16

Irina Stipanović, Sandra Škarić Palić, Aljoša Šajna, Henar Martin-Sanz, Eleni Chatzi

LCA and LCC assessment of UHPFRC application for railway steel bridge strengthening

LCA AND LCC ASSESSMENT OF UHPFRC APPLICATION FOR RAILWAY STEEL BRIDGE STRENGTHENING

Irina Stipanović[1, 2], Sandra Škarić Palić[2], Aljoša Šajna[3], Henar Martin-Sanz[4], Eleni Chatzi[4]

[1] University of Twente, Faculty of Engineering Technology, Enschede, Netherlands. e-mail: i.stipanovic@utwente.nl

[2] Infra Plan konzalting, Zagreb, Croatia, e-mail: irina.stipanovic@infraplan.hr; sandra.skaric@infraplan.hr

[3] Slovenian Nationa Building and Civil Engineering Institute, Department of Materials, Ljubljana, Slovenia, e-mail: aljosa.sajna@zag.si

[4] Department of Civil, Environmental and Geomatic Engineering (IBK), ETH Zurich, Switzerland, e-mail: chatzi@ibk.baug.ethz.ch

SUMMARY: Most of the existing railway steel bridges are nowadays older than 70 years, experiencing serious aging and overload problems. Therefore they either need to be replaced or strengthened to fulfil the increased requirements. The main idea of strengthening existing steel bridges is considering the possibility of adding load bearing deck above the main girders without replacing them. In this particular case study, the original steel structure of the 9m long railway bridge was dismantled and transported to the laboratory for the experimental assessment and development of the new rehabilitation method. Based on the assessment results, a strengthening slab was designed using Ultra High Performance Fibre Reinforced Concrete (UHPFRC) formula. In the life cycle analysis, using LCC and LCA models, the comparison of the application of UHPFRC cast in-situ deck is compared to the bridge replacement solution, which was actually selected method by the owner. The executed solution used also a temporary bridge in order to enable continuous traffic, which has caused very high construction costs. In order to compare different options, we have additionally analysed a solution without a temporary bridge, which created three life cycle scenarios. Most important steps during the construction, exploitation and end-of-life stage have been taken into account and integrated into the LCA and LCC models. Finally the environmental, economy and societal impacts of three solutions were compared over the period of 60 years. The rehabilitation option with UHPFRC deck has shown by far the lowest direct and environmental cost while the user delay costs only after the period of 50 years are not the most convenient for users. Superior characteristics of UHPFRC enabled the optimization of the load bearing deck and by that a very low total used quantity of material resulting in minimum direct and indirect costs.

KEY WORDS: railway steel bridge; UHPFCR; strengthening; LCA; LCC model.

1 INTRODUCTION

EU transport policy provides the challenge to railway infrastructure owners to increase the productivity of existing rail networks, prioritise renewal and optimise new sections to reduce bottlenecks, increase productivity and achieve a switch from transport by road to rail. In its 2011 white paper entitled ‘Roadmap to a Single European Transport Area — Towards a competitive and resource efficient transport system’ [1], the Commission set the goal of ensuring that the majority of medium-haul passenger transport is carried out by rail by 2050. In the medium term (by 2030), the length of the existing high-speed network should be tripled and a dense rail network in all Member States maintained. In the long term, a European high-speed rail network should be completed. On the other hand European rail infrastructure managers (IMs) are managing ageing rail infrastructure with 95% of the network being built before 1914 [2]. This needs to be achieved at a time when budgets are restricted whilst improving customer satisfaction and dealing with challenges from natural hazards and extreme weather events which are affecting all of Europe. In order to deal effectively with this grand challenge, researchers and professionals need to develop methods to maintain and upgrade the existing rail infrastructure across the whole European railway area. Bridges as critical structures on the transport networks, are usually requiring highest maintenance and/or replacement costs. The problem is particularly rising in railways, where high percentage of bridges were built more than 70 years ago and were not designed for current loads and high speed trains. These are mainly bridges made of hot rolled steel or cast iron, mainly connected by means of rivets. Due to economic and environmental reasons, extending the service life of these structures proves beneficial, in opposite to demolishing or reconstructing them. [3-6]

In the last few decades Ultra-High Performance Fibre Reinforced Concrete (UHPFRC) materials have been increasingly applied for rehabilitation projects of existing bridges, proving itself as a reliable, cost efficient and sustainable alternative against conventional methods, but mostly for strengthening and rehabilitation of concrete structures [7-11]. In this paper the comparison of the application of UHPFRC cast in-situ deck is compared to the standard concrete bridge replacement solution, which was actually selected method by the owner. All steps during the construction, exploitation and end-of-life stage, while taking into account the direct and indirect impacts of technology, duration of works, service life etc. are taken into account and integrated into the Life Cycle Assessment (LCA) and Life cycle cost (LCC)models. Finally the environmental, economy and societal impacts of two solutions are compared over the whole bridge life cycle. The initial research work has been done within the EU research project SMART RAIL. [12, 13] The concept of strengthening steel bridge sections by transforming them into a composite section has been developed earlier [14, 15], while the innovation of this research lies in the use of UHPFRC for the construction of a composite deck.

2 CASE STUDY – RAILWAY STEEL BRIDGE

The case study presented in this paper relates to the Buna bridge, which was a component of to the Croatian Railway network since 1953, until its decommissioning in 2010. It stands as a good example of the steel bridge construction techniques of that period, i.e., steel plates joined by riveted connections. The structure, almost 9 m long, comprises of two main girders of 0.9 m depth, tied to each other every 2.26 m by means of L shape profiles. Diagonal L beams in a zig zag disposition close the lattice on the top, leaving a space of 1.8m between the 81 two girders. Wooden sleepers were directly supported over the bridge without any covering slab. Figure 1 illustrates the configuration of the structure. When a decision was made to replace the steel superstructure of the Buna bridge, the opportunity came up for experimental investigations on a real characteristic example of a steel bridge connected with rivets. Once the bridge was decommissioned, it was transported to laboratory facilities, in order to determine its static and dynamic performance and to find an economical and practical strengthening solution that could prove useful in future projects [13-15].

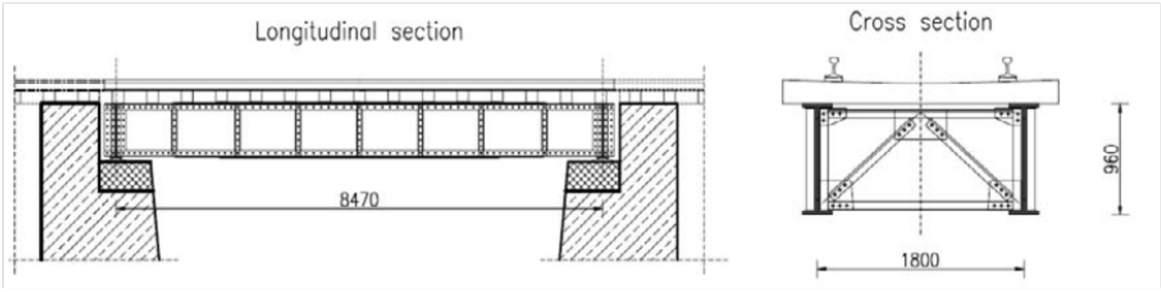


Figure 1: Schematic drawing of the tested steel bridge [12]

Figure 2: Original Buna bridge transported to the laboratory before testing [12, 13]

The main idea of strengthening existing steel bridges is considering the possibility of adding load bearing deck above the main girders without replacing them [4, 12-14]. Composite beams, subject mainly to bending, consist of a steel section acting compositely with a top flange of reinforced concrete. The two materials are interconnected by means of mechanical shear connectors. Converting alone metal section to composite cross-section raises the centre of gravity so that new composite cross-section can carry additional loads. In addition, the concrete deck stiffens upper steel flange and thus eliminates the problem of stability of compressed part of the cross-section (Figure 3).

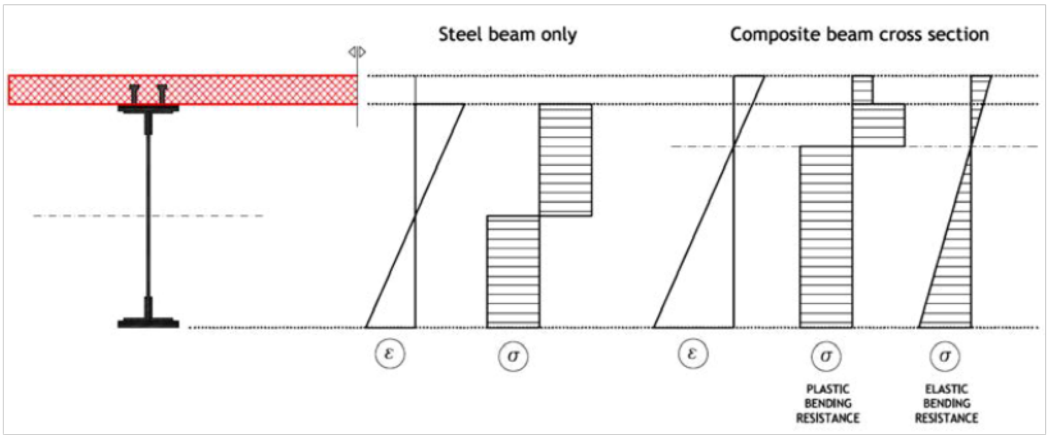


Figure 3: Composite effect shown through diagrams of strain and stresses [12]

The reason for using an UHPFRC for the strengthening of a steel railway bridge, apart from its excellent mechanical properties, is the fact that the deck is not reinforced with a standard reinforcement net, and it is expected that the procedure related to the execution of deck cast in situ will be shorter in relation to the standard reinforced-concrete deck. Therefore, the railway line will be closed to traffic for a shorter period of time, rendering not only economical but further advantages for the users. In addition, the UHPFRC deck height is less than the standard reinforced-concrete deck height, which minimizes problems related to adjustment of the track substructure geometry to the new height of the bridge.

3 LIFE CYCLE ANALYSIS OF UHPFRC REHABILITATION SOLUTIONS

3.1 UHPFRC strengthening solution

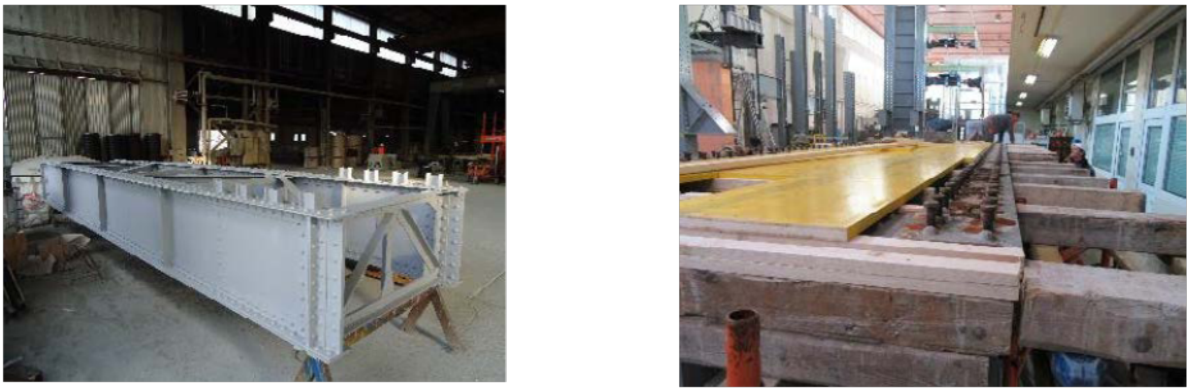
Ultra-High-Performance Fibre-Reinforced Concrete (UHPFRC) is a composite material which tends to exhibit superior properties such as advanced strength, durability, and long-term stability compared to conventional concrete. Mechanical properties like compressive and tensile strengths are much higher and this enables slender constructions due to increased capacity of transferring forces. Very dense matrix causes outstanding durability properties and it is shown that the concrete is very resistant to chloride and other chemical attacks and has a high abrasion and fire resistance. [7] It was decided to use the enhanced performance in strength and durability of UHPFRC and cast a deck slab upon the existing steel superstructure of a bridge in the lab. The original steel structure was transported and tested within a laboratory setting prior to the implementation of a cast in-situ UHPFRC deck. Results of these tests can be found in [13-15]. The main objective of strengthening the Buna bridge was converting the existing steel cross section to composite cross-section. This caused rising of the neutral axis, increase of the bearing capacity and finally enables the composite cross section to carry additional loads. In addition, the concrete deck stiffens the upper steel flange and thus reduces or even eliminates the problem of stability of the cross-section. The advantages of UHPFRC particularly valuable for rehabilitation of railway bridges are high strength and ductility, low added dead load, low added thicknesses, i.e. change in the track vertical alignment, extreme durability. [1, 4]

3.2 Rehabilitation process with UHPFRC

In the laboratory the whole process of the strengthening the existing bridge was performed as presented in Figure 4.

a) Steel structure was sandblasted and painted, two rows of steel studs on the upper flange of the steel girders were welded.

b) Formwork was built up



c) minimum secondary reinforcement in transverse direction was deployed and number of sensors were embedded inside the slab,.

d) UHPFRC slab was casted.

Figure 4: Strengthening process of the steel bridge

For improving the load transfer between the steel girders and the concrete slab, steel studs have been welded on the upper flange of the girders. The commercially available studs (type) were shortened to a length of 55mm, to fit into the concrete slab of designed thickness of 70 mm. Two rows of studs with an axial distance of 100 mm were welded on each girder using standard welding procedure, Figure 5a. The formwork for the slab was set-up as it would be done on-site, i.e. the formwork was supported by the steel girders only, see Figure 2b). The concrete slab was in the transverse direction reinforced with rebars of ϕ12 mm at a spacing of 250 mm, Figure 5c. The reinforcement was placed 2 cm under the designed upper surface of the slab. Finally the UHPFRC was placed, with the thickness of 70 mm. UHPFRC mix was designed using locally available raw materials, dolomite aggregate of maximum size of 4 mm, cement, limestone filler and superplasticizer. The selected concrete mix can be found in [16]. Fresh concrete properties were determined as follows: the slump (acc. EN 12350-2), the air content (acc. EN 13950-7) and the density. The concrete had a slump of 190 mm, air content of 3.3 % and density of 2620 kg/m^3.

3.3 Executed solution with new concrete bridge

The new bridge structure is designed as a composite concrete-steel structure. Seven steel girders IPB 450 are embedded in concrete at a distance of 60 cm with a span of 10.5 m. This will increase the clear opening of the bridge by 1.4 m, so that the new opening will be 8.70 m. The load-bearing structure will be of a total length of 11.80 m and will consist of seven steel girders embedded in a concrete at a distance of 60 cm with the compression slab 15 cm thick on top. The total height of the structure will be 60 cm, as presented in Figure 5. All concrete elements are made of concrete min. class C30 / 37, soft ribbed reinforcement type B500B, and embedded steel girders S235JRG2 [17].

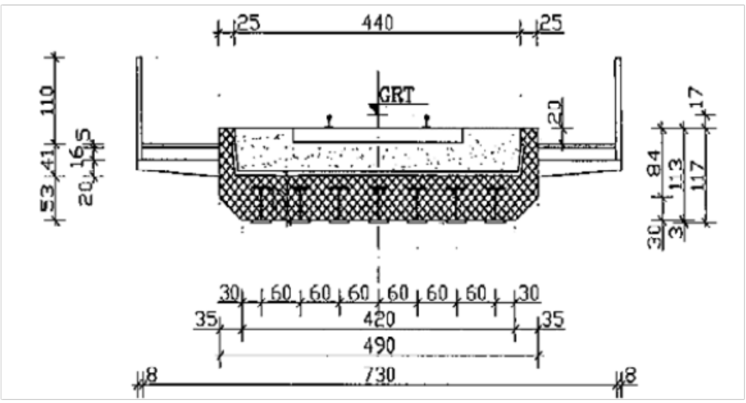


Figure 5: New Buna bridge

4 WHOLE LIFE CYCLE MODEL

The life cycle analysis were performed for three different bridge upgrade scenarios. Since the life cycle analysis are performed for comparative purposes, structural elements and equipment which are the same in different solutions are excluded from the analysis, e.g. substructure, rail equipment, bridge equipment. The life cycle scenarios include rehabilitation works, used materials, delays caused by the rehabilitation project and maintenance works for the 60 year period. The following three options are compared:

- Scenario 1: Old steel bridge is removed and new concrete bridge is constructed with rail traffic redirected on the provisional bridge – This option was actually performed for the rehabilitation work of the Buna bridge on the Croatian Railway network. The works included provisional bridge since the railway line had to be in operation the whole time during performance of rehabilitation works. This scenario includes *I*-shaped steel girders and conventional C30/37 concrete with ballast layer beneath the concrete sleepers and rails. In the life cycle scenario of 60 years regular maintenance, inspections and periodic concrete repair works are included.
- Scenario 2: Old steel bridge is removed and new concrete bridge is constructed with closed rail traffic for one month – The works are the same as in Scenario 1 but without provisional bridge meaning that the rail traffic is closed for one month. This has a large impact on users.
- Scenario 3: Old steel bridge is strengthened with the added UHPFRC slab on top of it – This scenario includes cleaning and painting of the existing steel superstructure, welding of steel studs and casting of thin layer of UHPFRC concrete deck, see Fig. 4.

4.1 Construction costs

The direct construction costs (CC) were retrieved from the original design and actual construction work costs provided by the owner of the bridge. These costs were used for the scenarios 1 and 2. The cost for scenario 3 is based on the cost of UHPFRC concrete installed in the deck in laboratory. Overall calculation of CC begins by first dividing the designed object into separate construction elements. The next step is determining the unit cost of a particular construction element and multiplying it by the amount that that element occurs in the design. This results in the total costs of that particular element in the total object. Doing this for every construction element and summarising these costs will yield the total assigned construction costs.

4.2 Maintenance costs

The maintenance costs will be calculated in a similar manner to the initial construction costs. First the maintenance scenario that most accurately describes the estimated required maintenance over the life cycle of the object has to be determined. This means determining the different necessary maintenance activities, their accompanying frequencies and their estimated unit costs. Next, the unit cost of a certain maintenance activity (AUC_i) is multiplied by the quantity of units related to that activity (Aq_i). The resulting yearly maintenance cost for that activity is attributed to all the years in the life cycle of the object in which that maintenance activity takes place (based on the frequency attributed to that activity). This creates a maintenance schedule with which the total maintenance costs of every year in the life cycle can be calculated. Summarizing the maintenance costs of every year in the life cycle of the object gives the total nominal maintenance costs of the object. Because the maintenance costs are made in the year the maintenance takes place, the future cash flows have to be discounted to create a present value. The total discounted maintenance costs may be increased by a certain percentage that cover the *unassigned costs*, *indirect costs* and *unassigned object risks* (but not *engineering costs* and *other additional costs*), if that is the owner's practice. For more details please refer to [18].

4.3 User delay costs

The equations used for determining the user delay cost are based on the work of [18, 19]. The total user costs are a summation of the two sub-categories; freight delay costs and passengers delay costs. Because the user costs are made during the life cycle of the bridge, future cash flows will have to be discounted to determine a total present value. The traffic delay costs are the costs that represent the valuable time of the network users itself. This economic value of the user's time is dependent on several factors, namely the type of traffic (passenger vehicle or freight traffic), the amount of persons/cargo per vehicle and the type of cargo/person (business/leisure). The input data for the calculation of traffic delay costs are coming from data provided by the owner of the railway line (0.31€ per min of delay). The traffic delay costs can be then determined as follows:

$$TDC_t = ETT \times ADT_t \times VOT \quad \times N_t \qquad \text{(Eq. 1)}$$

wherein TDC_t is traffic delay costs for year t (€), *ETT* is extra travel time per type of users (hours), ADT_t is the average daily traffic (separately for freight and for passenger trains) in year *t* passing the analysed section or bridge in question, *VOT* is a monetary value for the users time (€/hour), and N_t is the duration of a certain maintenance activity (days).

4.4 Environmental costs

In this case study for the LCA calculations GaBi software was applied. This software allows to estimate the relevant environmental indicators based on the CML-2001 method [20]. Using the 'revealed collective preference method' the environmental costs can then be determined. The environmental impact per kg of material for certain impact category has been determined and then monetized by using the method explained in [21]. The shadow prices are a way of monetizing environmental effects. For an explanation and in-depth discussion the author refers to the report by CE Delft [22] which provides the different environmental effect categories and their corresponding shadow prices are presented.

This is where the method used in this research differs from the framework of the ISO 14040 [23]. Instead of first determining the life cycle inventory (LCI) of one complete product life cycle and then determining the resulting impact via life cycle impact assessment (LCIA), this study first determines the environmental impact of one kg of material as a basic parameter of the model and then uses those values to calculate the total environmental impact by multiplying it with the amount of material present in the construction or maintenance activity. The total environmental costs can then be determined using the unit shadow price for each environmental category. Environmental costs incurred during the life cycle of the bridge are not discounted as recommended by [24].

5 RESULTS

The whole life cycle model takes into account direct and indirect costs, where direct are borne by the owner (construction and maintenance costs), and indirect costs (user delay and environmental costs) are borne by the society. In the case study three different rehabilitation scenarios are analysed as presented before. The aim of the model is to provide to the infrastructure owner the insights into the impacts of different maintenance strategies and enable optimal decision making. In the model input parameters can be changed according to the decisions made. Traffic closures and duration of the maintenance activities are used from the current practice and from the owners experience, and prediction of the future performance is based on the experts judgments and historical data. The graphs in Figure 6 clearly show that choosing different options in the beginning of a structures life cycle have a significant impact on different total costs in all phases. The rehabilitation option with UHPFRC deck (scenario 3) due to its small thickness of 7 cm, has by far the lowest direct and environmental cost while the user delay costs for a longer period of time is also the most convenient for users. Superior characteristics of UHPFRC enable much thinner structural elements and by that a very low total used quantity of material resulting in decreased costs. Scenario 2 where the bridge is closed for rehabilitation works reveals the highest user delay cost but lower direct and environmental costs since the provisional bridge is not built. Scenario 1 with the provisional bridge has the highest total costs, although the smallest user delay costs since with the solution of provisional temporary bridge no delays were caused.

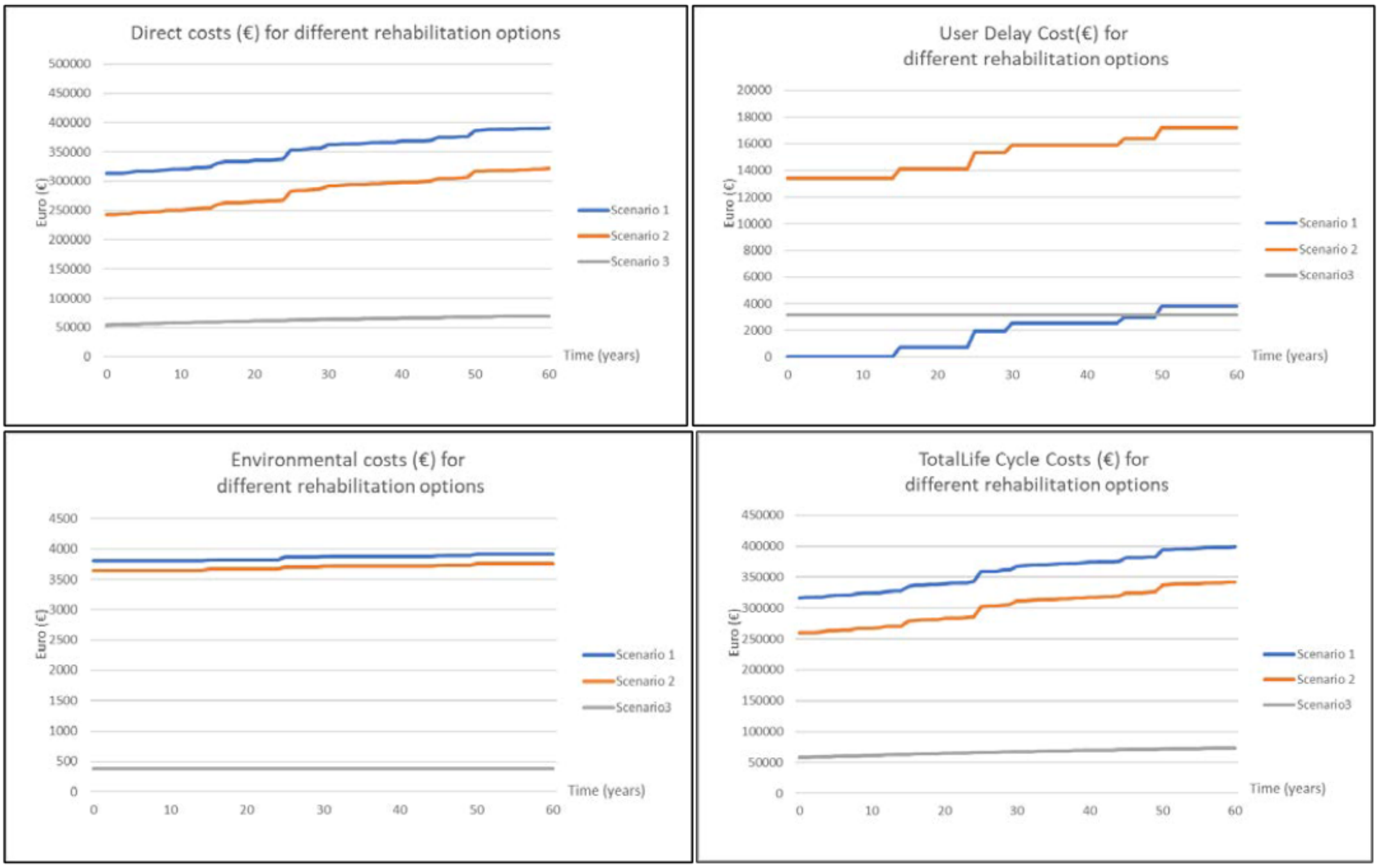


Figure 6: Direct costs, user delay, environmental and total life cycle costs for three different scenarios

6 CONCLUSIONS

In this paper the idea of strengthening existing steel bridge by adding UHPFRC deck, above the main girders without replacing it, has been explored and compared to the conventional solution of replacing the existing bridge with the new one. In this particular case study, the original steel structure of the 9m long railway bridge was dismantled and transported to the laboratory for the experimental assessment and development of the new rehabilitation method. Based on the thorough laboratory static and dynamic assessment, a strengthening UHPFRC slab was designed, satisfying all design requirements and the technological limitations, such as mixing, transporting and casting. In the life cycle analysis, using LCC and LCA models, the comparison of the application of UHPFRC cast in-situ deck is compared to the bridge replacement solution, which was actually selected method by the owner. The executed solution used also a temporary bridge in order to enable continuous traffic. This has caused very high construction costs. In order to compare different options, we have additionally analysed a solution without a temporary bridge, which created three life cycle scenarios. Most important steps during the construction, exploitation and end-of-life stage, while taking into account the direct and indirect impacts of technology, duration of works, service life etc. have been taken into account and integrated into the LCA and LCC models. Finally the environmental, economy and societal impacts of three solutions were compared over the period of 60 years. The rehabilitation option with UHPFRC deck has shown by far the lowest direct and environmental cost while the user delay costs only after the period of 50 years are not the most convenient for users. Superior characteristics of UHPFRC enabled the optimization of the load bearing deck and by that a very low total used quantity of material resulting in minimum direct and indirect costs.

ACKNOWLEDGMENTS

The authors would like to acknowledge the financial and in-kind support from the following entities: Slovenian

Research Agency within Research Programme P2-0273, company Trgograd d.o.o. from Litija, the Swiss National Science Foundation (SNSF) within the project 154060 and the COST Action TU1406.

REFERENCES

[1] European Commission, WHITE PAPER Roadmap to a Single European Transport Area – Towards a competitive and resource efficient transport system / COM/2011/0144 final, (2011)
[2] European Railway Agency, Intermediate report on development of railway safety in the European Union, (2013).
[3] McCarron, P. Way Beam Replacement and Bridge Deck Strengthening using Concrete Composite Construction, University of Surrey Department of Civil Engineering, (2005).
[4] Carroll, M. An Investigation into Concrete Composite Strengthening of a Continuous Wrought Iron Railway Bridge using Precast Concrete Deck Slabs, Dissertation, University of Surrey Department of Civil Engineering, (2010).
[5] Network Rail, Railway Bridges Today and Tomorrow, Proceedings of the conference, UK, (2006).
[6] Olofsson, I., Elfgren, L., Bell, B., Paulsson, B., Niederleithinger, E., Sandager, J., Jensen, Feltrin G., Täljsten, B., Cremona, C., Kiviluoma, R., Bien, J. Assessment of European railway bridges for future traffic demands and longer lives – EC project “Sustainable Bridges”, Structure and Infrastructure Engineering, Vol. 1, No. 2, pp. 93 – 100, (2005).
[7] Bøhnsdalen Eide M., Hisdal J.M., SINTEF Building and Infrastructure, Ultra High Performance Fibre Reinforced Concrete (UHPFRC) – State of the art, COIN Project report 44, (2012). http://hdl.handle.net/11250/2379433
[8] Brühwiler E, Denarié E. Rehabilitation and Strengthening of Concrete Structures Using Ultra-High Performance Fibre Reinforced Concrete. Structural Engineering International; (2013) 23(4): 450-7.
[9] G. Habert, E. Denarié, A. Šajna, P. Rossi, Lowering the global warming impact of bridge rehabilitations by using Ultra High Performance Fibre Reinforced Concretes, Cement and Concrete Composites, Vol. 38, (2013), pp. 1-11, ISSN 0958-9465, https://doi.org/10.1016/j.cemconcomp.2012.11.008.
[10]Franssen, R., Guner, S., Courard, L., Mihaylov, B., A study on the numerical modelling of UHPFRC-strengthened members, ICCRRR 2018, paper 09001, https://doi.org/10.1051/matecconf/201819909001, (2018).
[11] Sakr, M.A., Sleemah, A.A., Khalifa, T.M., Mansour, W.N. Behavior of RC beams strengthened in shear with ultra-high performance fiber reinforced concrete (UHPFRC), ICCRRR 2018, paper 09002, https://doi.org/10.1051/matecconf/201819909002, (2018)
[12]SMART RAIL FP7 Project, Deliverable 3.3 Rehabilitation of Bridges and Tunnels, Recommendations for the rehabilitation of engineering structures (bridges and tunnels), http://smartrail.fehrl.org/, 2013.
[13]Dzajic, I., Stipanovic Oslakovic, I., Sajna, A. Rehabilitation of steel railway bridges by implementation of UHPFRC deck. Proceedings of the International Conference on Road and Rail Infrastructure CETRA, (2014), Publisher: University of Zagreb, ISSN: 1848-9850.
[14]Martín-Sanz, H., Tatsis, K., Chatzi, E., Brühwiler, E., Stipanovic, I., Mandic, A., Damjanovic, D. & Sajna, A. Towards the use of UHPFRC in railway bridges: the rehabilitation of Buna Bridge, Life-Cycle Analysis and Assessment in Civil Engineering: Towards an Integrated Vision – Caspeele, Taerwe & Frangopol (Eds) © 2019 Taylor & Francis Group, London, ISBN 978-1-138-62633-1, pp. 203-209.
[15]Škarić Palić, S., Damjanovic, D., Stipanović Oslaković, I., Martín-Sanz, H., Koščak, J., Duvnjak, I., Šajna, A. Experimental Investigation of a Steel Railway Bridge Strengthened with UHPFRC Deck Slab, Proceedings of RILEM Conference “Spring Convention and Sustainable Materials, Systems and Structures Conference”, (2019), 20 – 22 March 2019, Rovinj, Croatia.
[16]Šajna A., Stipanovic I., Martin-Sanz H., Damjanovic D., ‘Rehabilitation of an old steel railway bridge using UHPFRC – material characteristics and casting technology’, RILEM International Conference on Sustainable Materials, Systems and Structures, (2019), 20 – 22 March 2019, Rovinj, Croatia.
[17]Railway Design Company (Zeljeznicko projektno drustvo d.d.) Rehabilitation design project Buna bridge, 2010 (in Croatian).
[18]Skaric Palic, Stipanovic (2019) SAFE-10-T Deliverable D2.4 Report on Whole Life Cycle Model, https://www.safe10tproject.eu/publications
[19]Sundquist, H., & Karoumi, R. (2012). Life Cycle Cost Methodology and LCC Tools. ETSI. Retrieved from http://www.etsi.aalto.fi/Etsi3/PDF/TG3/LCC%20Description.pdf
[20]Thinkstep. (2015, April 10). Description of the CML 2001 Method. Retrieved from http://www.gabisoftware.com/support/gabi/gabi-lcia-documentation/cml-2001/
[21]TNO-MEP. (2004, March 8). Toxiciteit heeft zn prijs: schaduwprijzen voor eco-toxiciteit en uitputting van abiotische grondstoffen binnen dubocalc.pdf. Rijkswaterstaat. Retrieved from http://publicaties.minienm.nl/download-bijlage/15533/toxiciteit-heeft-z-n-prijs-schaduwprijzen- voor-eco-toxiciteit-en-uitputting-van-abiotische-grondstoffen-binnen-dubocalc.pdf
[22]CE Delft. (2003, April). Weging in DuboCalc: Toepasbaarheid van de preventiemethodiek. CE Delft. Retrieved from http://www.ce.nl/?go=home.downloadPub&id=72&file=03_7486_13.pdf
[23]ISO 14040:2006 Environmental management — Life cycle assessment — Principles and framework
[24]Hellweg, S., Hofstetter, T. B., & Hungerbuhler, K. (2003). Discounting and the environment should current impacts be weighted differently than impacts harming future generations? The International Journal of Life Cycle Assessment, 8(1), 8–18.