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UPGRADING BRIDGES WITH FIBRE REINFORCED POLYMER DECKS – A SUSTAINABLE SOLUTION

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Abstract

Today, road authorities deal with a large stock of bridges in need for maintenance. An important issue for maintenance activities in urban areas is the traffic disruption and user delay costs. Hence, authorities are looking for new structural- and time-efficient maintenance methods. Meanwhile, sustainability is becoming an important requirement for new methods. One solution which has been developed and practiced in the past ten years is the application of fibre reinforced polymer (FRP) bridge decks for refurbishment of existing and construction of new bridges. FRP decks have shown many advantages compared to traditional ones. However, widespread application of these decks needs considering aspects such as sustainability. The aim of this paper is to increase the sustainability awareness of FRP decks by presenting a case study in which the existing concrete bridge deck is replaced with an FRP deck. Analyses prove that the application of the FRP deck is a more sustainable solution in comparison with traditional refurbishment methods.

Keywords: bridge deck, carbon emission, FRP, energy consumption, sustainability

1. Introduction

The growing number of bridges in need of maintenance has become one of the most challenging issues for bridge owners and authorities. This issue becomes even more critical in urban areas where the cost of maintenance projects is often governed by indirect costs, i.e. traffic disruption and user delay costs. Limited resources, necessitates careful planning as well as developing new, efficient and cost-effective methods for maintenance and upgrading of bridge structures. Planning for maintenance of bridges in urban areas is an interdisciplinary process involving different areas such as bridge engineering, urban planning and traffic and construction management. In this regard, European project PANTURA was initiated to contribute to 'resource-efficient, urban-friendly construction sites' with an effort on providing a systematic interaction between engineering sector, urban planning and construction management in order to improve cost efficiency, and minimize disturbance and disruption of mobility.

A survey in PANTURA shows that the most common system for superstructure of urban road bridges in Europe is concrete or steel beams with concrete decks. Regarding the age profile, these bridges have almost a uniform distribution for age intervals of <20 years, 20-50 years and 50-100 years. Even though, the majority of these bridges are considered to be young (<50 years), deterioration of the deck due to corrosion and trouble with deck joints are the most frequent problems. Today the common practice is to demolish the old deteriorated concrete deck and replace it by a new concrete deck which might be either precast or cast in place. However, this practice, as mentioned by experts who participated in the survey, is a time consuming process and therefore causes many troubles to traffic flow. Thus, a main demand that is put forward by road authorities is to minimize the traffic disruption time by developing new methods of refurbishment.

In this respect, one potential solution which has evolved during the past decade is the use of fibre reinforced polymer (FRP) composite bridge decks. FRP decks exhibit high stiffness- and strength-to-weight ratios, high fatigue and corrosion resistance and offer potential weight saving benefits over conventional materials such as concrete or steel. In addition, their lightweight together with the possibility of prefabrication offer quick installation and therefore minimization of traffic disturbance. Implementation of these decks in numerous bridges has proven these advantages and has demonstrated that these decks are a viable option for deck replacement as well as for construction of new bridges.

Despite the abovementioned advantages, FRP decks have not experienced widespread application in bridge construction yet, due to certain technical and institutional barriers such as lack of design codes, long-term performance, appropriate connection details, material acceptance and high initial costs. Another important concern is sustainability of these bridge decks since bridge authorities are pressuring and putting demands to incorporate sustainability principles in the design of bridges.

The aim of this paper is to evaluate the sustainability of FRP decks in a case study in which the existing concrete deck is replaced by an FRP deck.

2. Sustainability

Sustainable development has become an increasingly important theme for engineers around the world. Sustainability includes three interdependent main aspects (1) social development, (2) environmental protection and (3) economic development as shown in Figure 1.

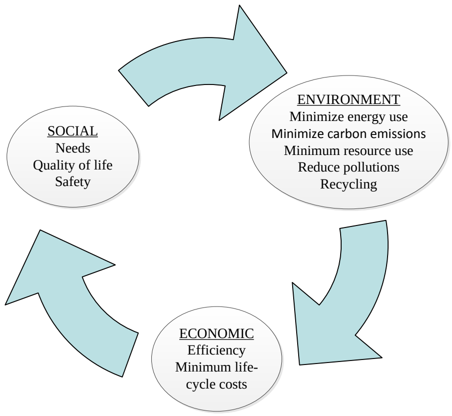


Figure 1 – The relationship of the aspects of sustainability

Infrastructural projects, especially in urban areas, either in form of new constructions or refurbishment of existing structures, involve a large investment with usually a significant impact on users and society as well as an adverse impact on the natural environment over the entire life cycle. The social impact of infrastructure industry is regarded considering issues such as safety of workers, users and residents and user’s convenience and welfare (service disruptions, accessibility problems, traffic jams, and dust and noise emissions). The adverse environmental impacts include energy consumption, carbon emissions, waste generation (recycling), virgin material usage and emission to water, air and soil. The last sustainability aspect includes economic viability for infrastructure due to limited resources.

Sustainable solutions should be developed with an attempt to support human well-being by reducing risks, minimizing the adverse impact to the environment and enhancing cost effectiveness. In order to reveal if FRP decks are a sustainable solution these aspects are considered in the sustainability analysis of the case study bridge considered in this paper.

3. Case-study Bridge

The bridge considered in this study was built in 1948 in north of Sweden over a small watercourse called Rokån. The bridge was simply supported, spanning 12 meters. It had a free width of 6 meters and carried two lanes of traffic. The bridge consisted of reinforced concrete deck carried by two steel girders having a spacing of 3.8 meters (see Figure 2). The bridge was in need of rehabilitation due to deterioration of the concrete deck, insufficient load carrying capacity of the girders for the current traffic and need of widening the deck by one meter. The rehabilitation was required to be performed in a short time in order to minimize the inconveniencies for road-users which lead to savings in terms of both time and cost. In 2002, the responsible authority decided to replace the entire superstructure of the bridge with a new prefabricated concrete deck on steel girders. This new bridge was assembled on site beside the old bridge for 35 days. When the assemblage was finished the old bridge was demolished and the new bridge was taken to place. During replacement, the bridge was closed for 30 hours and the traffic flow was diverted to an alternative path which was 16 km longer than the original way [1].

Another potential solution for this bridge would have been to replace the concrete deck with an FRP deck since the steel girders were still in good condition. It is evaluated that minimum performance-based requirements (such as deflection, load-carrying capacity) are met in this case [2]. The required time of bridge closure includes the time needed to demolish the old concrete deck and installing the new FRP deck. Demolishing of the old concrete deck was performed in 3 hours in the original case. The time to install the new FRP deck was assumed to be 12 hours which is based on previous experience of FRP deck installations (personal contact with Fiberline Composites, Denmark). Thus, the total bridge closure time for replacement of the bridge is estimated to be approximately 15 hours, which is half of the original solution. For consistency in the following text, replacement of the superstructure of the bridge is referred as alternative 1 and replacement of the deck with an FRP deck is referred as alternative 2.

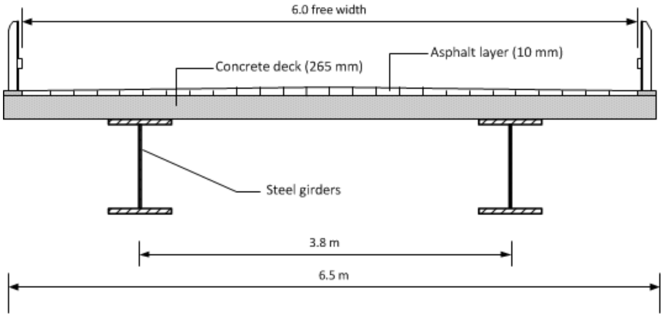


Figure 2 - Cross-section of Rokån Bridge

3.1 Cost analysis

The cost analysis is performed by considering direct construction costs and social costs for both alternatives. The expected maintenance and disposal costs were not evaluated in the analysis due to uncertainties and lack of information. The construction costs of replacing the superstructure are obtained by the analyses performed by Nilsson [1] and were converted to the present value by using an inflation rate of 4%. The social costs include driver delay costs, vehicle operating costs and accident costs. These costs are calculated based on the equations provided by Ehlen [3], except accident costs which were taken from the previous study of Nilsson [1]. In case of replacement of the deck with an FRP deck, time loss of drivers occurs due to detouring of the traffic. In the other case, in addition to this time loss, driver time loss is obtained due to limited traffic speed on the existing bridge during assemblage of the new bridge. The traffic speed was limited from the normal traffic speed of 90 km/h to 70 km/h for 14 days and to 50 km/h for 7 days. The length of affected roadway for this limited traffic speed was 200 meters. The other project parameters used in the study are tabulated below.

Table 1 – Project parameters

Item	Amount
Average daily traffic	796
Time loss of the drivers due to detour (hours)	0.3
Hourly time value of drivers (kr/h)	281
Hourly vehicle operating cost (kr/h)	207

The results of the cost analysis for each alternative are depicted in Figure 3. For this particular bridge, it is observed that social costs hardly comprise 10% of the total costs. This is because this bridge is located in rural area and the average daily traffic is low. Another motive is that the construction time for both alternatives was very short. Social costs are heavily dependent on bridge closure time, thus FRP deck alternative results in 44% lower social costs compared to the other alternative. In addition, for the first alternative the social costs are slightly increased due to limited traffic speed during assemblage of the new bridge beside the old bridge, which is not the case for the FRP deck option.

In total replacing of the deteriorated deck with an FRP deck resulted in 40% cost savings compared to the original solution of replacing the superstructure of the bridge, due to substantial material cost savings and social cost savings.

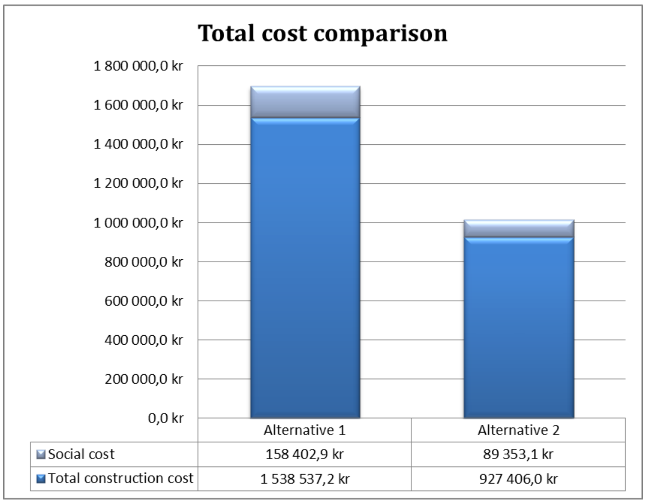


Figure 3 – Total cost comparison for the two alternatives

3.2 Environmental impact

The environmental impact of the two bridge options is investigated in terms of carbon emissions and energy consumption during the construction stage. Carbon emissions and energy consumptions during maintenance and disposal stages are not included in this study due to lack of information.

3.2.1 Carbon emissions

The activity sequences of both bridge alternatives and the related carbon emission are presented in the following figure.

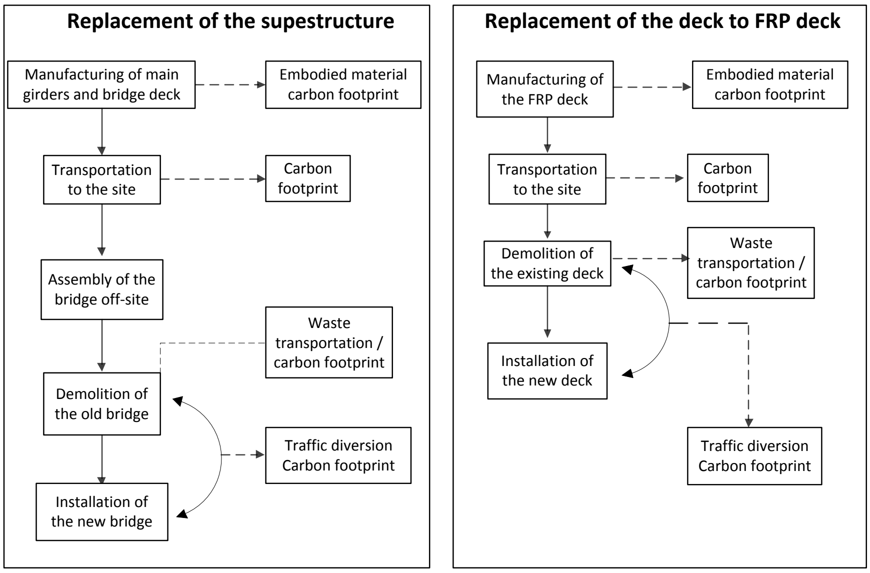


Figure 4 – Carbon emission sources during bridge construction activities for replacement of the superstructure to a new concrete-steel superstructure versus replacement of the deck to an FRP deck

As depicted in the figure above, the sources of carbon emissions are related to the material production, material/product/waste transportation and traffic diversions. Other sources of carbon emissions during construction phase are construction equipment use and on-site activities. These sources are not included in this study but if they were, the carbon emissions for alternative one are expected to be increased considerably compared to alternative two due to the assemblage of the new superstructure for 35 days.

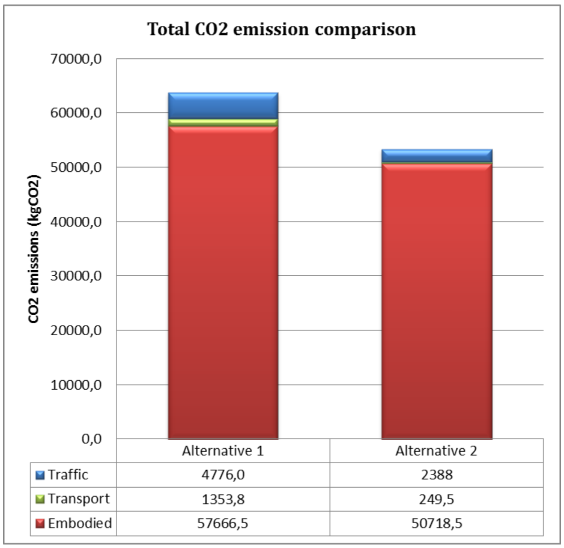
Table 2 shows the unit carbon emissions for material, transportation and vehicle operation used in this study. The embodied material carbon emissions are mostly based on the Inventory of Carbon and Energy [4]. The unit embodied energy value of FRP is slightly modified since the only reference in the ICE database is available from1998. The continuous development and widespread application of FRP material since 1998 leads to expected lower value of unit embodied carbon emission value which in other studies is quoted to vary from 3-5 [5]. The unit amount of carbon emissions of transportation and vehicle operation are taken as the values proposed by the Environmental Agency in London [6]. Transportation includes road and water transportation as the FRP deck is assumed to be transported from Denmark. Road transportation of the prefabricated elements on-site is considered to be approximately 100 km, while water transportation is assumed 300 km. Transportation of the disposal of all the waste during demolition of the old bridge is assumed to be a constant distance of 20 km.

Table 2 – Unit carbon emission amounts

Heading		**Unit**	**Unit amount of CO2 emissions**
Materials	Prefabricated concrete	$kgCO_2/kg$	0.215
	Reinforcement steel		1.71
	Steel		1.77
	Asphalt		0.14
	FRP		5
	Polymer concrete		1.48
Transportation	Road	$kgCO_2/t$ km	0.1067
	Water		0.015
Vehicle	General	gCO_2/km	300

Another source of carbon emissions is associated with the traffic disruption during construction work. This depends on daily traffic volume, detouring distance and the period of disruption. Daily traffic volume passing the bridge is 796 vehicle/day where 16% is heavy traffic and the rest is personal cars [1]. The period of disruption is 30 hours for the first alternative and 15 hours for the FRP option and the detouring distance in this project is 16 km.

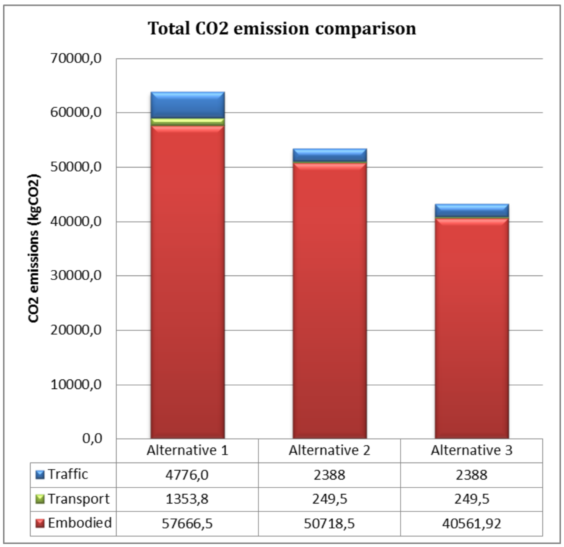
Considering all these carbon footprint sources, the results of the carbon emissions for each alternative are shown in Figure 5.



	Alternative 1	Alternative 2
🟦 Traffic	4776,0	2388
🟩 Transport	1353,8	249,5
🟥 Embodied	57666,5	50718,5

Figure 5 – Carbon emissions for the two bridge options during construction stage

It is observed that embodied material carbon emissions are dominant for both alternatives. For FRP deck option, beside the high embodied carbon emissions of FRP material, the result of high total embodied carbon footprint is attributed also to the use of polymer concrete as an overlay, which is approximately 10 times higher than asphalt. Polymer concrete is the most common used wearing surface for FRP decks, but asphalt is also applicable. If asphalt was to be considered as an overlay for the FRP deck (alternative 3) the embodied carbon emissions are decreased furthermore by 20% compared to alternative 2 (see Figure 6).



	Alternative 1	Alternative 2	Alternative 3
🟦 Traffic	4776,0	2388	2388
🟩 Transport	1353,8	249,5	249,5
🟥 Embodied	57666,5	50718,5	40561,92

Figure 6 – Carbon emissions of considered three different alternatives

Regarding carbon emissions from transportation, water transportation yields much less carbon emissions than road transportation and this is highly dependent on the accessibility of the FRP deck. If road transportation was selected for FRP decks, there would be no difference between the two options. However, as noted carbon emissions from transportation are almost negligible for both alternatives. Carbon emissions generated by traffic diversion are closely related to bridge closure time, thus FRP deck option is dominant over alternative 1. In total, the deck replacement option (alternative 2) is favourable by 16,5% lower carbon emissions compared to the first alternative. If asphalt was considered as an overlay this percentage would have been increased to 30%.

3.2.2 Energy consumption

Since the embodied material carbon emissions dominate in this case study, it was decided to estimate also the embodied material energy consumption for both initial alternatives plus the third alternative of an FRP deck with asphalt as overlay. The data on energy consumption for material units is presented in Table 3.

Table 3 – Energy consumption data [4]

Materials	**Energy consumption (MJ/kg)**
Prefabricated concrete	2
Reinforcement steel	24.6
Steel	24.4
Asphalt	2.41
FRP	33
Polymer concrete	35

The analyses show that the energy consumption for replacement of the deck (alternative 2) is 30% lower than replacement of the whole bridge (see Figure 7). A decrease of 62% could have been achieved if asphalt is considered as an overlay for FRP deck option instead of polymer concrete (alternative 3).

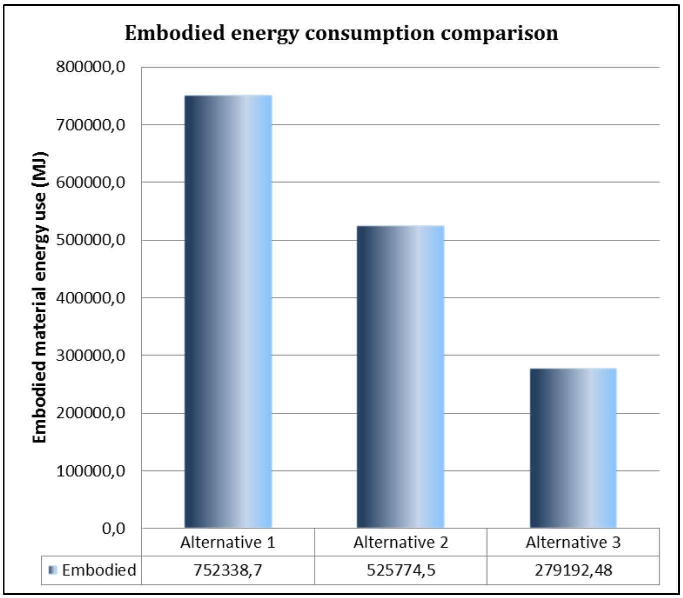


Figure 7 – Embodied material energy use for replacement of the superstructure (alt. 1) and replacement of the deck to FRP deck (alt.2 polymer concrete overlay; alt.3 asphalt overlay)

4. Conclusions

A sustainability analysis was performed on two refurbishment options in a case study bridge including replacement of the entire superstructure with a prefabricated concrete deck on steel girders and replacement of the existing deck with an FRP deck. Following conclusions could be drawn from this study;

- Substantial cost savings can be achieved considering FRP decks as a refurbishment option for functionally obsolete bridges instead of replacing the entire superstructure. Although the studied bridge was located in a rural area and the user delay costs were not dominant, the refurbishment method with the FRP deck was a more suitable concept. In order to further increase the cost efficiency of FRP decks, the target bridges might be selected as those with heavy traffic where user costs from traffic delays are significant.

- The refurbishment method with the FRP deck results in lower environmental impact. In this case study, the total amount of carbon emissions for FRP deck option decreased by 16,5 % than replacement of the entire superstructure option whereas the embodied energy consumption decreased by 30 %.
- Alternative wearing surfaces with lower embodied carbon emissions and energy consumption other than polymer concrete (without compromising the structural integrity) will further improve the environmental impact of refurbishment methods with FRP decks
- It should be mentioned that social impact cannot be quantified but this impact is improved in case of FRP decks. The installation of the FRP deck is faster, which in turn means less traffic delays, less pollution to the air due to the traffic and construction equipment used and a safer work-zone.

According to these conclusions, FRP decks have a potential to offer a more sustainable solution for replacement of deteriorated decks or rehabilitation of functionally obsolete bridges in comparison with traditional refurbishment methods.

5. Acknowledgements

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6. References

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