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Assessment Procedure and Rehabilitation Criteria for Riveted Road Bridges

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Abstract

Traffic patterns increasing and the degradation of existing roadway steel bridges due to poor maintenance has led to the need of an assessment deciding whether to retrofit or to supply a structure replacement. This paper focusses on the rehabilitation of steel truss bridges in order to extend the lifetime of such bridges. Two case studies are presented: the Adige Bridge, located between the provinces of Padua and Rovigo, and the Po Bridge, which connects the Rovigo and Ferrara provinces in northern Italy. In both cases, stress data and displacements are obtained by a 3D finite element model and the results show that loads defined in the European code are enough to compromise material strength in several sections. Appropriate retrofitting criteria are proposed and compared. A multi-criteria decision approach is introduced at the end of the paper to help in the decision-making process of selecting the best option for an additional reinforcement strategy, taking into account four criteria: reliability of the solution, ease of construction, estimated cost and embodied carbon.

Keywords: steel bridge; rivet; composite structure; rehabilitation; cost optimization; MCDA—multi-criteria decision analysis

Introduction

Riveted constructions were widely used in railway and road bridges during the second half of the nineteenth century up to the middle of the twentieth. Most of these wrought-iron or older steel bridges are still in use around Europe and particularly in Italy. Sixty percent of Italian railway steel bridges are about 100 years old as they were built between 1900 and 1920. The evolution of the society during the twentieth century has led to the increase of traffic, cargos and speed limits, so old steel bridges have, right now, a reduced performance level. ASCE (1982) reported that 80–90% of failures in steel structures are related to fatigue and fracture. However, other factors affecting the structural aging of bridges are reported in Refs. [1–11]. Vibrations, transverse horizontal forces, internal constraints, localized and diffused defects as corrosion damages, are concurring causes of damages.[12] In order to conform to these needs and for the safety of people, it is necessary to adapt the Italian infrastructural network, or at least to improve performances of their bridges; moreover a total bridge replacement is not possible, due to financial constraints.

In the specific case of steel truss bridges, a suitable method to extend the lifetime of existing structures is represented by the introduction of new deck systems combined with localized strengthening interventions. In this paper, two old steel riveted road bridges in Italy are studied. In both cases, different strengthening alternatives are analyzed and discussed: the introduction of orthotropic deck; the construction of composite deck with different slab thicknesses and ordinary concrete strength; the construction of composite deck with different slab thicknesses and high concrete strength; in some cases, also steel-to-steel interventions on the bridge are provided. It will be shown that the best structural strengthening alternative lies in the construction of a composite concrete or of an Ultra High-Performance Concrete (UHPC) or an Ultra High-Performance Fiber Reinforced Concrete (UHPFRC) deck with a reduced thickness (compared with traditional interventions) resting on the existing steel structure combined with steel-to-steel interventions. At the end of the paper, a multi-criteria decision approach is introduced to help in the decision-making process of selecting the best option for an additional reinforcement strategy, taking into account four criteria: reliability of the solution, ease of construction, estimated cost and embodied carbon.

Structural Modeling

Structural Modeling and Calibration

The bridge structures were modeled using the FEM software Midas Civil,[13] using only beam elements. Rigid links (rigid body) were used to represent eccentricities of the elements. A Young's modulus of 210 000 MPa (kN/mm^2), a Poisson's ratio of 0.3 and a material density value of 7850 kg/m^3 (weight density of 76.98 kN/m^3) were used for the analyses. All beam members sections were modeled as the as-built structure, as measured during geometrical survey. The bridge is subjected to permanent loads such as self-weight of steel elements and of non-structural elements and to variable loads such as temperature and traffic. In order to validate the theoretical model that is used to capture the bridge structural behavior (force and displacement behavior), data shall be obtained from the experimental testing. For the case of existing bridges, either dynamic[14,15] and static load tests can be used because both provide synthetic information representing the overall response of the bridge.

Safety Verifications

The optimization of the structure is calculated at the Ultimate Limit State checking the safety factor of all members for all load combinations considered, according to EN 1993-1-1:2005.[16] All structural members are grouped into subsets (e.g. for trusses: lower chords, struts, stringers, bottom bracing, floor beams, diagonals, upper chords, superior transverses, top bracings) in order to proceed gradually to the optimization of each subsets of members. The analysis results report for each load combination the maximum ratios Ed/Rd defined as the minimum safety factor of all ultimate limit state (ULS) checks; ratios less than 1 imply that all the member strength verifications are verified. Then, serviceability limit state (SLS) optimization and verification are performed. In addition, one of the most relevant structural aspects of existing steel bridge strength is to cope with fatigue damage issue. The adopted procedure for fatigue assessment is provided by EN 1993-1-9:2005.[17] Fatigue verification is performed with the Fatigue Load Model 3 defined in EN 1991-2:2003[18] and the equivalent damage procedure. It is noted that for those cases in which the orthotropic steel deck solution is adopted as the retrofit solution, the new fatigue-sensitive details must be assessed according to its fatigue strength category on the basis of "Table 8.8: Orthotropic decks—closed stringers" and "Table 8.9: Orthotropic decks—open stringers".[17] FLM3 verification is of fundamental importance for orthotropic deck in order to understand concentrated loads fatigue effects due to the vehicle wheels instead of uniformly distributed loads as in the FLM1 and could reveal fatigue-sensitive regions for the orthotropic steel deck alternative. Cover-plating intervention should be analyzed as it introduces newly fatigue-sensitive details in the bridge steel truss members. As cover plating is assumed to be built based on Details 7 of Table 8.1 of EN 1993-1-9[17] the fatigue strength category is represented by $\Delta\sigma_C = 56$ MPa. A conservative hypothesis concerning the adoption of the Ultra-High-Performance Concrete (UHPC) deck, should be adopted: this consists in the reduction of the deformation modulus of the UHPC by 50%, the worst found in literature. This decision is supported by recent investigations: e.g. Xu et al. (2017) conducted the fatigue test of the reactive powder concrete, which indicated a decrease of 50% in the original value of the elastic modulus before reaching the fatigue damage. Similar results are reported in Makita and Bruwhiler (2015) which investigated the damage models for UHPFRC and R-UHPFRC tensile fatigue behavior finding a decrease of 30% in the original value of the elastic modulus before reaching the fatigue damage.

Rehabilitation Strategies

Loading Conditions

The loads considered for the assessment of existing bridges in this paper include: (1) dead loads of the bridge; (2) thermal loads; (3) live loads according to two alternatives: (3a) historical design code or (3b) actual design code. Seismic loads have been introduced into the bridge testing its influence on the whole calculation procedure. It should be noticed however that imposed loads defined in codes and standards are intended to be used for the design of new bridges, including piers, abutments, upstand walls, wing walls, flank walls, and their foundations. An open question remains on existing bridges, where reduced traffic loads could be used during the structural assessment and imposed in new traffic limitations, to avoid for the bridge retrofit or reconstruction. In fact, in this case, only some nations provide detailed guidelines or codes on the assessment of existing bridges. When analyzing an existing bridge, a progressive analysis should be considered, by using:

- HS-LOAD, the historical load adopted by the original designer;
- AD1 Load, 1st category: Load Model 1, EN 1991-2:2003[18];
- AD2 Load, 2nd category: Load Model 1, EN 1991-2:2003[18] taking a reduction of 20% for all loads of Lane number 1.

While the historical load should be considered to have a reference model, the use of AD1 and AD2 loads allows to understand if an acceptable performance of the bridge could be reached with a small load reduction, enabling the possibility to strengthen the bridge without an excessive financial investment.

Strengthening Alternatives

To achieve the possibility of extending the lifetime of these bridges, various strengthening strategies could be adopted. However, the first question to be solved is if the bridge could be used with a reduction of allowable live loads: in this case, most of the existing steel bridges could be subjected to a structural analysis able to identify the allowable traffic loads, and then with usual maintenance interventions the bridge could be opened to traffic with a clear identification of the new bridge category. In this study, strengthening alternatives considered includes:

(a) making composite on existing non-composite deck;
(b) building an orthotropic deck;
(c) building a new concrete deck, directly connected to the main structure.

All these strategies are normally combined with steel-only interventions (including cover-plating, element replacement, etc.). All the strengthening solutions aims to redistribute the live loads adequately onto the bridge with a new or modified deck. As can be observed in the following, the beneficial use of a rigid deck is often the best solution able to extend the bridge life adequately. In the present study, the reference strengthening solutions considered are:

- (BR00) The existing bridge is calculated with the historical live load, HS-LOAD, without any strengthening intervention; even if these models are no longer representative for modern/future road traffic, this calculation is useful both for the structural calibration of the Fem model, and also to compare the efficiency of the strengthening solution proposed in the following;
- (BR01) The existing bridge is calculated with the actual code live load, AD1-LOAD, without any strengthening intervention;
- (BR02) The existing bridge is calculated with the actual code live load, AD2-LOAD, without any strengthening intervention;
- (RROOR1-2) The bridge is strengthened with the introduction of an orthotropic deck laying between stringers, with open ribs considering both the AD1-Load and AD2-Load;
- (RROCR1-2) The bridge is strengthened with the introduction of an orthotropic deck laying between stringers, with closed ribs considering both the AD1-Load and AD2-Load;
- (RRA1-2) The bridge is strengthened with the introduction of a concrete deck considering both the AD1-Load and AD2-Load; welded shear studs are introduced in the bridge to connect the new concrete deck with the stringers; a parametric analysis is developed varying both the concrete deck thickness (with a fixed strength of C40/50) among 100 mm (RRA1, 2–10), 150 mm (RRA1, 2–15), 200 mm (RRA1, 2–20), 250 mm (RRA1, 2–25), 300 mm (RRA1, 2–30) and the deck concrete strength (fixing the deck thickness at the lowest value

of 100 mm) among C30/37 (RRA1, 2-R1), C35/45 (RRA1, 2-R2), C40/50 (RRA1, 2-R3), C45/55 (RRA1, 2-R4), C55/67 (RRA1, 2-R5);
- (RRA1-2-I) The bridge is strengthened with the introduction of a concrete deck considering both the AD1-Load and AD2-Load, fixing the concrete strength at C40/50 and the deck thickness at 100 mm; moreover, steel-to-steel intervention are introduced adopting S355 new members;
- (RRB1-2-I) The bridge is strengthened with the introduction of a concrete deck considering both the AD1-Load and AD2-Load, introducing a UHPC concrete of C90/105 strength class and fixing the deck thickness at 50 mm; moreover, the steel-to-steel intervention are introduced adopting S355 new members;
- (RRC1-2-I) The bridge is strengthened with the introduction of a concrete deck considering both the AD1-Load and AD2-Load, introducing a UHPFRC concrete of C150/160 strength class and fixing the deck thickness at 30 mm; moreover, the steel-to-steel intervention are introduced adopting S355 new members.

The above strengthening solutions are considered in the two case studies provided in the following paragraphs.

Case Studies

The Adige Bridge

General Description

The Adige bridge is a two-lane roadway steel bridge located between the provinces of Padua and Rovigo. The historical bridge was built in 1857 as a wood bridge and was burned by Austrian troops in 1866. After the arson the bridge was built again same as before and in 1933 was demolished and rebuilt as a steel bridge. The bridge was destroyed by the US Desert Air Force during World War II and then, two years later, built again. The overall bridge length is about 120 m through three spans (40 m each one) and is illustrated in *Fig. 1*. Simple truss girders at 7.6 m are simply supported on the abutment and on two central piles in the river bed. The superstructure consists of riveted built-up truss members. Lower chords are reverse T shaped sections, diagonals and upper chords are C-coupled built-up elements with

Fig. 1: Lateral view of the Adige bridge

battens (stiffening brackets), while vertical rods are I section shaped built-up elements composed of 4L shaped elements and a plate. The deck is realized with longitudinal stringers, and transverse floor beams. The floor beams have a fixed distance of 4 m, while the stringers are at 1.15 m one to the other. Top and bottom double-L bracings stiffen (flexural and torsional) the structure. Built-up members, realized with plates, L-profiles or C profiles, are connected by hot riveting and also connection joints are made of gusset riveted plates.

Bridge Model and Retrofitting Proposals

The strengthening of the bridge is made according to the followed procedure:

- Step 0—the bridge is verified according to the Italian ministerial Decree 09/06/1945, n. 6018, which was the building code of the time of construction;
- Step 1—the bridge is verified according to the Eurocodes, considering 1st and 2nd bridge categories;
- Step 2a—introduction of an orthotropic deck to redistribute traffic loads and relieve not verified elements;
- Step 2b—in case the above solution is not enough, a concrete deck is considered considering the composite action;
- Step 3—in some cases, the above solutions are not enough and steel to steel interventions are needed.

In this case, the following alternatives are considered:

- Retrofit solution 1—new floor beams are introduced to improve deck redistribution, top bracings are replaced by higher sections and bottom bracing is removed; in addition, to comply with a 1st category bridge, larger cover-plating is considered;
- Retrofit solution 2—the same as above but with a thinner concrete slab made by UHPC C90/105, to lighten the weight but keeping the stiffness;
- Retrofit solution 3—to further lighten the weight of the slab, this solution considers a concrete slab made by UHPC C150/160.

The strengthening solutions considered in this case study are summarized in *Table 1*.

Bridge Verification and Discussion of Results

The results of the analysis are illustrated in *Table 2*, reporting for each alternative the maximum ratios E_d/R_d defined as the minimum safety factor

Model name	Retrofitting proposals	Bridge category	Deck type solutions
BR01-BR02	None	AD1-load AD2-load	None
RROOR	Orthotropic deck introduction	AD2-load	Using two different orthotropic plate sections
RROCR	Concrete deck introduction	AD2-load	Varying deck thickness R.C. and varying concrete class
RRA1	Retrofit solution 1	AD2-load	Using R.C. deck C40/50 100 mm thick
RRA2		AD1-load	
RRB	Retrofit solution 2	AD1-load	Using R.C. deck UHPC C90/105 50 mm thick
RRC	Retrofit solution 3	AD1-load	Using R.C. deck UHPC C150/160 30 mm thick

Table 1: Retrofitting proposal for the Adige bridge

	BR01_ AD1-load	*BR02_ AD2-load*	*RROOR_ AD2-load_ T-ribs*	*RROOR_ AD2-load_ U-ribs*	*RROCR_ AD2-load*	*RRA1_ AD2-load*	*RRA2_ AD1-load*	*RRB_ AD1-load*	*RRC_ AD1-load*
	E_d/R_d	**E_d/R_d**	**E_d/R_d**	**E_d/R_d**	**E_d/R_d**	**E_d/R_d**	**E_d/R_d**	**E_d/R_d**	**E_d/R_d**
lower chords	2.114	1.865	7.412	7.768	1.653	0.949	0.972	0.925	1.144
vertical rods	inf.	inf.	1.960	2.135	1.018	0.901	0.951	0.900	0.813
stringers	inf.	6.806	3.938	4.319	-	-	-	-	-
bottom bracings	0.715	0.629	1.477	1.414	0.539	-	-	-	-
floor beams	5.261	4.482	1.965	1.994	1.907	0.849	0.932	0.959	1.376
diagonals_A	5.164	1.767	1.204	1.213	1.105	1.000	0.973	0.957	0.976
diagonals_B	3.015	1.333	0.997	1.006	0.969	0.898	0.947	0.842	0.862
diagonals_C	1.402	1.208	0.982	0.989	0.831	0.792	0.831	0.675	0.683
diagonals_D	3.326	1.221	0.864	0.873	0.832	0.791	0.842	0.790	0.800
upper chords	1.020	0.895	1.005	1.015	1.031	0.938	0.977	0.980	0.989
superior transverses	0.360	0.315	0.350	0.353	0.322	0.294	0.297	0.229	0.230
top bracings	1.555	10.787	1.622	1.636	2.510	0.147	0.151	0.102	0.100
floor beams (HEB 280)	-	-	-	-	-	0.754	0.885	0.964	1.188

Table 2: Safety checks for the Adige bridge

of all ultimate limit state (ULS) checks mentioned herein[13]; ratios less than 1 imply that all the member strength verifications are verified.

As observed from *Table 3*, the most viable hypothesis of retrofit intervention are RRA and RRB. These retrofit interventions allows, using high-strength concrete, to redistribute traffic loads by reducing weight and achieving ULS and fatigue standards for 1st category bridge. SLS verification have been performed and wherever ULS and fatigue are satisfied, also SLS verification have been found to be checked positively. Consequently, it is economically convenient because it reduces costs.

The Po Road Bridge

General Description

The structure is a two-lane roadway steel bridge located between the provinces of Ferrara and Rovigo. The historical bridge was built in 1911 by Officine di Savigliano and collapsed in 1944 for 2nd world war bombing. In 1945 a Bailey Bridge was built by Allied Forces and 1949 the bridge was rebuilt as a steel bridge. The overall bridge length is about 305 m through four spans (69 m length terminal spans, 83 m length central spans). Simple truss girders at 7.7 m are simply supported on the abutment and on three central piles in the river bed. The superstructure consists of riveted built-up truss members. Lower chords are reverse T shaped sections, diagonals and upper chords are C-coupled built-up elements with battens (stiffening brackets), while vertical rods are I section shaped built-up elements composed of 4L shaped elements and a plate. The deck is realized with longitudinal reverse T shaped section stringers, and transverse I shaped section floor beams. The floor beams have a fixed distance of 7 m, while the stringers are at 1,15 m one to the other. Top and bottom double-L bracings stiffen the structure (flexural and torsional). Built-up members, realized with plates, L-profiles or C profiles, are connected by hot riveting and also connection joints are made of gusset riveted plates. The lateral view of the bridge is provided in *Fig. 2*.

Retrofitting Proposals

The strengthening of the bridge is made according to the procedure described for the Adige bridge. In this

Model name	**Retrofitting proposals**	**Bridge category**	**Deck type solutions**
BR01-BR02	None	AD1-load AD2-load	None
RROOR1	Orthotropic deck introduction	AD2-load	Using two different orthotropic plates sections
RROCR1	Concrete deck introduction	AD2-load	Varying deck thickness R.C.
RRA1	Concrete deck introduction and coverplating	AD2-load	Concrete class C40/50
RRB1	Concrete deck introduction, coverplating and deck cables	AD2-load	Concrete class C40/50
RRC1	Concrete deck introduction, coverplating and deck cables	AD2-load	Concrete class C90/105

Table 3: Retrofitting proposal for the Po bridge

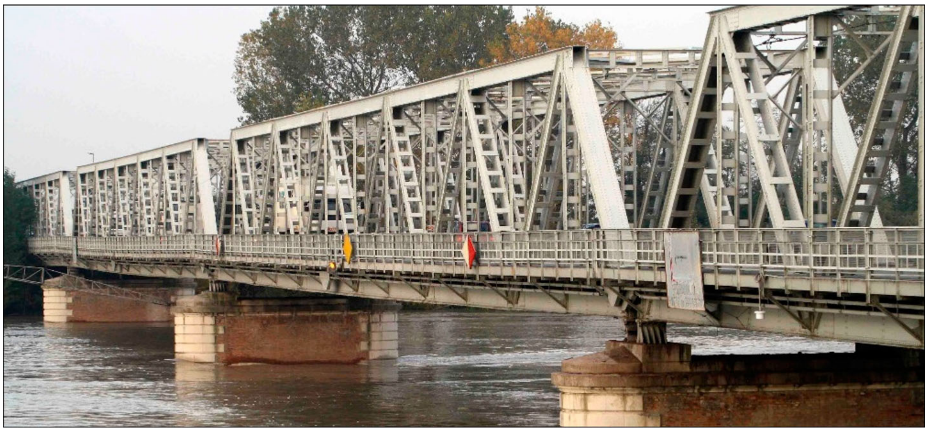

Fig. 2: Lateral view of the Po bridge

case, the reference strengthening solutions considered are indicated in *Table 3*.

Bridge Verification and Discussion of Results

The analysis results are illustrated in *Table 4*, reporting for each alternative the maximum ratios E_d/R_d defined as the minimum safety factor of all ultimate limit state (ULS) checks mentioned herein[13]; ratios less than 1 imply that all the member strength verifications are verified. In the composite section case, for example, when stringers are modified to composite sections in the strengthening solution analyzed, the symbol "V" implies that the ultimate limit state (ULS) verification of the composite section is satisfied.

In this case, the most viable hypothesis of retrofit intervention is evidently RRC1. This retrofit intervention allows, using high-strength concrete, to redistribute traffic loads by reducing weight and achieving ULS and fatigue standards for 2nd category bridge. SLS verification have been performed and wherever ULS and fatigue are satisfied, also SLS verification have been found to be checked positively Consequently, it is economically convenient because it reduces costs.

Multi-Criteria Decision Analysis

General Procedure

A multi-criteria decision approach was adopted to aid in the decision-making process of bridge rehabilitation and strengthening. The multi-criteria approach shall aid the Decision Maker (DM) in the process of selection of the best rehabilitation strategy. The method adopted in this work is the Preference Ranking Organization Methodology of Enrichment Evaluation (PROMETHEE).[19,20] PROMETHEE belongs to the family of outranking methods and is a quite simple ranking method in conception and application compared with the other methods for multi-criteria analysis.[21] One of the extensions of PROMETHEE (PROMETHEE II) enables a complete ranking of alternatives, while other approaches provide partial rankings including possible incompatibilities. Moreover, PROMETHEE is a suitable approach for an integrated analysis thanks to its flexible algorithm enabling tailor-made enhancements to meet specific requirements for an

	BR01_ AD1- load	***BR02_ AD2-load***	***RROOR1_ AD2- load _ T-ribs***	***RROOR1_ AD2- load _ U-ribs***	***RROCR1_ AD2- load***	***RRA1_ AD2- load***	***RRB1_ AD2- load***	***RRC1_ AD2- load***
	E_d/R_d	E_d/R_d	E_d/R_d	E_d/R_d	E_d/R_d	E_d/R_d	E_d/R_d	E_d/R_d
lower chords	17.940	1.770	4.574	4.397	4.999	0.988	0.562	0.967
floor beams	3.442	2.717	22.376	20.934	1.867	1.528	1.275	-
vertical rods	inf.	13.550	20.735	14.864	4.686	1.019	0.968	0.967
diagonals_A	2.183	1.908	2.074	2.06	2.365	0.956	0.775	0.867
diagonals_B	1.685	1.479	1.205	1.196	1.565	1.041	0.786	0.892
upper chords	1.768	1564	1.780	1.757	2.022	1.052	0.724	0.724
superior transverses	1.187	0.964	0.978	0.979	0.969	0.788	0.792	0.817
superior stiffenings	5.237	4.708	5.719	19.284	10.765	0.368	0.236	0.280
stringers	21.026	4.947	inf.	inf.	V	V	V	V
new floor beams (HEB650)	n.p.	n.p.	n.p.	n.p.	n.p.	n.p.	n.p.	1.000
new floor beams (HEB320)	n.p.	n.p.	n.p.	n.p.	n.p.	0.729	0.710	0.797
cables	-	n.p.	n.p.	n.p.	n.p.	n.p.	0.322	0.322

Table 4: Safety checks for the Po bridge

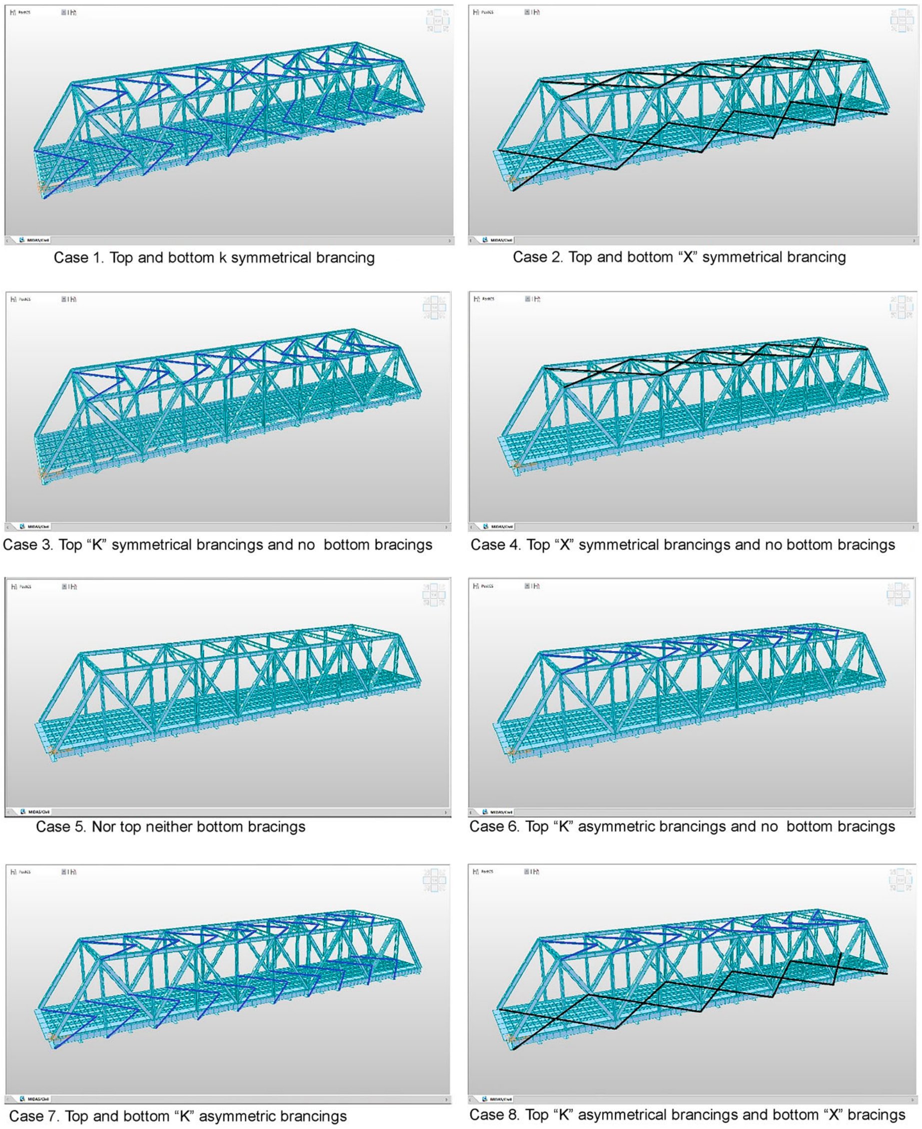

Fig. 3: Parametric analysis

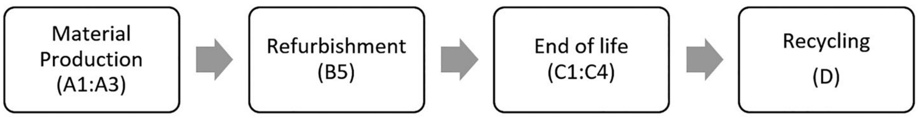

Fig. 4: Scope of the life cycle environmental analysis

integrated assessment approach the explicit consideration of uncertainty in the input values (this issue will further be developed in the following sections). PROMETHEE has a widespread use in decision-making situations varying from environmental management to business and financial management, medical applications, etc.[22] The solution of a multi-criteria problem depends on the basic data included in the evaluation of criteria and on the individual preferences of the decision-maker. Therefore, additional information representing these preferences is required to provide the DM with useful decision aid. In the case of PROMETHEE it is necessary to add information between the criteria and within each criterion. Information between criteria is given by a set of weights {w_j, j = 1, 2, … , k} representing the relative importance of the different criteria. The higher the weighting factor the more important the criterion. The information within each criterion, the preference structure, is based on pairwise comparisons.[23]

Indicator	**Space scale**	**Time scale**
Global warming (GWP)	Global	100 years
Acidification (AP)	Local/continental	∞
Eutrophication (EP)	Local/continental	∞
Photo oxidant formation (POCP)	Local/continental	-
Ozone depletion (ODP)	Global	∞
Abiotic depletion (ADP)	Global	-

Table 5: Environmental impact categories

Application to Adige Bridge

A parametric analysis was carried out for the Adige bridge, varying the type and arrangement of the top and bottom bracings, to assess which solution is more performant and improves the overall behavior of the bridge. As assumed in retrofit solution RRB, the best solution is to eliminate the lower bracings, also considering that it is now introduced concrete deck and to insert top “k” bracings. Eight solutions were considered as illustrated in *Fig. 3*. In all cases S355 coupled L140×15 bracings were used, both above and below.

The multi-criteria approach described above was used in this parametric analysis, to identify the solution with the best performance taking into account the following criteria: (i) reliability of the analysis (Crit_1); (ii) ease of execution (Crit_2); (iii) estimation cost of the solution (Crit_3); and (iv) the environmental criteria of embodied carbon (Crit_4). In addition, three different sets of weights were considered, as illustrated in *Fig. 4*. The first criterion was assessed based on the structural analysis of the different solutions (the assessment varied from 1 for the solution with lowest reliability to 5 for the solution with highest reliability). The second criterion was qualitatively assessed based on the experience of the bridge designer (the result varied from 1, very easy execution, to 8, very difficult). The third criterion is based on the estimated cost of the retrofit solution. Finally, the last criterion, was assessed based on the life cycle analysis

Normalization Factor		Unit
Abiotic Depletion (ADP elements)	3,6E + 8	kg Sb eq.
Abiotic Depletion (ADP fossil)	3,8E + 14	MJ
Acidification Potential (AP)	2,39E + 11	kg SO2 eq.
Eutrophication Potential (EP)	1,58E + 11	kg Phosphate eq.
Global Warming Potential (GWP 100 years)	4,22E + 13	kg CO2 eq.
Ozone Layer Depletion Potential (ODP, steady state)	2,3E + 8	kg R11 eq.
Photochem. Ozone Creation Potential (POCP)	3,7E + 10	kg Ethene eq.

Table 6: Environmental impact categories

of the different solutions, taking into account the additional materials needed in each case. Concerning in particular the environmental analysis, this focussed on the environmental category of embodied carbon. The main goal of this analysis is to assess the environmental impacts produced by the materials used on each rehabilitation strategy. Therefore, the impact assessment stage is performed with the information related to the bill of materials and transportation data. The scope of this life cycle environmental analysis was defined considering EN 15804:2013[24] and EN 15978:2011.[25] It covers a total of four stages: the material production stage (A1:A3) is the first one to be considered which includes the raw material supply, its transport to the factories and its manufacture. These materials are then used for the refurbishment of the structure (stage B5) in which the transport of materials to the construction site is considering as well as the material installation/construction. The use of equipment (energy consumption, for example) was not considered in this analysis. At the end of life of these materials, they are removed from the structure and transported to the waste processing facility. These operations of waste processing and final disposal of construction products are included in End-of-Life stage (C1:C4). Finally, the benefits of reuse/recovery/recycling are assessed at recycling stage (D). For the impact assessment stage, the environmental indicators were selected

	Crit_1	Crit_2	Crit_3	Crit_4
Alternative 1	2	3	441882 €	+ 38 tonnes
Alternative 2	2	3	441882 €	+ 38 tonnes
Alternative 3	2	2	388688 €	+ 21 tonnes
Alternative 4	4	2	388688 €	0
Alternative 5	4	1	326592 €	+ 21 tonnes
Alternative 6	5	2	388688 €	+ 21 tonnes
Alternative 7	3	3	441882 €	+ 38 tonnes
Alternative 8	1	3	441882 €	+ 38 tonnes

Table 7: Multi-criteria data

Transportation					
Material	**Distance to the construction site [Km]**	**Distance to the disposal/recycling [Km]**			
Concrete grade C90/105 (50 mm thick)	15	100			
Reinforced steel grade B450C	5	100			
Shear Studs (Steel grade Fuk = 450 Mpa)	90	100			
Steel plates S275	15	100			
Environmental Impacts					
Indicators	**Production Stage (A1:A3)**	**Refurbishment (B5)**	**End-of-Life Stage (C1:C4)**	**Recycling Stage (D)**	**Total**
ADP Elements (Kg Sb eq.)	−5.05E-01	−2.78E-02	6.63E-03	−1.07E + 00	3.02E + 06
ADP Fossil (MJ)	3.87E + 06	1.82E + 05	7.23E + 04	−1.10E + 06	9.27E + 02
AP (Kg SO2 eq)	1.02E + 03	4.75E + 01	2.67E + 01	−2.50E + 02	2.88E + 05
EP (Kg PO4 eq)	7.81E + 01	3.55E + 00	3.65E + 00	−6.90E + 00	7.84E + 01
GWP 100 years (Kg CO2 eq)	3.71E + 05	1.67E + 04	5.51E + 03	−1.06E + 05	2.88E + 05
ODP steady state (Kg R11 eq)	1.44E-03	7.19E-05	1.04E-08	3.35E-03	4.86E-03
POCP (Kg C2H4)	1.85E + 02	8.51E + 00	2.22E + 00	−5.59E + 01	1.40E + 02

Table 8: Transportation and environmental impacts

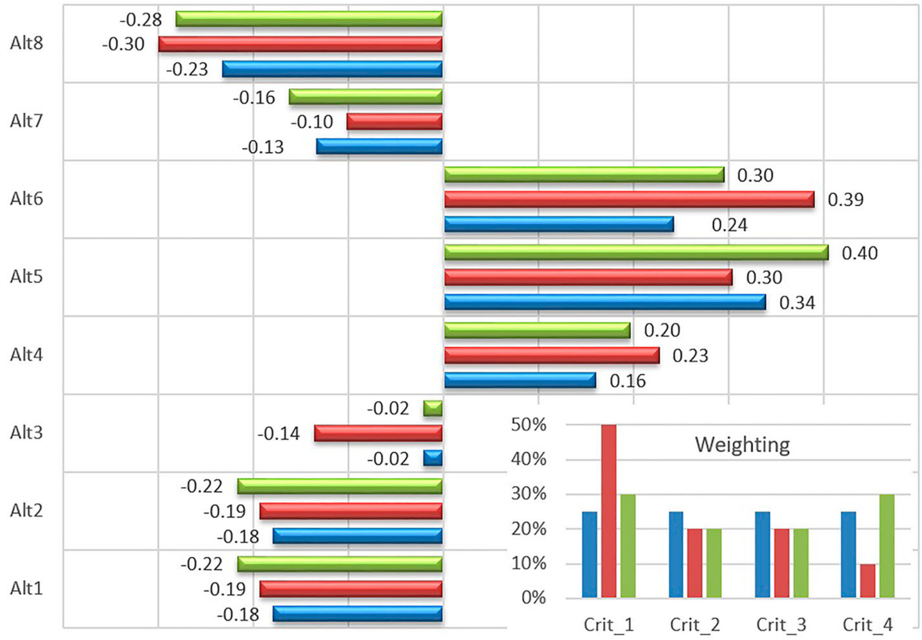

Fig. 5: Multi-criteria decision analysis

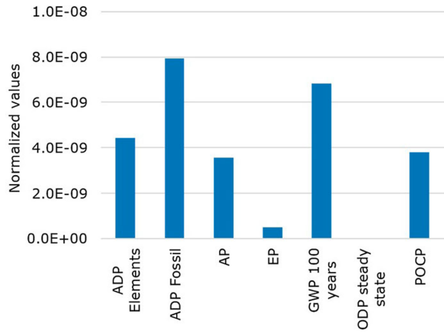

Fig. 7: Normalized results for each impact category (Adige Bridge—RRA)

from the Operational Guide to the ISO standards[26] developed by the Centre of Environmental Sciences (CML) in the University of Leiden. These environmental impacts categories are stated in the following. The quantification of these environmental impact categories for each material in each phase of the analysis was performed through the consultation of Gabi databases and Environmental Product Declarations (*Table 5*). For each rehabilitation strategy, the bill of materials was collected as well as the information about the distance between the supplier and the construction site and the distance to the disposal/recycling. In order to simplify the interpretation of the analysis and, thus contribute to an easier decision-making process, normalization of the obtained results should be performed. It is considered by ISO standards[26] as an optional step of a life cycle impact assessment, however, it provides a better understanding of the relative importance and magnitude of impact categories. The adopted values for these normalization factors are presented in *Table 6*. These are the values used in the CML methodology. Thus, the normalized category indicator for a given reference system ($I_{(cat,ref)}$) is calculated by the ratio between the impact category score (I_{cat}) and the relative normalized factor ($N_{(cat,ref)}$) as shows Eq. (1):

$$I_{cat,ref} = \frac{I_{cat}}{N_{cat,ref}} \qquad (1)$$

A diagram with the stages considered in the life cycle environmental analysis is presented in *Fig. 4*, together with the results for each criterion illustrated in *Table 7*. While *Table 8* and *Fig. 6* illustrate the environmental impacts and the emissions produced throughout the life period of the bridge due to the rehabilitation RRA alternative.

Finally, the results of the multi-criteria analysis are illustrated in *Fig. 5*, showing the ranking of the different alternatives. Hence, the three most interesting solutions are alternatives 4, 5 and 6.

Within these, alternatives 5 and 6 are the ones with the best ranking, depending on the set of weights. Hence, when equal weights are selected for the four criteria or when the weight of Criteria 1 and 4 is 30% and the weight of criteria 2 and 3 is 20%, then alternative 5 achieves the best ranking. On the other hand, alternative 6 achieves the best ranking when the weight of criteria 1 is 50% and the weights of the remaining criteria are illustrated in *Fig. 4*.

As is presented in *Fig. 6*, the material production stage (68%) is the most relevant phase in the analysis. In *Fig. 7* it is observed that ADP Fossil, GWP 100 years and ADP Elements are the most important environmental categories.

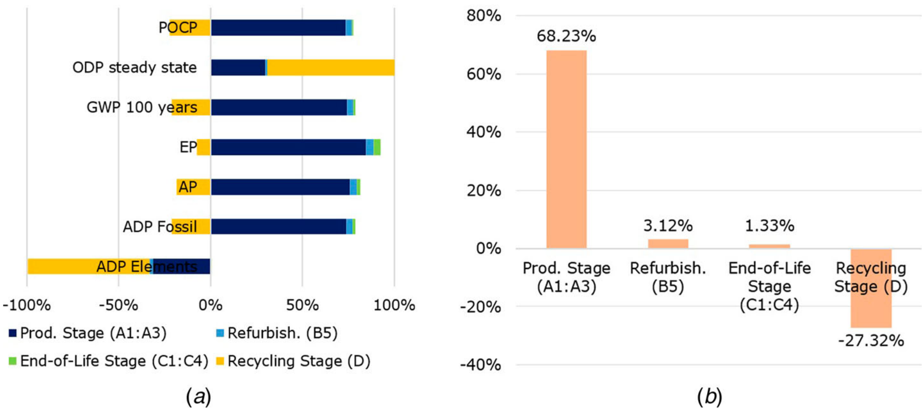

Fig. 6: Contribution of environmental impact each stage (Adige Bridge—RRA): (a) per impact category; (b) total impact

Conclusions

As can be concluded from the study performed, only specific alternatives satisfy the verification, in detail RRA and RRB for the Adige bridge, and RRC for the Po bridge. General observations are the following:

- new orthotropic steel decks or a composite concrete deck improve the overall structural behavior of the bridge compared with the original situation, even if ULS checks were still not verified for all members. The bridge generally

shows a good capacity to redistribute the live load by the new or improved decking; however, some other members on the truss system demonstrated understrength capacities (struts, upper chords, floor beams and lower chords). This called for a wide amount of retrofit works on the whole structure, including new floor beams, top bracing replacement, and the bracing geometry changes (K-bracings are used despite the original X-bracings), etc;
- fatigue checks often govern the whole structural retrofit procedure; it is consequently relevant to perform ULS, SSL, and fatigue verification for all the retrofit alternatives analyzed, to gain the best performance with a safe analysis of all structural parameters and checks;
- steel-to-steel reinforcements on key members of the truss (e.g. floor beams) are always needed, and should be realized with higher steel grade in order to control the total weight increase;
- the UHPFRC thick deck retrofit solution is conceived to lighten the weight of the slab while maintaining its stiffness and increasing at the same time the loading capacity to cope with actual codes and standards. As shown before, a high concrete class deck ensures high performances with lower weight, and reduced displacements compatible with the use of the bridge.

Findings of the study are relevant and innovative: in fact, while common procedures of intervention imply the use of new concrete deck resting on the existing steel structure with thickness of approximatively 300 mm,[24,27,28] or rather the present study highlighted that the strengthening of steel trusses could be done by the realization of UHPFRC thicker slab (50–100 mm), thus reducing the self-weight of the bridge; this then becomes an extra live load allowance, able to cope with live loads in line with those requested by the current codes and standards. It should be further noticed that other studies confirm that a very thick UHPC layer (50 mm) connected with short welded shear connectors could enhance the fatigue performance of an orthotropic existing deck.[29]

This study finally proposes a novel approach for the strengthening of existing steel truss bridges, to extend their life with optimized interventions. Based on the current investigations, the following conclusions can be drawn:

(a) the existing bridges can carry the historical loads HS-LOAD (Italian ministerial Decree 09/06/1945, n. 6018); without any intervention;
(b) the existing bridge is not able to carry the actual loads AD-LOAD[30], without any intervention;
(c) detailed parametric studies were performed for the strengthening alternatives to gain deeper insight into the structural behavior of the bridge and of all structural members. Many structural alternatives have been considered, based onto the deck strengthening of existing steel truss bridge introducing orthotropic deck or composite deck;
(d) the analyses show that the final optimized strengthening solution represented by a composite UHPC deck resting on the existing steel structure has an excellent structural performance compared with other alternatives via FEM and parametric analysis; this is also in line with recent research with similar deck strengthening solution calibrated with FEM and real scale testing[29];
(e) the multi-criteria decision approach introduced to aid in the decision-making process of bridge rehabilitation and strengthening, confirm that this solution is at the same time the best retrofit structural solution and the lowest environmental impact, ensuring long life endurance.

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