COMPARATIVE STUDY OF DIFFERENT BRIDGE CONCEPTS BASED ON LIFE-CYCLE COST ANALYSES AND LIFE-CYCLE ASSESSMENT

V. Mara [1], R. Haghani [2] A. Sagemo [3] L. Storck [4] and D. Nilsson[5]
[1, 2, 3, 4] Department of Civil and Environmental Engineering,
Chalmers University of Technology, Sweden. E-mail: valbona.mara@chalmers.se
[5] COWI AB, Sweden

ABSTRACT

Sustainable development has gained increasing interest in the bridge industry in the recent years, with special regard to economic and environmental impacts. In line with this, holistic approaches considering all costs and environmental impacts in a life-cycle perspective are needed. The aim of this study is to conduct a life-cycle cost analysis and life-cycle assessment of four different bridge design alternatives; a conventional steel-concrete composite bridge and three steel bridges with fibre reinforced polymer (FRP) deck. The results reveal that two design alternatives for steel-FRP bridges are competitive in terms of costs and environmental impacts compared with the conventional bridge option.

KEYWORDS

FRP, bridge, composite, life-cycle cost analysis, LCC, life-cycle assessment, LCA, sustainability.

INTRODUCTION

In the past two decades, fibre reinforced polymer (FRP) materials have emerged as a new construction material for civil engineering applications. FRP offers unique material characteristics such as high stiffness- and strength-to-weight ratios, high fatigue and corrosion resistance and also potential weight saving benefits over conventional materials such as concrete or steel. These materials may be advantageous for use in bridge decks under certain circumstances. FRP bridge decks provide a modular and prefabricated design solution that has been proven effective in rehabilitation of existing bridges as well as new construction of bridges where accelerated erection is desired.

Despite the advantages offered by FRP decks in terms of structural performance and rapid installation, FRP decks might seem unattractive due to their high initial cost. By considering only the initial costs, the advantages of FRP decks could easily be overlooked. In reality, there are costs beyond the initial costs that should be considered in the cost estimation of bridges. Life-cycle cost (LCC) analysis, which sums up the total life-cycle cost including all costs from acquisition to demolition, is a good evaluation method to assess the economic viability of bridges. In addition, the environmental impact of bridges in a life-cycle perspective has gained a lot of attention from bridge authorities due to today's extensive resource consumptions. Another known method is the Life-cycle assessment (LCA), which can be used to assess the environmental impacts of a product from cradle to grave. Together, LCC and LCA analyses are valuable tools for aiding in the decision-making process in order to achieve cost efficient and/or environmental friendly infrastructure projects.

Concerning FRP, the studies performed to evaluate the cost efficiency and environmental impact of bridges utilizing FRP decks compared to conventional bridge designs are very limited (Chao *et al.*, 2012, Daniel, 2010,), Ehlen (1999,), (Nishizaki *et al.*, 2006, Nystrom *et al.*, 2003, Sahirman *et al.*, 2008, Zhang *et al.*, 2011,). This lack of studies in the field motivated the authors to perform an assessment of the life-cycle costs and the environmental impacts of different bridge designs incorporating FRP decks. This assessment was performed by evaluating and comparing an existing conventional composite steel-concrete bridge, to alternative bridge designs incorporating FRP decks.

CASE STUDY BRIDGE

Description of the bridges

The bridge considered in this study is a flyover bridge across highway E6/E20, which is the main north/south route through Göteborg, Sweden. The bridge consists of two continuous, equally long spans of 22 meters each with a width of 20 meters carrying four lanes of traffic and one pedestrian lane. The bridge superstructure consists of four main steel girders in composite action with a cast-in-place reinforced concrete deck. The mid support consists of four concrete piers on which the four steel girders rest (see Figure 1).

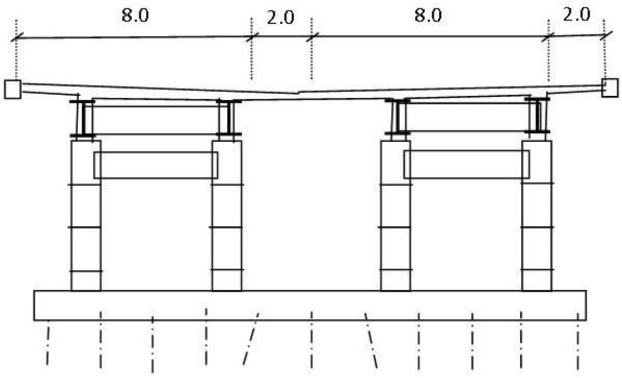
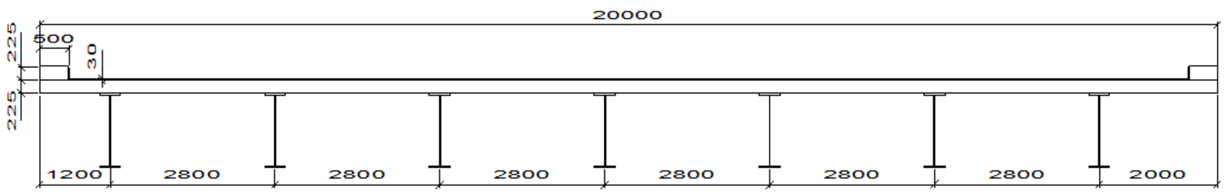


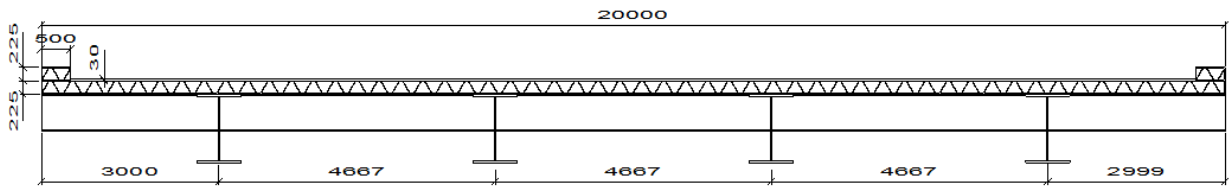
Figure 1. Cross-section of the bridge at the mid-support

Based on this bridge geometry and the surrounding conditions, three other bridge alternatives utilizing FRP decks were preliminary designed:

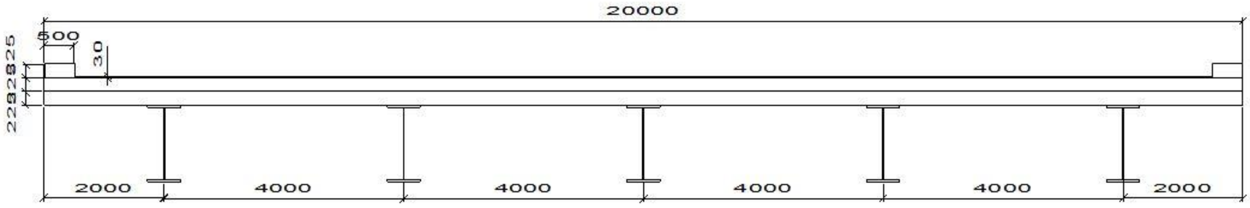
1) In the first design alternative, the FRP deck was orientated transversally to the direction of the traffic, as shown below in Figure 2a). A simplified model of the FRP deck, acting as a continuous beam over the longitudinal steel girders, was studied and showed that seven steel girders were needed in order to satisfy the deflection limit of the bridge deck.
2) The second design alternative, the FRP deck is orientated in the direction of the traffic flow. This design alternative included load-bearing transverse beams connected to the longitudinal steel girders. The purpose of using transverse beams as load-bearing elements was to allow for a larger spacing between the steel girders as well as creating a plate action in the FRP deck. In this case it was estimated that four steel girders with a spacing of 4.67m were needed (see Figure 2b)).
3) The third alternative included two transversal FRP decks on top of each other, thus increasing the stiffness of the deck allowing the spacing between the steel girders to be increased accordingly, without compromising the deflection limit. The design was similar to alternative 1, but with an increase in the spacing between the longitudinal girders from 2.8 meters to 4 meters, which reduced the number of steel girders from seven to five (see Figure 2c)).



a) *FRP alternative 1*



b) *FRP alternative 2*



c) FRP alternative 3

Figure 2. Cross-section of design alternatives with FRP bridge deck

Input for LCC and LCA analyses

The general input data for the life-cycle cost analyses of all bridge alternatives is given below in Table 1. The LCC includes both agency cost (construction, maintenance and end-of-life costs) and user costs (travel delay costs and vehicle operation costs).

Table 1. Input data for the life-cycle cost analyses

General: Technical service life: 100 years Discount rate (SWE): 3.5% **Traffic situation and user costs:** Average daily traffic (ADT) on the bridge: 19,715 veh/day Percentage of trucks on the bridge: 5.1 % Normal traffic speed: 50 km/h Reduced speed: 40 km/h User costs (cars): 19.5 euros/h User costs (trucks): 40 euros/h	**Investment costs:** Cost of RC deck: 176 euros/m^2 Cost of FRP deck: 725 euros/m^2 Cost of asphalt + insulation: 189 euros/m^2 Cost of polymer concrete + surfacing: 105 euros/m^2 Cost of steel: 2,882 euros/tonne **Disposal costs:** Concrete: 130 euros/tonne Steel: -59 euros/tonne* Asphalt: 4,7 euros/tonne Polymer concrete: 130 euros/tonne

* The steel material is recycled and is considered as a profit

Only the maintenance activities related to the superstructure were considered in this study, as presented below in Table 2. The intervals between maintenance activities were determined from interviews with experts in the field, whereas the costs were mainly retrieved from a Swedish database (BaTMan) price list (Trafikverket, 2012,).

Table 2. Maintenance activities considered for LCC and LCA

Concrete-steel bridge	Activity	Interval [year]	Cost [euros/unit]
Edge beams	Replacement of edge beam [m]	45	1,270
Overlay	Replacement of insulation [m^2]	40	176
	Replacement of asphalt [m^2]	10	70.5
FRP-steel bridge	Activity	Interval [year]	Cost [euros/unit]
Overlay	Change of polymer concrete [m^2]	20	105
Deck maintenance*	Various small repairs [m^2]	20	9.5
Common	Activity	Interval [year]	Cost [euros/unit]
Steel	Repainting of girders [m^2]	30	200

*Reference (Nystrom *et al.*, 2003)

The life-cycle assessments included the environmental impacts associated with the construction materials and emissions caused by traffic disruptions during the entire service life of the bridge. Transportation of the materials from gate to site and from site to deposition was excluded due to limitations in BridgeLCA, the excel-based software that was used in the study. BridgeLCA is part of the Scandinavian ETSI-project and specialized to perform LCA on bridges (Hammervold *et al.*, 2009,). The software uses emission vectors, retrieved from the Ecoinvent database, and considers eight different impact categories at midpoint level, which is a problem-oriented approach (Brattebo & Reenaas, 2012,). These are global warming potential (GWP), ozone depletion (ODP), terrestrial acidification (AP), freshwater eutrophication (EP), fossil depletion (FD), human toxicity cancer (HTC), human toxicity non-cancer (HTNC) and ecotoxicity (ET). The results of the LCA are then represented by category. Moreover, a normalization of the categories GWP, ODP, AP, EP, and FD is conducted based on the population of Europe. The toxicity categories are excluded from the normalization step since the methods for this were considered to be too uncertain.

RESULTS

LCC results

The LCC for all bridge alternatives are presented below in Figure 3. Overall, FRP alternative 2 had the lowest LCC, but the final costs were comparable for all alternatives except FRP alternative 3, which had a significantly higher LCC. This was due to the high material cost of the FRP deck that contributes to the large portion of the LCC. The steel/concrete bridge had the lowest agency costs, but falls short compared to FRP- alternative 1 and 2 due to higher maintenance caused user costs.

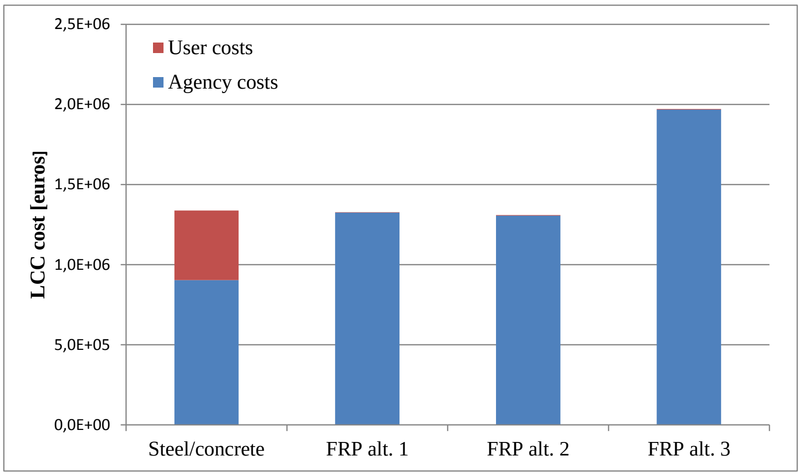


Figure 3. Total life-cycle cost for each bridge design

For each bridge design, the distribution of costs over the life-cycle phases is presented below in Figure 4. A majority of the costs for the FRP alternatives occur in the investment phase while the steel/concrete alternative has greater needs and costs for maintenance. The costs for the end-of-life phase were negligible for all designs.

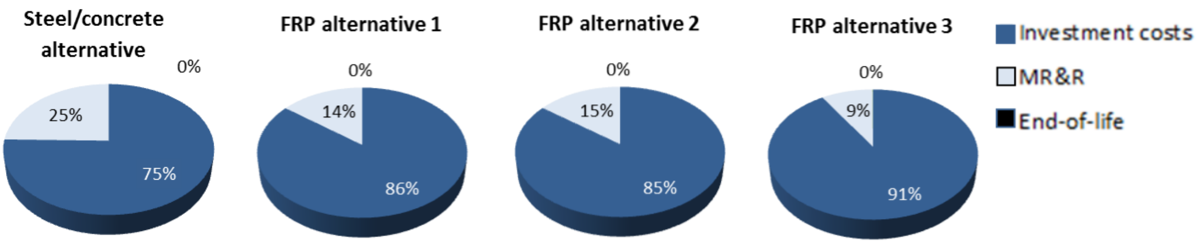


Figure 4. Cost distribution over the life-cycle phases of the bridges

LCA results

The results of the LCAs at midpoint level are presented for five of the eight impact categories: GWP, ODP, FD, AP and EP IN Figure 5. It can be seen that FRP alternative 1 and 2 causes lower emissions than the other alternatives in all impact categories except freshwater eutrophication.

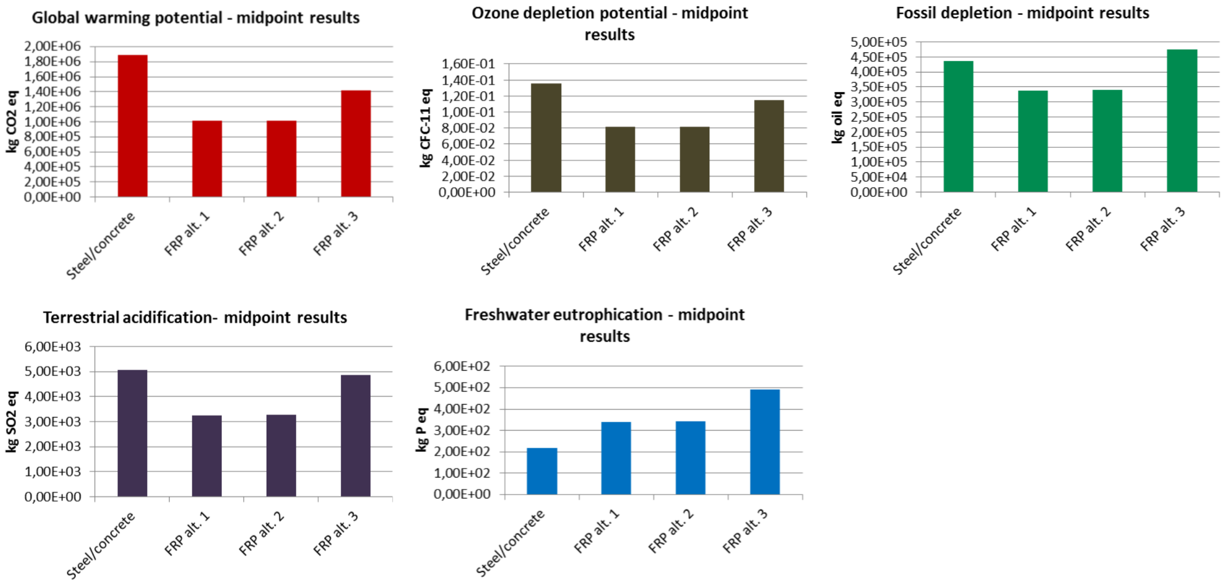


Figure 5. LCA midpoint result for each impact category

Moreover, a comparison of the final normalized results is shown below in Figure 6. The normalized results are presented in the unit person equivalent, in which one person equivalent corresponds to the environmental impact of one person per year. The total normalized result shows that the steel/concrete bridge causes the least amount of person equivalents, followed closely by FRP alternative 1 and 2.

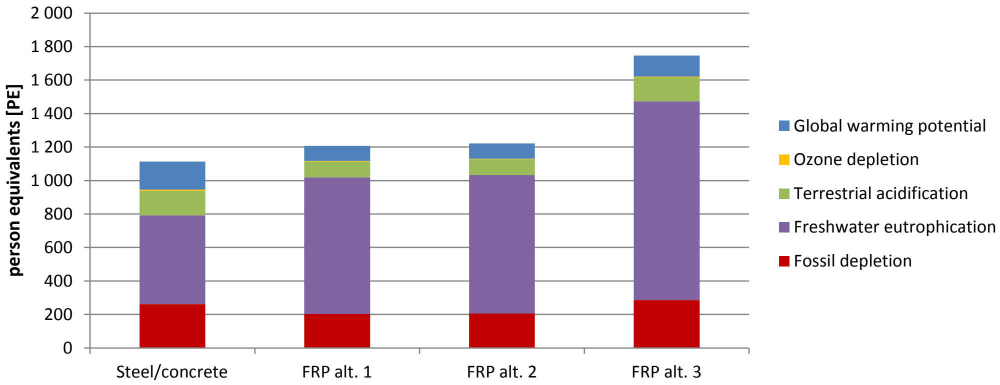


Figure 6. Comparison of normalized results of LCA for all bridge alternatives

When the midpoint results from the LCA are normalized, the impact category freshwater eutrophication is scaled up, thus composing a large portion of the total impact, whereas the ozone depletion is scaled down to a negligible amount. This implies that the normalization factors have a large impact on the total result and that they should be chosen with care in order to get fair results. In previous studies, the environmental impact of FRP bridges has been compared to other bridge types by only taking carbon emissions into account. The results from these case studies show that such a comparison can be quite misleading, since carbon emissions are not dominating to the total environmental impact.

CONCLUSIONS

In this study, a conventional steel/concrete bridge concept was compared to three different design alternatives incorporating FRP bridge deck in terms of LCC and LCA. One of the FRP alternatives included the use of a double FRP deck, intended to increase its stiffness. The results from LCC and LCA analyses showed that this alternative yielded much higher costs and emissions throughout the life cycle. In conclusion, this FRP alternative was considered to be an unsuitable solution.

Regarding the other two concepts of FRP alternatives, the LCC results were slightly more favourable. The results suggested that a conventional alternative with lower production costs and longer production time could be more profitable, as long as the affected traffic volumes was limited to the size considered in this study. However, considering a more complex traffic situation, such as those in densely populated urban areas with high traffic volumes, favors consideration of prefabricated alternatives, such as FRP, with a higher investment cost but a significantly shorter construction time. A combined effect of a busy traffic situation, decreased FRP pricing and a low discount rates would definitely benefit the FRP alternatives.

The results from the LCA showed that the steel/concrete bridge had a slight advantage regarding the total normalized impact over the other design alternatives. However, all categories except freshwater eutrophication favoured FRP alternative 1 and 2 when studied individually at midpoint level. The normalized result indicates that a simplified LCA analysis considering only one impact category might be misleading.

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