

THE EUROPEAN PROJECT SUREBRIDGE

Analysis of a case study bridge

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Summary

The European research project SUREBridge (Sustainable Refurbishment of Existing Bridges) is developing a new concept for the structural strengthening of road bridges: glass fibre-reinforced polymer (GFRP) sandwich panels are installed on top of the existing concrete slabs; pre-stressed carbon fibre-reinforced polymer (CFRP) laminates are adhesively bonded to the bottom of the longitudinal girders.

A real bridge located in San Miniato (Pisa) was selected as a case study for the design of a strengthening intervention. A finite element model of the existing bridge was created by using the commercial finite element software Straus7[®]. The outcomes of an *in situ* experimental campaign were used to define the geometry of the BEAM and PLATE elements, as well as their material properties. A finite element model of the strengthened bridge was then developed to evaluate the increased load-carrying capacity and demonstrate the effectiveness of the proposed technique.

Keywords

fibre-reinforced polymers, structural strengthening, road bridges

Introduction

The European research project SUREBridge [1] (Sustainable Refurbishment of Existing Bridges) is developing a new concept for the structural strengthening of road bridges. The target is to exploit the remaining capacity of the superstructure of concrete and steel-concrete bridges, preserving the structural elements of the deck (girders and slab) and increasing the load-carrying capacity to the desired level. This is achieved by using light-weight, tailor-made glass fibre-reinforced polymer

(GFRP) sandwich panels [2], installed on top of the existing concrete slab, and carbon fibre-reinforced polymer (CFRP) laminates applied to the bottom side of the girders. Such laminates are pre-stressed using an innovative technique [3], which avoids stress peaks at the laminate ends, thus preventing early delamination. Furthermore, the GFRP panels can be manufactured of the same width or wider than the existing deck, thus enabling to widen the road section if needed.

To evaluate the effectiveness of the SUREBridge solution, its application to a real bridge was analysed [4]. The selected case study is a bridge crossing the Elsa river in a small town named Isola di San Miniato (Tuscany, Italy), from now on referred to as the “San Miniato bridge” (Figure 1).



Figure 1: Location of the San Miniato bridge:
a) in Italy; b) within Tuscany; c) within the Municipality of San Miniato

The bridge, built in 1968, has a length of nearly 60 m subdivided into four spans of 15 m each. The 3 m wide deck, crossed by vehicles one way alternatively, is composed of a 160 mm thick, cast-on-site concrete slab and four prefabricated pre-stressed concrete girders, 780 mm high and 1 m distant one from another (Figure 2). Although little is known on the design and construction history of the bridge, the original documents indicate that it was designed by the Italian engineer Francesco Lorenzi. The construction was motivated by the collapse of a pre-existing pedestrian iron bridge, caused by the riverbed lowering and constant erosion of the banks. Such phenomena were in turn due to the strong flows and vortices between the Arno river and a nearby dyke, collapsed too some years later.

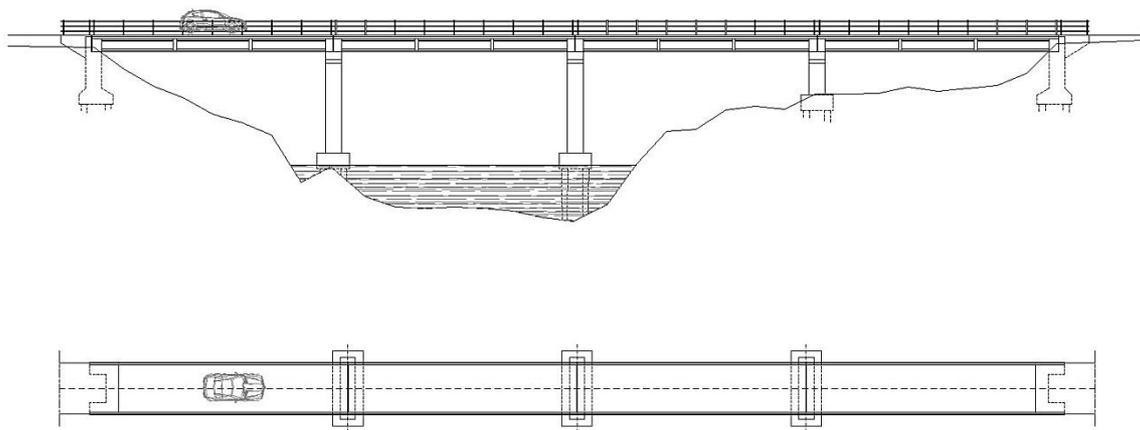


Figure 2: Geometry of the San Miniato bridge

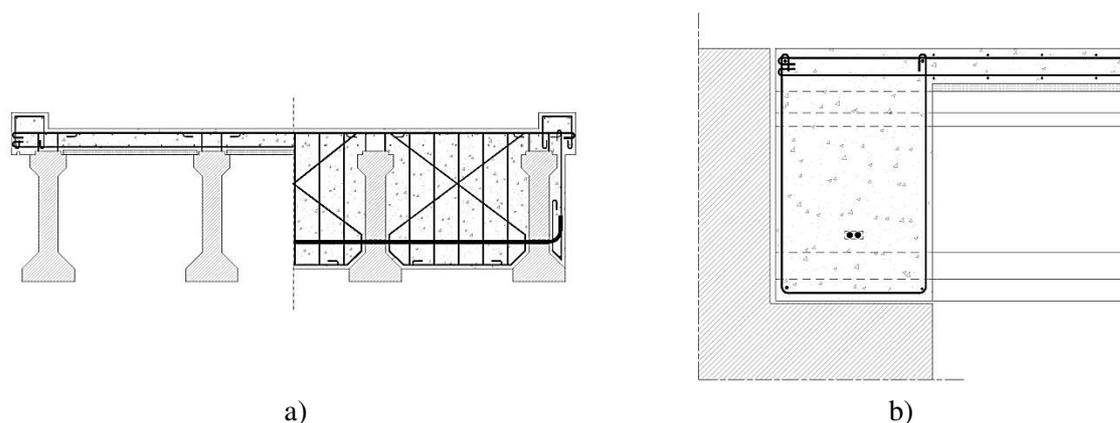


Figure 3: Cross section of a) bridge deck, transverse beam

Assessment of current load-carrying capacity

SOP – Standard Operating Procedure

A standard operating procedure (SOP) for the assessment of the load-carrying capacity of existing bridges was defined within the SUREBridge project and described in detail in a dedicated technical report [5]. The developed SOP was then applied for the assessment of the San Miniato bridge [6].

The suggested operation flow, including both experimental activities and theoretical analyses, is intended to help bridge owners, consultants, and designers to evaluate the load-carrying capacity of existing bridges and envisage the needs for strengthening. The tasks suggested by the SOP include:

- structural investigations, mainly consisting of experimental activities to be carried out on site (on the whole structure or parts of it) or in the laboratory (on collected samples);
- structural analysis, mainly based on theoretical models, to be conducted in the office.

Figure 4 shows a flowchart of the activities involved in the structural investigations for the assessment of an existing bridge. The results of such activities consist of documentation on the bridge including:

- standard rules for design at the time of construction and at present;
- original design documents;
- reports on past structural assessments and strengthening interventions;
- drawings and reports on current conditions of the bridge;
- survey and testing report.

Figure 5 presents a flowchart of the activities involved in the structural analysis. The results of this phase are typically included in a structural analysis report, containing a quantitative assessment of the load-carrying capacity, defined as the amount in percentage of the traffic loads prescribed by current regulations that the investigated bridge can sustain in safety, *i.e.* not violating any verifications.

The on-site structural investigations led for the assessment of the San Miniato bridge will be described in the next section. In particular, from the information acquired during this investigation campaign, it was possible to develop a finite element model of the existing structure to evaluate its load-carrying capacity in compliance with the load levels and combinations of the current Italian regulations. The results of the dynamic and static analyses carried out for the San Miniato bridge will be described in the next section as well.

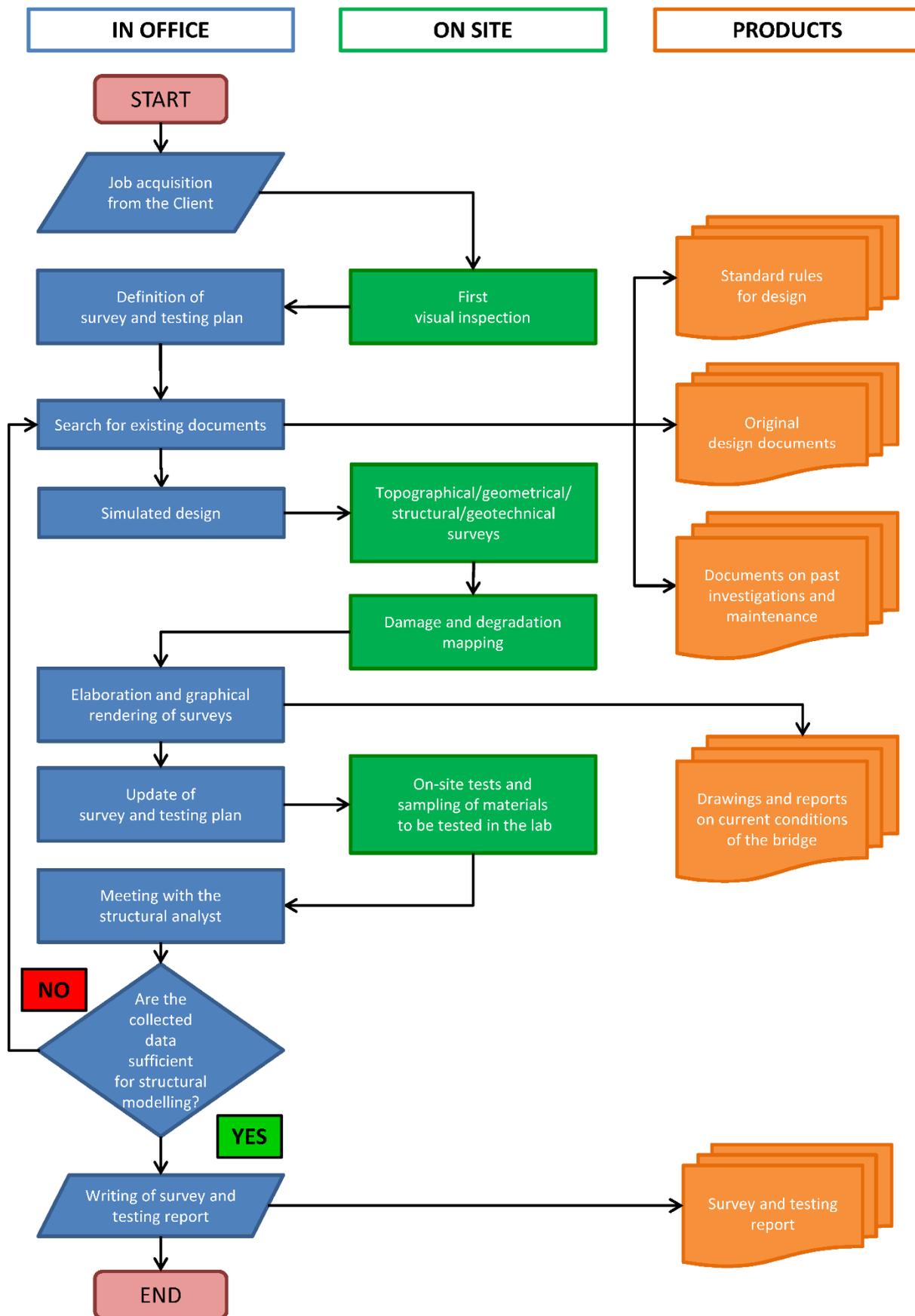


Figure 4: Flowchart of structural investigations according to the SOP

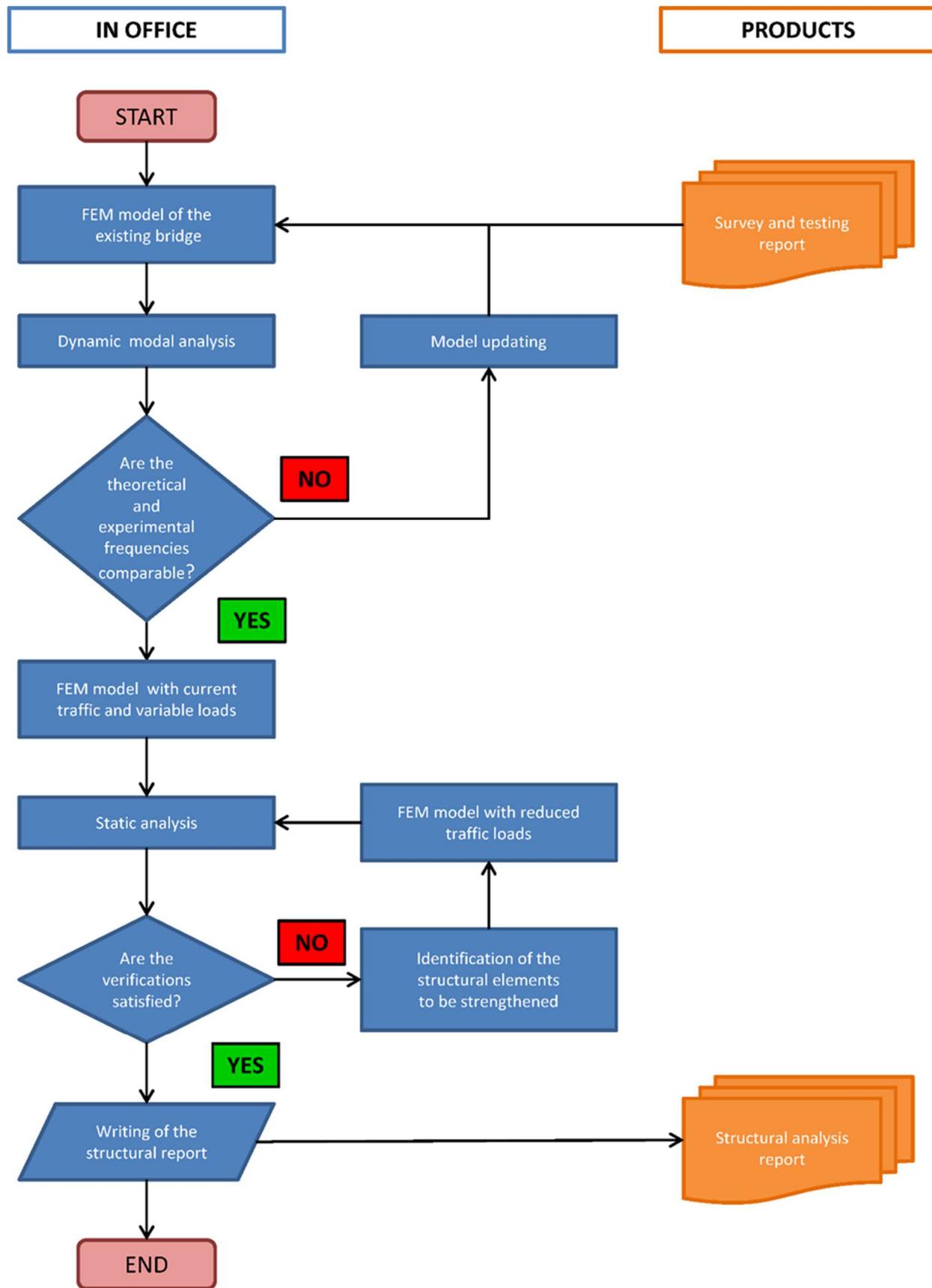


Figure 5: Flowchart of structural analysis according to the SOP

On-site investigations

The San Miniato bridge was the subject of a structural investigation conducted in 2006 by the engineering company AICE Consulting Srl, partner of the SUREbridge project. The Client was the Province of Pisa, as the Authority owning the bridge and responsible for its maintenance. After the damage of a railing, the Client had decided to lead an investigation campaign on the bridge to highlight possible other degradation issues and to evaluate its residual load-carrying capacity. The first step of the investigation campaign was an on-site visual inspection (Figure 6a). From this inspection, some of the main problems affecting the bridge were immediately apparent: corrosion and breakage of some pre-stressing wires (Figure 6b), concrete spalling and reinforcement corrosion (Figure 6c), and general degradation of concrete surfaces (Figure 6d).

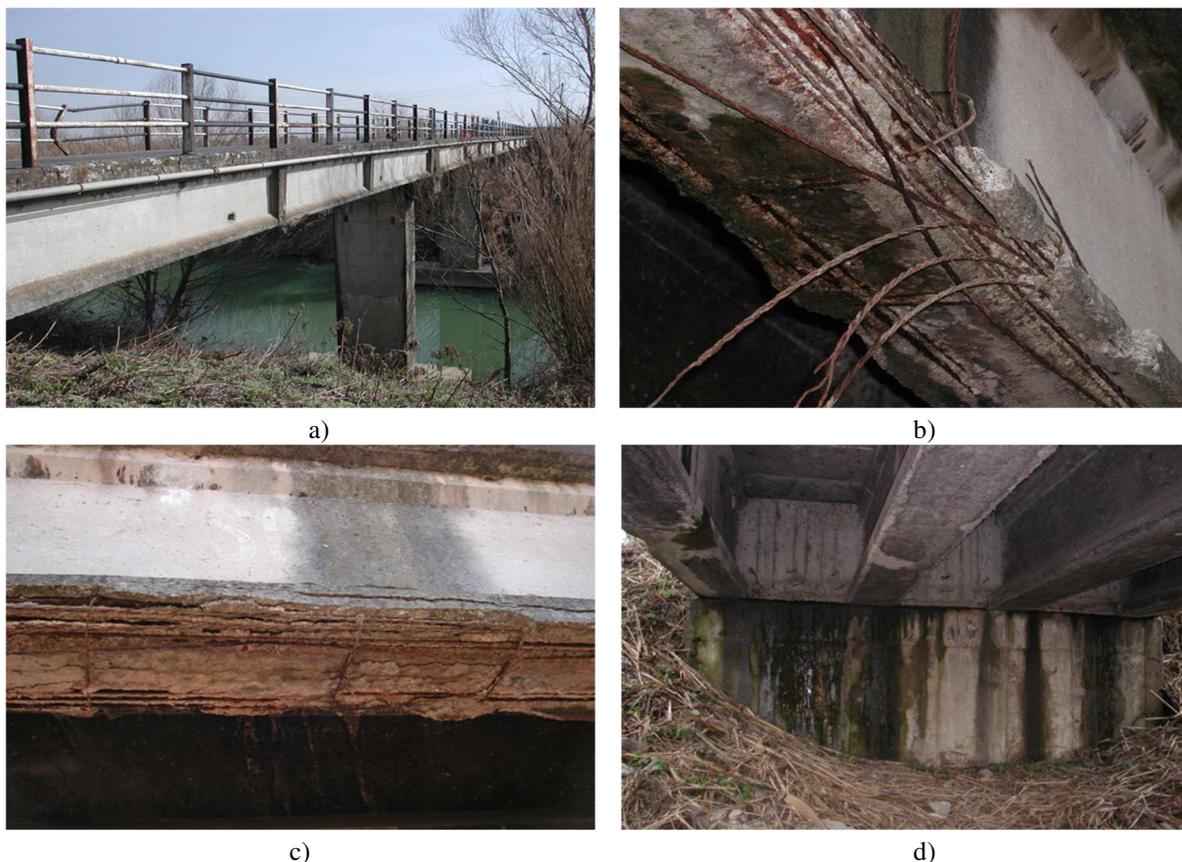


Figure 6: Visual inspection on the bridge: a) General view; b) Corrosion of pre-stressing wires; c) Concrete spalling and reinforcement corrosion; d) Degradation of concrete surfaces

A survey and testing plan was developed involving sclerometric and ultrasonic tests, as well as dynamic acquisitions. The values of the mechanical properties of concrete for structural modelling and verifications were obtained from *in-situ* tests. Instead, since the types of steel used in the construction were clearly indicated in the original design documents, it was decided not to take samples of reinforcement bars and wires, but only to verify their positions and diameters by using a pacometer and make spot checks by removing parts of the superficial concrete layers.

Experimental dynamic acquisitions were done at different locations of each span of the bridge (Figure 7). Such measures enabled the determination of the natural frequencies and mode shapes of the bridge, which were used later to calibrate the finite element model of the existing structure. The first natural frequencies measured were in the range 8.6-9.2 Hz for the flexural modes and 12.5-13.3 Hz for the torsional modes (Table 1).

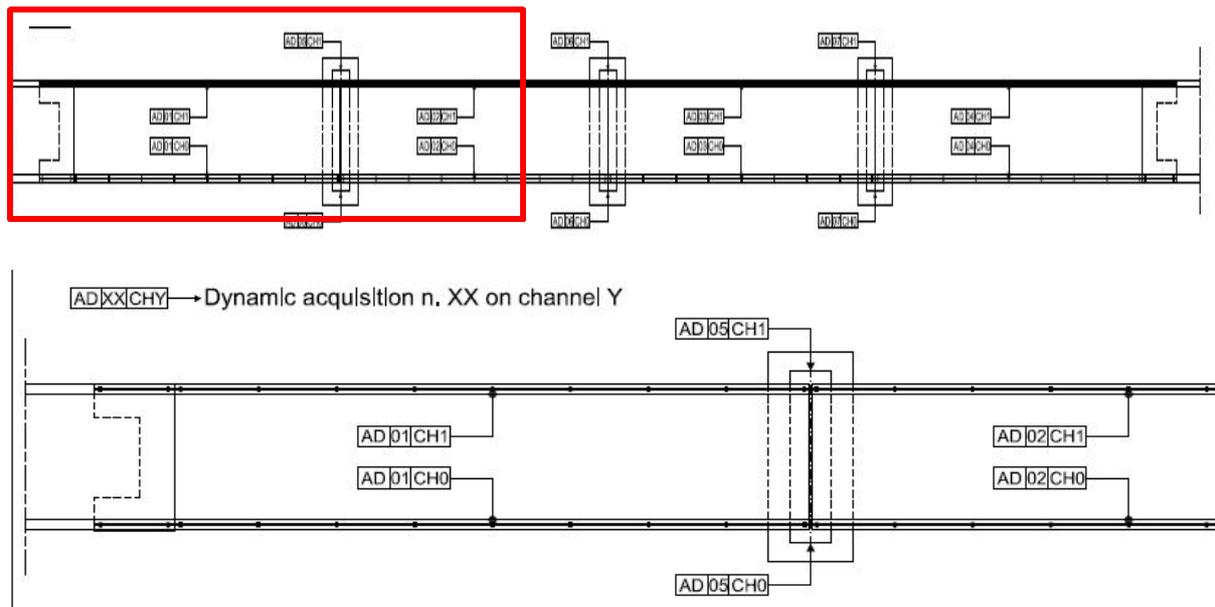


Figure 7: Position of the dynamic acquisitions on the first span of the bridge

Test	Channel	f_1 (Hz) flexural	f_2 (Hz) torsional
AD1 (Span 1)	CH0	9.2	12.9
	CH1	9.2	12.9
AD2 (Span 2)	CH0	8.6	12.5
	CH1	8.6	12.5
AD3 (Span 3)	CH0	8.9	13.3
	CH1	8.9	13.3
AD4 (Span 4)	CH0	8.6	–
	CH1	8.6	–

Table 1: Experimental natural frequencies

Finite element analysis

A finite element model of the bridge (Figure 8) was created using the commercial finite element software Straus7[®] [7]. The outcomes of the experimental campaign were used to define the geometry of the BEAM and PLATE elements, as well as the mechanical properties of the materials, the internal and external constraints. Table 2 summarises the mechanical properties of the materials, obtained from the original documents and the *in-situ* investigation campaign.

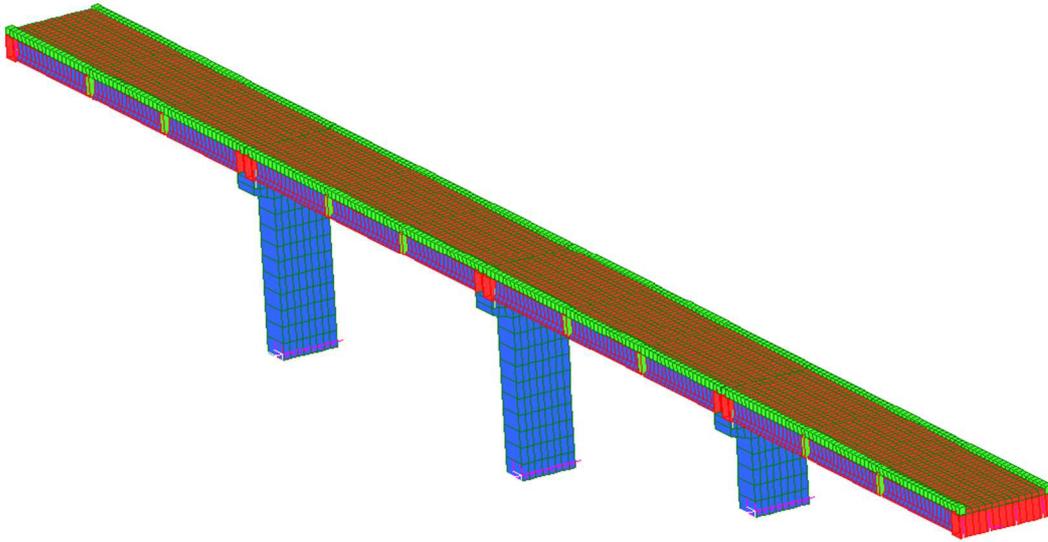


Figure 8: Finite element model of the bridge

Element	Property	Value	Source
Girder	Unit weight	25 kN/m ³	Literature
	Elastic modulus	36000 MPa	On-site ultrasonic test
	Poisson coefficient	0.1	Literature
	Density	2500 kg/m ³	Literature
Pier	Unit weight	25 kN/m ³	Literature
	Elastic modulus	29500 MPa	On-site ultrasonic test
	Poisson coefficient	0.1	Literature
	Density	2500 kg/m ³	Literature
Slab	Unit weight	25 kN/m ³	Literature
	Elastic modulus	31200 MPa	On-site ultrasonic test
	Poisson coefficient	0.1	Literature
	Density	2500 kg/m ³	Literature

Table 2: Mechanical properties of the materials

Dynamic modal analysis

The dynamic modal analysis was needed to determine the theoretical natural frequencies and mode shapes of the structure to be compared with the experimental results obtained from the on-site dynamic acquisitions. No force loads were considered, but only the masses of the structural and non-

structural elements, such as the road pavement and railing. The mass of the structural elements is automatically calculated by the software and attributed to the nodes of the model, once the geometry and material properties of each element are defined, while the masses of the road pavement and railing are introduced into the model as NON-STRUCTURAL MASS per unit area of the PLATE elements representing the concrete slab.

Table 3 summarises the natural frequencies of the first vibration modes obtained from the dynamic modal analysis of the structure. The modes with the higher mass participation factors are given in boldface character. A good agreement was obtained between the experimental results (see Table 1) and the output of the analysis, so that the model was considered well calibrated.

Mode	Theoretical frequencies (Hz)	Mode participation factor X (%)	Mode participation factor Y (%)	Mode participation factor Z (%)
1	6.435	16.702	0.000	19.681
2	6.585	0.000	56.824	0.000
3	7.233	0.139	0.000	0.288
4	8.308	1.046	0.000	0.002
5	9.259	1.636	0.000	35.624
6	9.676	0.000	0.048	0.006
7	10.72	0.000	2.313	0.000
8	11.08	0.000	5.809	0.000
9	11.52	60.099	0.000	8.151
10	12.40	0.000	0.062	0.000
11	12.47	0.000	1.365	0.000
12	14.86	0.000	16.276	0.000

Table 3: Theoretical and experimental natural frequencies

Linear static analysis

The bridge was designed following the Italian regulations of the time of construction, namely the Circolare n. 384/1962 [8] and Circolare n. 1398/1965 [9]. In order to assess the current load-carrying capacity of the bridge, static analysis of the model was carried out considering the load configurations and combinations according to the present Italian regulation NTC 2008 [10]. Such loads were applied per unit area or unit length for the PLATE and the BEAM elements, respectively. The stresses on the structural elements of the bridge were determined for the single load cases and their combinations. Table 4 shows the strength demand obtained from linear static analysis in terms of design bending moment, M_{sd} , and shear force, V_{sd} , compared to the corresponding capacities of the composite section (girder + concrete slab), M_{rd} and V_{rd} , evaluated according to NTC 2008 [10].

The structural analysis of the bridge revealed that the composite girder sections lack both flexural and shear strength. In addition, pre-stressing has to be restored in one of the border beams featuring some damaged wires (see Figure 6b). Furthermore, the road section turns out to be not sufficient for the road category assigned to the San Miniato bridge by Italian road regulations [11], so that it needs to be properly widened. Lastly, local analysis of the concrete slab highlighted the need for both flexural and shear strengthening of this element in the transverse direction.

Accordingly to the above-mentioned standard operating procedure and to the performed structural analyses, it was estimated that the load-carrying capacity of the existing structure corresponds to the 51% of the traffic loads assigned by the current Italian regulations.

Section	M_{sd} (kNm)	M_{rd} (kNm)	V_{sd} (kNm)	V_{rd} (kNm)
Internal girder	1231	991	360	285
Border girder	1156	962	260	285
Damaged girder	1156	721	260	285

Table 4: Maximum design internal forces and corresponding resistances

Preliminary design of the strengthening intervention

Several widening hypotheses were evaluated to make the road section compliant with current Italian road regulations [11]. After a preliminary analysis, it was decided to choose a single lane solution with the widening of the existing deck from 3 to 3.5 m and the addition of two lateral walkways (Figure 8). A new finite element model (Figure 9) representing the widened structure was then created to evaluate the increase in the demand. The resisting bending moment of the strengthened composite section, M_{rd} , was evaluated by extending the conventional hypotheses for ultimate limit state (ULS) verifications of reinforced concrete elements to the present case (Section 6.1 Eurocode 2 [12]):

- plane sections remain plane with no relative sliding between concrete and steel;
- the tensile strength of concrete is ignored;
- the stresses in concrete in compression are derived from the design stress-strain relationships given in Section 3.1.7 of Eurocode 2 [12] (here, a bilinear stress-strain relationship is used);
- elastic-plastic behaviour is assumed for steel reinforcements.

In addition to the above, further specific assumptions were made:

- the whole composite section remains plane after deformation with no relative sliding between CFRP/GFRP elements and concrete;
- both CFRP and GFRP are assumed to behave as elastic-brittle materials;
- delamination of CFRP/GFRP from concrete is not taken into account.

Table 5 shows the demand and capacity in terms of bending moment of the composite section obtained by using GFRP panels or CFRP laminates only, and the SUREBridge solution, which uses both. The benefits of the SUREBridge solution are clear: the ultimate bending moment can be considerably increased from 721 to 1535.5 kNm, above the design value of 1382 kNm. Instead, using the GFRP panels only would require very thick panels and even a height of 1 m would not be sufficient for the damaged border girder. Besides, using only CFRP laminates would imply brittle

failure of concrete in compression. In the conducted calculations, the limit strain of CFRP laminates is assumed as given by the corresponding material strength with no reduction to avoid delamination as prescribed by the Italian standard CNR-DT 200 R1/2013 [12]. This was done since the CFRP pre-stressing technique has demonstrated to considerably delay delamination failure with respect to passive laminates [3].

Section	M_{sd} (kNm) Widened	M_{rd} (kNm)			
		Existing	+ GFRP	+CFRP	+GFRP +CFRP
Internal girder	1228	991	1236 (2)	1251 (4)	1487 (1) (4)
Border girder	1382	962	1409.5 (3)	1427.5 (6)	1463 (1) (4)
Damaged girder	1382	721	–	1406 (7)	1535.5 (1) (5)

Table 5: Ultimate bending moment for strengthened sections

- (1) GFRP: H = 150 mm, webs in the transverse direction;
- (2) GFRP: H = 250 mm, webs in the transverse direction;
- (3) GFRP: H = 500 mm, webs in the transverse direction;
- (4) CFRP: No. 1 laminates 80 mm x 1.4 mm;
- (5) CFRP: No. 2 laminates 80 mm x 1.4 mm;
- (6) CFRP: No. 3 laminates 80 mm x 1.4 mm;
- (7) CFRP: No. 4 laminates 80 mm x 1.4 mm.

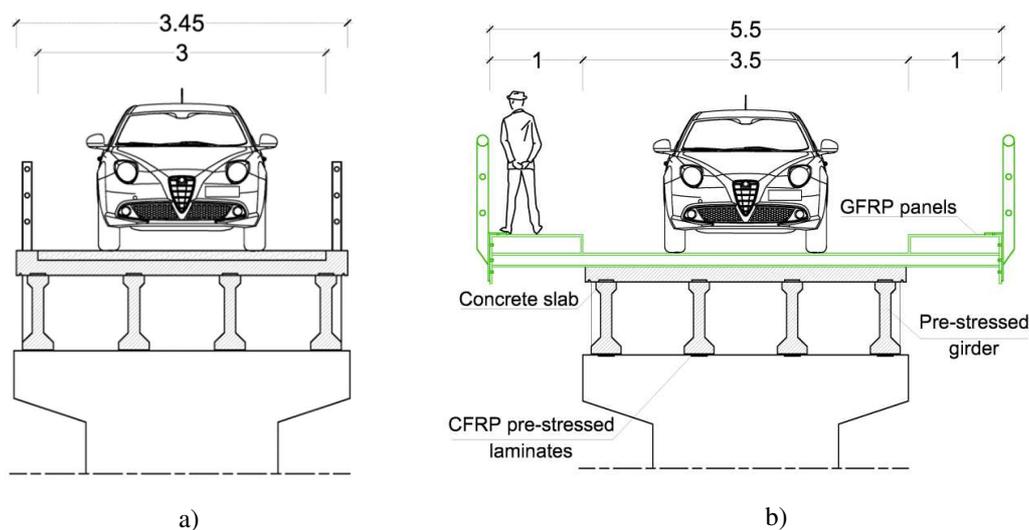


Figure 9: a) Existing cross section and b) widened cross section

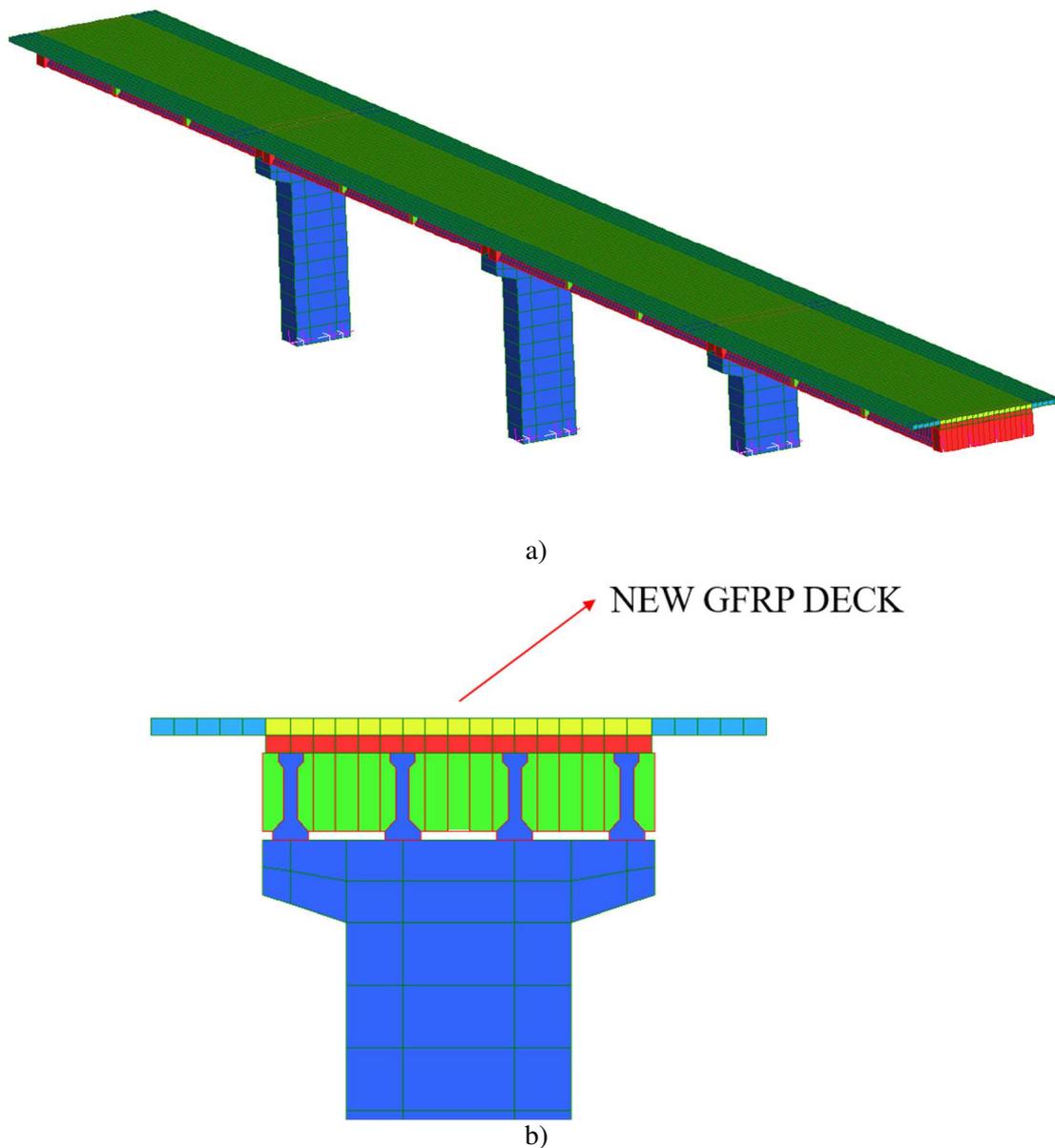


Figure 10: Finite element model of the widened bridge a) general view ; b) cross section

Conclusions

The innovative solution developed within the European project SUREBridge for the refurbishment of road bridges has been presented. The proposed technique applies to bridges with reinforced concrete slab and longitudinal girders made of either reinforced concrete or steel. Longitudinal girders are strengthened by bonding pre-stressed CFRP laminates to their bottom surfaces. GFRP panels are connected to the deck to increase its overall bending strength and to widen the road section, if necessary.

Application of the developed technique for the strengthening and widening of the San Miniato bridge, chosen as a case study, has demonstrated the feasibility and effectiveness of the proposed solution.

Acknowledgements

Financial support from the ERA-NET Plus Infravation 2014 Call within the SUREBridge Project is gratefully acknowledged.

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