

Sustainable structural rehabilitation and strengthening of the “Ponte delle Grazie” bridge in Faenza, Italy

M Micheloni¹, M La Monica¹, D Parmeggiani², P Barchi²

¹ Studio Micheloni, Florence, Italy

² Unione Romagna Faentina – Settore Lavori Pubblici, Faenza, Italy

E-mail: michelangelo@micheloni.org

Abstract. The “Ponte delle Grazie” is a three span bridge, with a total length of 72 meters, built between 1948 and 1952 in Faenza, Italy. The reinforced concrete main beams of the deck have undergone a strong deterioration over the years. In detail atmospheric agents and chemical aggressions caused a strong deterioration of the concrete, up to the point of making the structure not accessible and at risk of collapse. In fact, the five main beams were heavily damaged, as well as the concrete bearings were strongly compromised. So, an urgent intervention was necessary to save the structure of this historic bridge. A delicate restoration has allowed to remove the deteriorated concrete and to restore the resistant sections with new materials compatible with the old remaining structures. In particular, a specific rehabilitation procedure was studied using fiber-reinforced cement mortar with low elastic modulus, that is shrinkage compensated, in combination with composite materials reinforcements. Without modifying the structural behaviour of the bridge, the deteriorated concrete was restored and reinforced, in a sustainable way, in order to make the structure safe and usable again.

Keywords: bridge, infrastructure, rehabilitation, concrete, FRP

1. History and description of “Ponte delle Grazie”

The “Ponte delle Grazie” is a three span bridge, with a total length of 72 meters, designed and built between 1948 and 1952 in Faenza, Italy. The bridge has a historical value linked not only to its age but also to its role as a link between the two oldest parts of the city: the historic center of Faenza and the Borgo Durbeco.

In the last years a strong deterioration of concrete was found in the main beams of the lateral spans, in the Gerber half joints of the central span and in the reinforced concrete bearings on the breast walls of abutment. The deterioration of the concrete was extended up to the point of making the structure not accessible and at risk of collapse and an urgent intervention was necessary to save the structure of this historic bridge, following the procedure described in the following.





Figure 1. The “Ponte delle Grazie” bridge located on the Lamone River in an original postcard.

1.1. Description of the bridge

The bridge belongs to the category of "Gerber Bridge" (isostatic) with three spans with "internal half joints".

The type in question was usually used when it was desired to have an advantageous distribution of the stresses in the structure (less positive moments in exchange for negative moments on the supports), without renouncing the advantages of the isostaticity. The disadvantage of this structural typology is that the detail in the beam seat region represents a potentially sensitive structural detail.

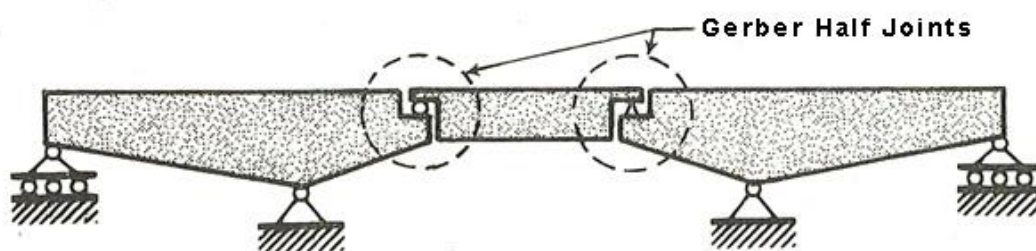


Figure 2. The structural scheme of the bridge with two Gerber half joints inside the central span

The side spans have a length of 21 meters, while the central span has a total length of 30 meters. The part of the bridge between the two piers is made by two 6 meters cantilever spans with a suspended span of 18 meters between them. The connection between cantilever and central span is made with Gerber half joints. The total length of the bridge is 72 meters.

The cross section of the deck is made of 5 beams of variable height in reinforced concrete with 240cm wheelbase, and connected with stringers. The total deck width is 13 meters.

1.2. History of the bridge

The bridge was designed in 1949 and built between 1950 and 1952. The original project of the bridge and many documents regarding its construction are conserved at “Archivio di Stato di Faenza” [2], and so it was possible to analyze and study these documents to increase the knowledge of the bridge.

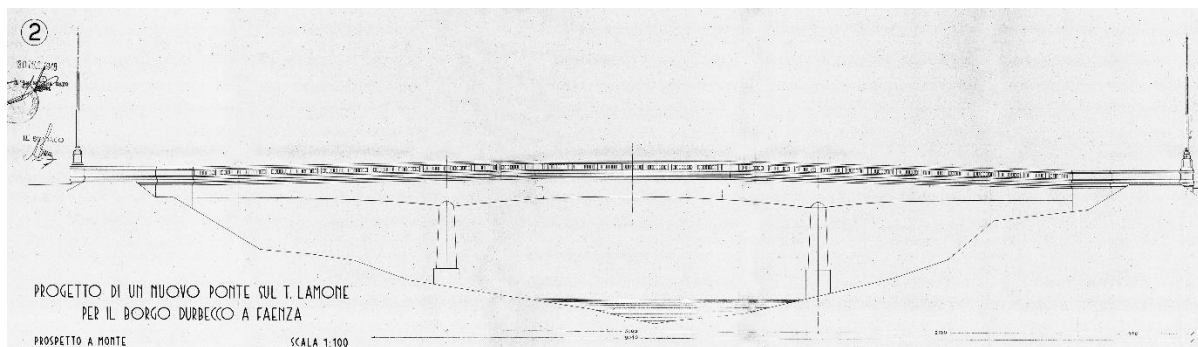


Figure 3. The elevation of “Ponte delle Grazie” in the original drawings from “Archivio di Stato di Faenza” [2]

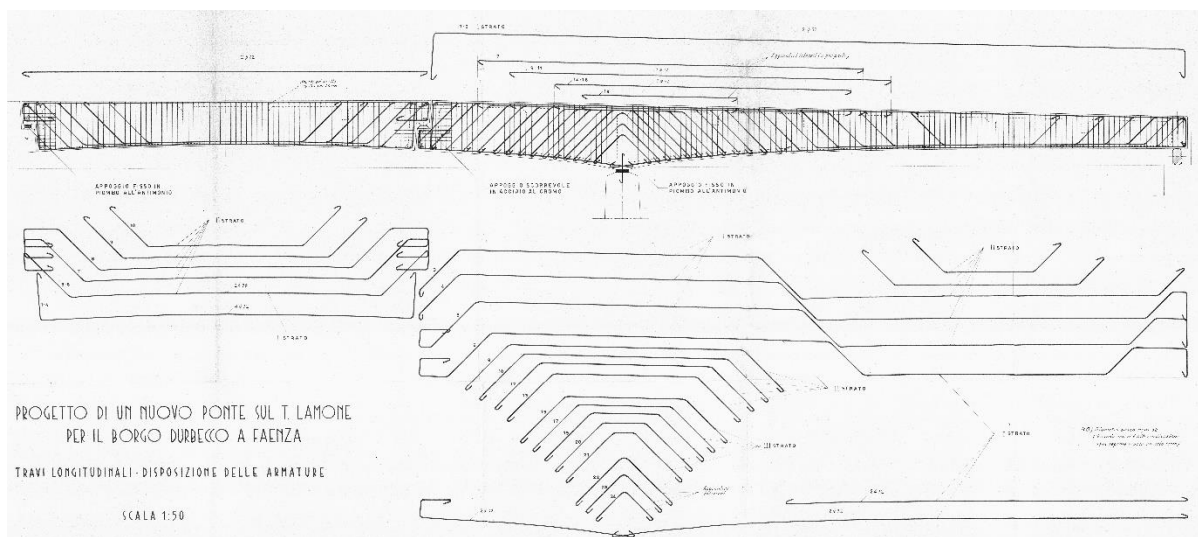


Figure 4. Main beams rebars design in the original drawing from “Archivio di Stato di Faenza” [2]

2. The knowledge process

The knowledge of the structure and its state of conservation goes through the analysis of the following steps.

- Analysis of the deterioration of the concrete and reinforcement steel
- Analysis of materials
- Analysis of the structure and its service level

3. The deterioration of the concrete and reinforcement steel

The first task to be carried out was the identification of the critical aspects of the structure and its deterioration.

The most critical deterioration was found in the following parts:

- Main beams of the side spans
- Gerber half joints of the central span
- Reinforced concrete bearings on the breast walls of abutment

3.1. Main beams deterioration

The main beams of the side spans presented a strong deterioration, especially near the abutment, as demonstrate by visual inspections and laboratory tests on materials.



Figure 5. Beams deterioration on the side span



Figure 6. Beams deterioration on the side span

The dangerous state of the main beams in the area near to the abutments was evident. In fact not only the concrete is strongly damaged, but also the steel bars are deeply corroded and the stirrups are exploded.

3.2. Gerber half joints deterioration

A disadvantage inherent in “Gerber bridge” type of construction is that there are problems associated with leakage through the half joint. This enables moisture to accumulate at the beam seats thereby increasing the propensity for the deterioration of the concrete and reinforcement steel.

Furthermore, together with water leakage and moisture, there is also an accumulation of chlorides, dangerous for concrete and steel bars.

The situation is adversely compounded by limited access to the bearing seat joint, which leads to both inspection and maintenance issues.

So, it is very important to analyze the detailing deficiencies and deterioration.



Figure 7. Gerber half joint at actual state

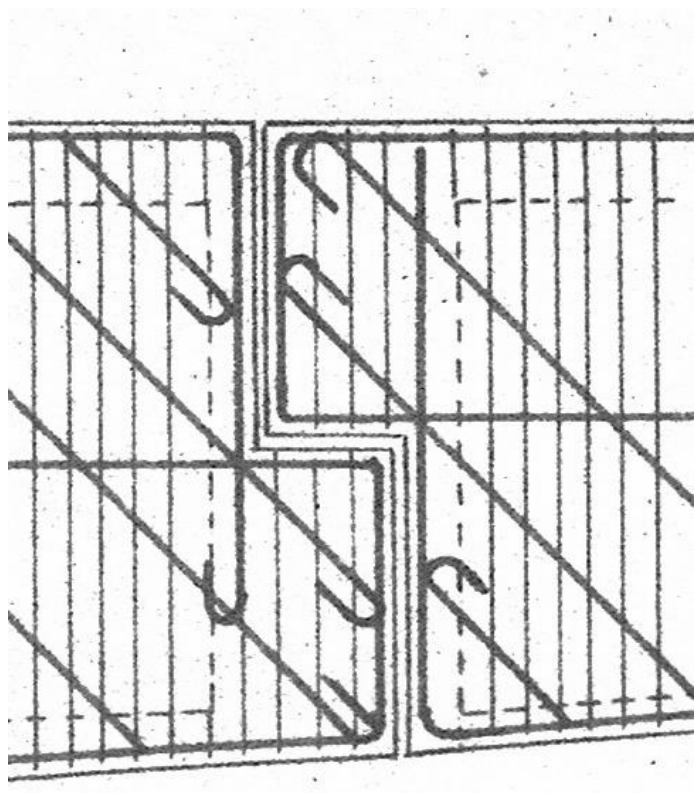


Figure 8. Gerber half joint in the original drawing from “Archivio di Stato di Faenza” [2]

3.3. Bearing deterioration

The main beams of the side spans rest on the breast walls with reinforced concrete bearings. This kind of “pendulum bearing” is made with reinforced concrete and they represent a very sensitive detail.



Figure 9. Deterioration and cracks on the concrete pendulum bearing

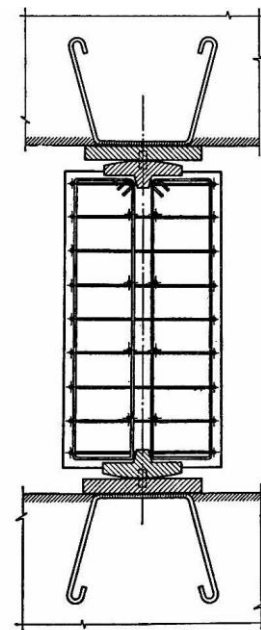


Figure 10. Concrete pendulum bearing typical scheme [1]

In detail this concrete bearings exhibit a strong degradation phenomena, with evident breaking lesions in place, as evidenced by the following images.

The dangerous state of the supports is evident and it has become necessary to take urgent action.

4. Analysis of materials

The first task to be carried out was the identification of the critical aspects of the structure and its deterioration.

A detailed test program was performed on the existing concrete to determinate the mechanical properties:

- Compression Test On Concrete Cores
- Sclerometric Hammer Test
- Son-Reb Test

and to determine the concrete deterioration:

- Carbonation Test
- Chlorides Test

4.1. Compression Test On Concrete Cores

Sixteen concrete cores were taken from various parts of the structure and subjected to compression tests in the laboratory.

Although it is possible to average the values of the compressive strength of the 16 concrete cores and although the average values obtained are in line with the requirements of the original project, it is clear that some cores have given very low values compared to the others. It is therefore essential to investigate in more detail with an approach that divides concrete cores according to the structural elements that form the bridge.

In fact, the structure has been realized in 3 parts of works and therefore each of these phases has been characterized by different concrete supply. Furthermore, the exposure of the concrete is also different for the various structural elements and therefore also the deterioration of the characteristics over time may have happened differently.

The samples are then divided according to the structural elements stated in the following table 1.

Table 1. Properties of concrete

Bridge parts	Average compression strength - f_m	Concrete class
Pier (1 st part of works during 1948)	18,6 MPa	C10/13
Abutment (2 nd part of works during 1949)	31,8 MPa	C23/28
Deck slabs (3 th part of works during 1950)	41,9 MPa	C33/41
Longitudinal girders of central span (3 th part of works during 1950)	27,5 MPa	C19/23
Longitudinal girders of side span (3 th part of works during 1950)	17,9 MPa	C9/11
Whole bridge	24,4 MPa	C16/20

These results are confirmed also by Sclerometric Hammer and Sonreb site tests.

4.2. Test for the determination of carbonation

Following the codes UNI 9944:1992, all the samples of concrete cores, after breaking, were also subjected to carbonation tests in the laboratory.

The test allows the detection of the state of conservation of structural elements in concrete through the chemical process of carbonation, which provides for the action of carbon dioxide that is present in the air to neutralize the lime present in the concrete.

The average value of the carbonation depth on the 15 cores is about 6cm. This is symptomatic of a strong phenomenon of carbonation and deterioration of the concrete in progress.

4.3. Test for the determination of chlorides

Following the codes UNI 9944:1992 and UNI EN 206-1, some samples of concrete cores have been subjected to this test that allows to determine the percentage of water-soluble chlorides present in a mass of concrete, so as to be able to give a judgment on the risk of corrosion by chlorides that can reach a critical level on the surface of the concrete, with consequent verification of localized breakdown of the film of passivity of the reinforcements and subsequent priming of the corrosion mechanism.

From the tests carried out, there was a low percentage content of chlorides in the concrete of the slabs and of the internal parts of the beams, lower than the indicated range of 0.2-0.4% in UNI EN 206-1. Instead, in the first 4 cm of the edge beams a high risk of chloride corrosion was found with a percentage of chlorides above the maximum limit of the regulatory range, i.e. 0.6% compared to the mass of the cement.

Table 2. Depth of chlorides

Depth	percentage of chlorides in concrete mass - %
4cm	0,61
11 cm	0,09
16 cm	0,07

The strong attack of the chlorides in the concrete cover of the lateral beams is therefore evident (first 4cm) confirming the high corrosion caused by the reinforcement bars.

5. Analysis of the structure and its service level

The results of the test on materials are used to develop a finite element model that represents the real geometries and mechanical characteristics of the bridge. The software SAP2000 is used to generate the FEM of the bridge.

Three different types of loading scheme are applied to the model:

1. The loading scheme of current Italian regulations (D.M. 14.01.2008) [4], that is a scheme with on lane no. 1 a load per axis $Q_{1k} = 240$ kN and a distributed load $q_{1k} = 7.2$ kN / m² and on lane no. 2 a load per axis $Q_{1k} = 200$ kN and a distributed load $q_{1k} = 2.5$ kN/m² and on the remaining area $q_{Rk} = 2.5$ kN/m².
2. The loading scheme of the original design of the bridge of 1949 (R.D.L.16.11.1939 n. 2229) [5], that is, a pattern of civilian loads consisting of an indefinite column of 12ton trucks with 8ton axes and 4ton alternating and equidistant of 3m.
3. A loading scheme with reduced loads, that is a scheme of two lanes, each composed of an indefinite column of 6 ton vehicles. (60 kN) with a length of 5 meters, inside which there is a 20 ton vehicle. (200 kN) with length 8 meters. In combination with this group of actions a load of 2.5 kN/m² is considered along the carriageway and on the sidewalks.

Considering the results of the materials test, the safety level of the bridge is not satisfied for any of the three loading scheme.

This critical situation is confirmed also by a site load test with a column of 5 ton vehicles. During this test a very high deformation is recorded with unusual residual deformation.

All these facts imposed the closure of the bridge and the urgent start of consolidation works.

6. The structural rehabilitation and reinforcement process

The structural rehabilitation and reinforcement follow two approaches:

- Repair of concrete and reinforcement of the bearings on the abutment and of the side span of the main beams.
- Install of new steel structures to protect the bearings on the abutment and the Gerber half joints.

In fact, the desire to maintain the original scheme of the bridge, in a sustainable way, requires not only to repair and reinforce the concrete, but also to insert new structures to protect the most delicate parts. The main beams of side spans and the concrete pendulum bearing were repaired and reinforced to comply with the requirements of the loading scheme 3, described in the previous paragraph 5. Moreover the Gerber half joint and the concrete pendulum bearing are very critical structural details, so, even if the structural check is satisfied, a new “protection” structures are placed on these parts.

6.1. Main beams rehabilitation and reinforcement

The main beams of the side spans are repaired with a deep cleaning and restoration of concrete and reinforced with a wrapping of carbon fiber textiles. The bearing strengthening in this way is verified considering the loading scheme n. 3 described in the previous section 5.

The phases of these works are the following:

- Deep cleaning of concrete surfaces with high pressure hydro-scarification (2000 bar)
- Reconstruction of the concrete section with a two-component thixotropic, fiber-reinforced cement mortar with low elastic modulus that is shrinkage compensated.
- Wrapping with carbon fiber textiles.

In the areas where the cognitive tests on the concrete had given the lowest results, a large quantity of deteriorated concrete was removed. In these points the 40cm wide beam has been reduced to only 18cm.



Figure 11. The main beams after the cleaning with hydro-scarification.

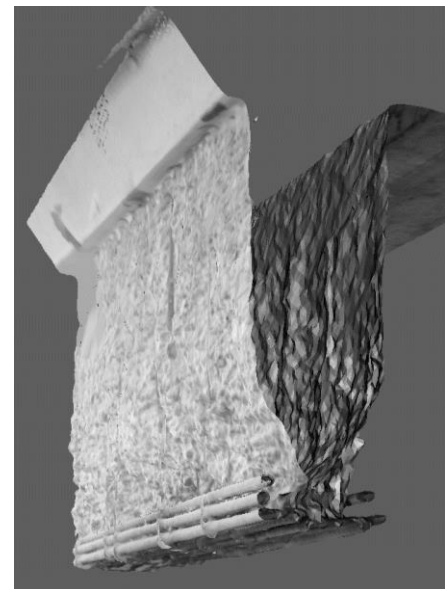


Figure 12. 3D laser scanner of the main beams after hydro-scarification

The reconstruction phase was very critical, because it was very important to guarantee the perfect adhesion of the new cement mortar to the existing concrete. In the mean time the new material must have the same low elastic modulus of existing concrete. To comply with these requirements a specific two-component thixotropic, fiber-reinforced cement mortar was selected. Some pull-off tests are performed to check the adhesion between the new and old concrete.

Inside the new part of concrete reconstruction, a steel net and some steel bars are placed to increase the reinforcement bar cross-section, that was lost due to corrosion.

After the reconstruction of the beam section a wrapping with carbon fiber textiles of 1000gr/sqm was necessary to satisfy the verification for the shear loads, in accordance with the CNR-DT code [7].

A specific detail is designed to wrap the FRP textiles around the beam cross-section. In the lower part of the beam the FRP textile can be laid on the beam surface, but to pass true the deck slab, it is necessary to place the FRP textile true holes with 30mm diameter.

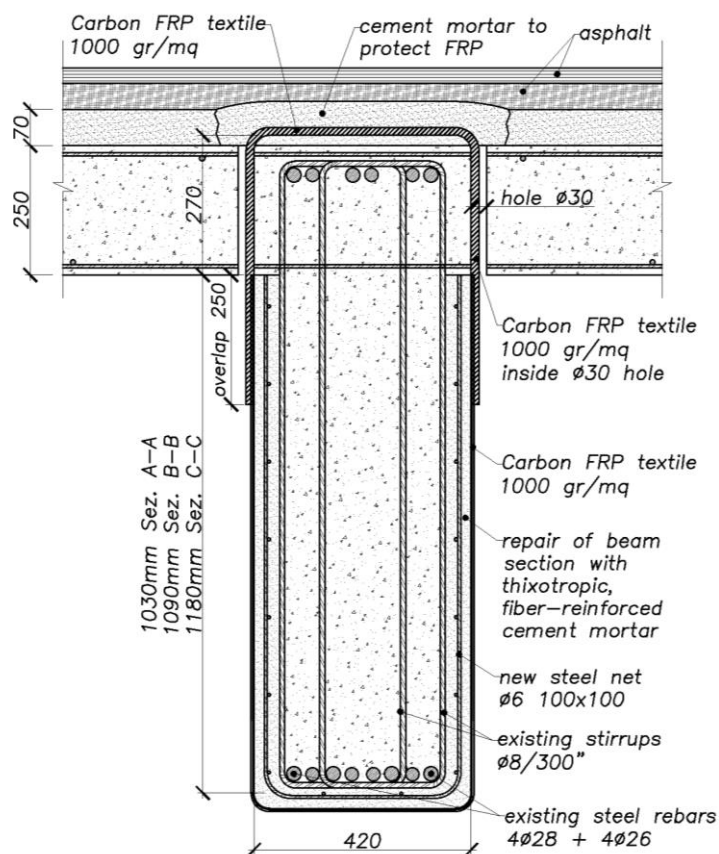


Figure 13. Scheme of reconstruction and strengthening of main beams

6.2. Gerber half joints protections

The Gerber half joints on the central span are verified considering the results of the test on the materials and the loading scheme n. 3 described in the previous paragraph 5. However it is important to consider the limited access to the bearing seat joint which leads to both inspection and maintenance issues. So there is no guarantee that the actual situation can get worse without the possibility of intervention.

For these reasons a protective metal structure, that comes into operation only in case of collapse of the half joint and prevents the collapse of the bridge central span, was considered.

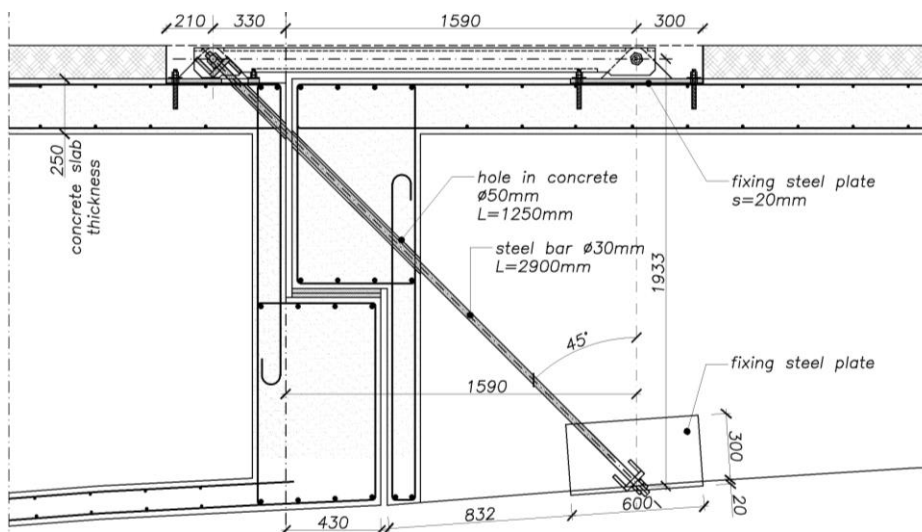


Figure 14. Scheme of steel structure for half joint protection

The steel structure works with a strut and tie scheme, where an upper strut is placed under asphalt and a tie rod tilted through the existing structure up to the lower face of the beam. This steel structure does not modify the working scheme of half joint, but it sustains the central span in case of half joint collapse.

6.3. Reinforced concrete bearings rehabilitation and reinforcement

The reinforced concrete pendulum bearings are repaired with a soft cleaning and restoration of concrete and reinforced with a wrapping of carbon fiber textiles. In this way the bearing strengthening is verified considering the loading scheme n. 1 described in the previous paragraph 5. However, it is important to consider the particularity and delicacy of this kind of bearing. So there is no guarantee that the actual situation can get worse without the possibility of intervention.

For these reasons some steel columns are put in place as a structure of defense, that comes into operation only in case of collapse of the concrete bearings.



Figure 15. Reinforced concrete bearing after concrete reconstruction.



Figure 16. Concrete bearing after wrapping with FRP and the steel protections.

7. Final tests and conclusions

The quality of the work was confirmed by a complete series of final test on the materials and on the structure. In particular a specific set of static and dynamic test with vehicle loads were performed on the entire bridge structure.

In detail the static tests demonstrate the safety of the structure and the correct execution of the works, but it is very interesting to underline the results of dynamic testing through microwave interferometry [3]. In fact, as a result of the reinforcement works, there was an increasing of the natural frequency of the structure of about 0,15Hz. This value is synonymous with a substantial increase in bridge deck stiffness.

At the end it is possible to conclude that the delicate restoration work with specific materials and procedures, has allowed to reinforce the bridge, in a sustainable way, in order to make the structure safe and usable again.

References

- [1] Pozzati P. Ceccoli 1977 Teoria e tecnica delle strutture vol 2, tomo 2, fig. 3.38 p 223
- [2] Original project of “Ponte delle Grazie” placed in “Archivio di Stato di Faenza” - fondo b.51/1952
- [3] Pieraccini M, Parrini F, Fratini M, Atzeni C, Spinelli P, Micheloni M 2007 Static and dynamic testing of bridges through microwave interferometry *NDT&E International* 40 pp 208–214.
- [4] Italian regulations at the time of rehabilitation project: NTC2008 - D.M. Infrastrutture del 14 gennaio 2008 “Nuove norme tecniche per le costruzioni” e Circolare 2 febbraio 2009 n. 617 Consiglio Superiore Lavori Pubblici “Istruzioni per l’applicazione delle <Nuove norme tecniche per le costruzioni> di cui al DM 14 gennaio 2008”
- [5] Italian regulation at the time of the bridge project (1949): “Regio Decreto Legge del 16 novembre 1939 n. 2229 Norme per l’esecuzione delle opere in conglomerato cementizio semplice ed armato” and “Normale n. 6081 del 9 giugno 1945 del Ministero dei Lavori Pubblici per le strade di grande traffico con importanza militare”.
- [6] UNI EN 1992-1-1 - Eurocodice 2 - Progettazione delle strutture di calcestruzzo - Parte 1-1: Regole generali e regole per gli edifici.
- [7] CNR-DT 200R1/2013 "Istruzioni per la Progettazione, l'Esecuzione ed il Collaudo di Interventi di Consolidamento Statico mediante l'utilizzo di Compositi Fibrorinforzati" – Consiglio Nazionale delle Ricerche Italiano - 10 ottobre 2013 – versione del 15 maggio 2014.