maintenance as well as competitive cost. However, SSCBs had never been examined in terms of environmental performance.

Life Cycle Assessment (LCA) is a standardized and internationally recognized approach for quantifying consumption of resources, environmental impacts, emissions as well as health impacts linked to a product or service [5-8]. LCA only started to be applied in the construction sector in recent years. When compared to the building sector, its use in the bridge industry is very rare [9, 10]. According to the literature review in [11], a pilot study of LCA for bridges was first performed in 1998 by [12] and [13]. Since then, a broader LCA implementation has been more focused on structures other than bridges. This paper intends to presents a generalized LCA framework for bridges, aiming to demonstrate a practical approach to bridge LCA 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 used in the 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, 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 based on their environmental performance at the early stage.

2. LCA METHODOLOGY

This paper follows 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, through construction, maintenance and operation until the end of life (EOL). The dominant structural components and critical activities that contribute to the most adverse environmental burdens are identified and tracked. The analysis is performed with the aid of the GreenBridge calculation tool developed by [16].

The reliability of LCA is primarily determined by the quality of the LCI database and by input accuracy. The same material may have different LCI profiles due to variations in regional production technology. This paper has adopted the European data from Ecoinvent v2.2 database to represent the Swedish conditions. 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 bridge related scenarios. Each data type includes thousands of gaseous, liquid and solid substances.

Figure 1. A concrete slab frame bridge [18]

3. CFB AND SSCB

In Sweden, both CFB and SSCB are commonly used as short-span bridges, serving the same technical function, often for a design lifetime of 80 years. In 2006, the Swedish Transport Administration owned 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 a corrugated pipe surrounded by 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 takes 2 to 3 months, excluding the time necessary for foundation works and backfilling. The necessary machinery usage includes earthwork excavators for formwork foundation preparation, soil compactors, 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 entire structure cannot be built at the same time. The foundation slabs are built first, followed by the front walls, the 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 further reduces the construction and transportation time, and the steel plate can be installed immediately after initial earthworks have been completed. Once bolted, the conduit can be backfilled using frictional soil which is then carefully compacted. The shorter SSCB construction time as compared to CFB can substantially reduce traffic disturbances, thus further mitigating 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 provided by the 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 serial numbers 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 scope of the study covers the entire bridge through the entire life cycle from cradle to grave.

Table 1. General data for the selected bridges

Bridge Registration no.	–	**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. Material manufacture phase

The material manufacture phase encompasses all 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. Summarized bills of material quantities are presented in Table 2, taking into account the structural components used in construction. The items listed include concrete, reinforcement, bitumen sealing for the bridge deck waterproofing, and steel railings.

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

4.1.2. 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 3. Summary of transportation operations

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

4.1.3. Maintenance and operation phase

This phase predicts future maintenance and operation scenarios and is regarded as the longest stage for bridges assuming the expected design lifetime [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 historical data and personal communication with experts on site, a list of general scheduled maintenance and repair plans is presented in Table 4. As stated above, this study covers periodic maintenance schedules related to repairs of concrete and reinforcement and replacement of bitumen sealing for waterproofing and steel for railing. All upstream processes involved in manufacturing these materials were obtained from Ecoinvent database, covering all stages ranging from raw material extraction until ready-made products availability at the factory gate.

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

4.1.4. End of life

Recycling in the end-of-life stage is environmentally beneficial, as it contributes to the reduction of original material usage and the 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 those environmental impacts that are directly caused by that product, is applied for the allocation issues in this study, thus avoiding inclusion of indirect impacts related to other concerned products. Therefore, energy and raw materials saved due to steel recycling are already counted in the initial material manufacture phase through using the ready-made LCI data from Ecoinvent v2.2, which represents the average manufacturing situation in Europe, assuming a mixture of 63% primary steel and 37% of secondary steel from the electric furnace. After demolition, waste concrete is assumed to be crushed into aggregate for further usage in road construction. Under the Swedish conditions, it is assumed that 16.99 MJ diesel and 21.19 MJ electricity is consumed when producing one ton of aggregate from crushing waste concrete [22].

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.

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

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 Figures 3 to 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.

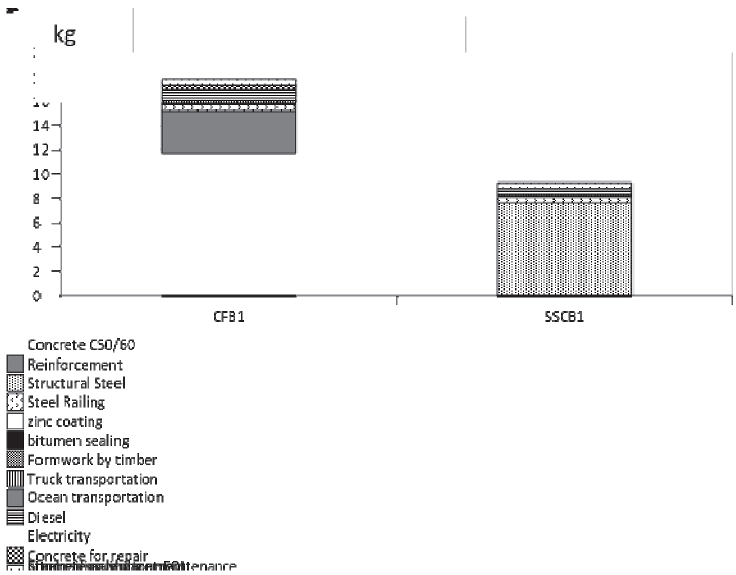

Figure 3. Global warming potential (kg CO_2 eq. per m^2 per year)

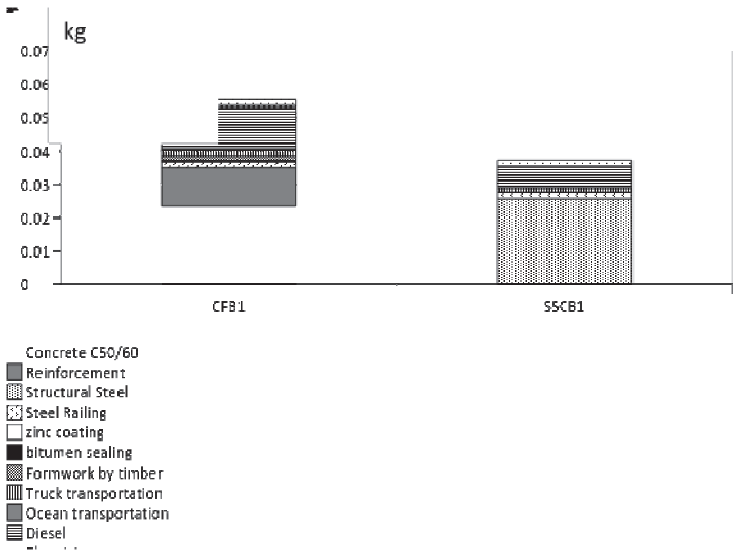

Figure 4. Photochemical oxidant formation (kg NMVOC per m^2 per year)

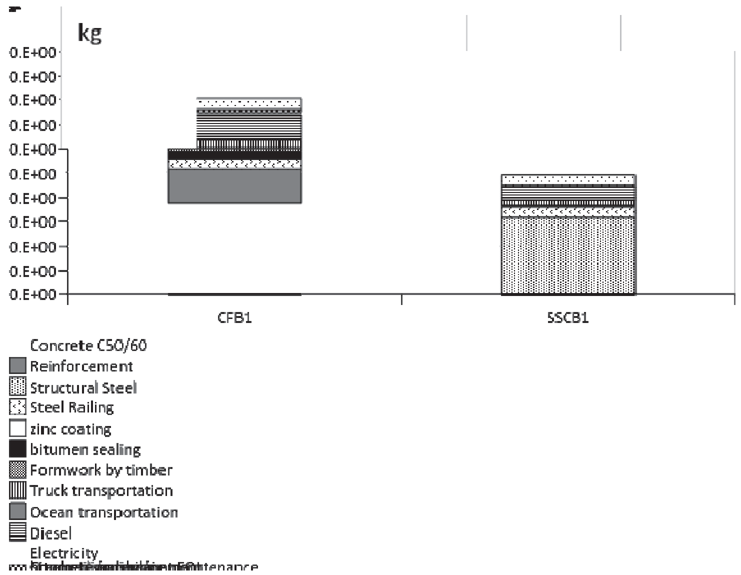

Figure 5. Ozone depletion potential (kg CFC-11 eq. per m^2 per year)

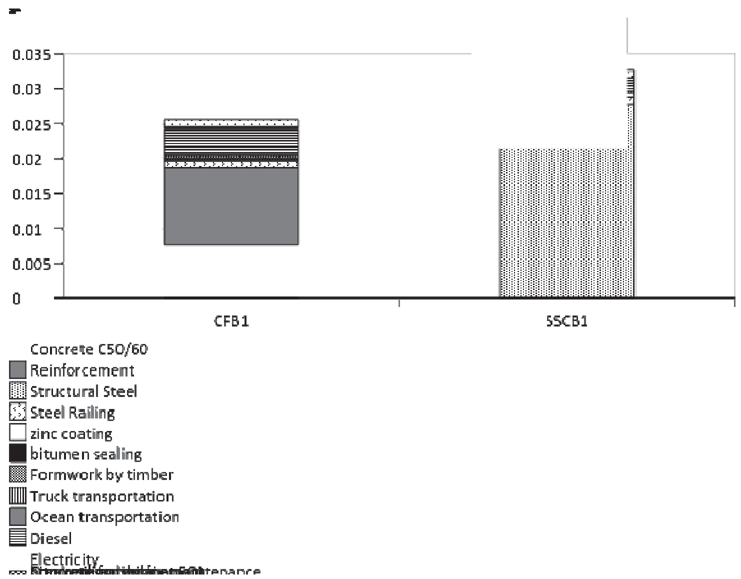

Figure 6. Particulate matter formation (kg PM_{10} per m^2 per year)

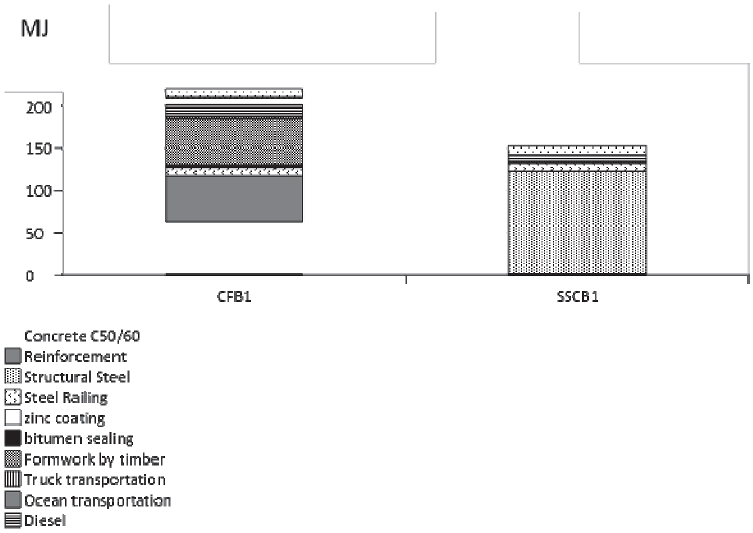

Figure 7. Cumulative Energy demand (MJ per m^2 per year)

5. CONCLUSIONS

This paper compared two types of commonly used short span bridges in Sweden: SSCB and CFB. A detailed procedure of LCA implementation for bridges was presented for 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 of construction and maintenance of SSCB. The initial material stage was found to be dominant in the total environmental impact.

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