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Rehabilitation and seismic upgrading of the masonry arch bridge over the Magra river in Villafranca

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Abstract

The paper deals with the rehabilitation of an historical masonry bridge crossing the Magra river and connecting the small towns of Mulazzo and Villafranca in the northern part of Tuscany (I).
The masonry arch bridge, characterized by eight arches spanning 19 m around each and by around 12 m height intermediate masonry piers on shallow foundations, was built in 1874.
Since the original carriageway width was not sufficient to allow two lanes, in 1961 it was widened by means of two lateral prestressed concrete beams, supported by the piers, so hiding the arches and modifying severely the original aspect of the bridge itself.
In 2011, during the Magra flooding, two arches on the Mulazzo side collapsed due to scour of the extreme pier.
The reconstruction of the collapsed arches and rehabilitation and the strengthening of the bridge, which has been completed last year, is discussed and the execution of the interventions, which has performed without erection of temporary support in the riverbed, is also illustrated.
Particular attention is devoted to the original solutions which have been adopted for the full seismic upgrading of the bridge according to the Italian Building Code currently in force, recovering the original architectural aspect of the bridge and widening the carriageway as well.

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Keywords: Masonry arch bridge, Seismic upgrading, Historical bridge, Strenghtening;

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1. Introduction

The paper deals with the rehabilitation of an historical masonry bridge crossing the Magra river and connecting the small towns of Mulazzo and Villafranca in the northern part of Tuscany (I) (Fig. 1).

The single lane carriageway masonry arch bridge, characterized by eight arches spanning 19 m around each and by around 12 m height intermediate masonry piers on shallow foundations, was built in 1874. In Fig. 2 it is shown the bridge during the erection phase of the piers. It must be stressed, that at that time the course of the river was slightly different; the bridge was on a right bend, so that the velocity of the current was usually higher on the left bank, Villafranca side, than on the right bank, the Mulazzo, as it is evident looking at the river bed in fig. 2. This is presumably the reason why the dept of the original pier foundations diminished from Villafranca toward Mulazzo.

Fig. 1. Map of the Magra river in Villafranca - Mulazzo area

Fig. 2. The Villafranca bridge during the erection phase (1874)

Since the original carriageway width was not sufficient to allow two lanes, in 1961 it was widened by means of two lateral prestressed concrete beams, supported by the piers, so hiding the arches and modifying severely the original aspect of the bridge itself, as shown in Fig. 3.

More recently, due to the modification of the river course, scour occurred at the piers on the Mulazzo side, so that in the years 2005-2010 a relevant crack pattern was detected on the last two arches, as illustrated in Figs. 4 and 5.

Despite the monitoring program setup to control the structural decay, in 2011, during the Magra flooding, two arches on the Mulazzo side collapsed due to scour of the extreme pier, and a temporary Bailey bridge was placed on the deck to allow at least light car traffic (Fig. 6).

Fig. 3. Elevation of the bridge after the carriageway widening (1961)

Fig. 4. Inspection of a damaged arch - monitoring phase (2010)

In the paper, the reconstruction of the collapsed arches and the rehabilitation and the strengthening of the bridge, which has been completed in 2016, is discussed and execution of the interventions, which has performed without erection of temporary support in the riverbed, is also illustrated, devoting particular attention to the original solutions adopted for the full seismic upgrading of the bridge according to the Italian Building Code in force at that time (NTC, 2008), recovering the original architectural aspect of the bridge and widening the carriageway as well.

Fig. 5. Main crack on the arch (Mulazzo side 2010)

Fig. 6. The temporary Bailey bridge after the collapse of the two arches (2012)

2. Rehabilitation, strengthening and seismic upgrading of the bridge

The rehabilitation, strengthening and seismic upgrading interventions were defined not only considering structural aspects, but also taking into account the needs of the preservation of the historical value of the bridge, according the Guidelines of the Italian Ministry of Cultural and Historical Heritage (2011), the ISO standard 13822 (2001) and the general approached widely described by Croce and Holicky (2013, 2015).

The intervention involves, inter alia, the consolidation of 6 of the 8 arches, the reconstruction of the collapsed pier and of the two arches closest to the right bank and the strengthening of the remaining parts. The two collapsed arches have been rebuilt in reinforced concrete as well as the collapsed pier (see Fig. 7.a), characterized by micro-pile foundation. For casting these new concrete parts, special non-removable lateral formworks have been used, overlaid with bricks and stones looking similar to the original ones, anyhow underlining the modern replacement (Fig. 7.b).

Fig. 7.(a) The new r.c. arches and pier

(b) The lateral formworks overlaid with stones and bricks

These two new spans are a continuous beam on three supports, with varying cross section, being the end sections prevented from lengthening, so allowing the transfer of the trust of the adjacent arch to the right embankment, whose structure has been executed with cast in-situ reinforced concrete. Finally, the foundations of the pile are realized with "tubfix" type steel micro-piles 300 mm in diameter, around 12.0 m long.

The 6 spans subject to rehabilitation were strengthened through a continuous reinforced concrete deck, supported by the existing piers, duly reinforced using tubfix micropiles extending till to the extrados of the existing arch bridge (Figs. 8 and 9), supplemented also by local strengthening interventions on the piers based on ϕ24 injected horizontal rebars (Fig. 10). In this way, at the end of the intervention the deck behaves like a new reinforced concrete bridge, of variable thickness, whose scheme is a continuous slab on seven supports, so transferring directly the traffic loads to the existing piers and through their micro-pile reinforcement to the soil, also relieving the existing masonry arch structure, without modifying its behavior (see Fig. 10), contributing to prevent also the scour of the pier. Moreover, to limit the execution time avoiding temporary works in the riverbed, the two r.c. arches were cast on temporary trusses placed above the 200 years flood return period (see Figs. 7.b and 11), so eliminating problems during flooding, that occurred several times during the works (Fig. 12)

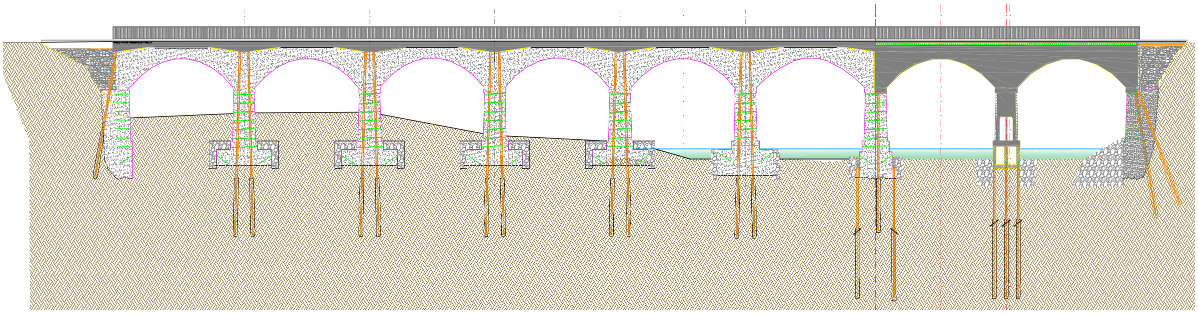

Fig. 8. Longitudinal cross section of the bridge

Fig. 9. Execution of micro-pile trough the existing piers

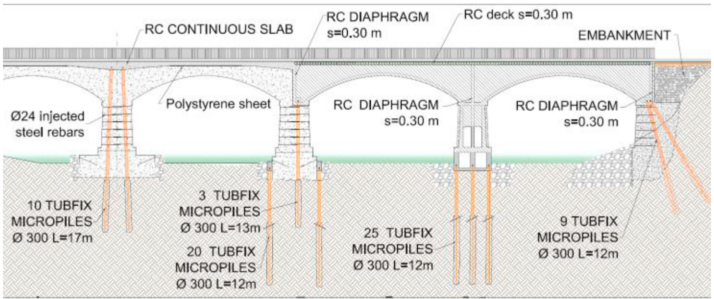

Fig. 10. Detail of the strengthening interventions

Fig. 11. Temporary trusses

Fig. 12. Flooding during temporary phase of erections

The static and seismic assessments of the bridge have been performed adopting the same actions as for new bridges, so adopting the traffic actions given in the Italian code (NTC, 2008), conforming with those given in Eurocode EN1991-2 (2003), and the seismic actions given in the aforementioned Italian code, considering a soil of category E, according to Eurocode EN1998-1 (2004) and referring, where possible, also to EN1998-2 (2005).

In defining the seismic actions, it has been considered that the bridge, for its particular position, and function, is strategic for the civil protection needs, so that it belongs to Class IV structures, according to Italian Code (NTC, 2008), so resulting in a coefficient of usage C_u=2.0. Moreover, the relevance of the bridge from the historical point of view imposed to consider a notional design working life of 100 years, so that the reference period for the structure resulted 200 years, to which corresponds, according to the Italian code, a return period of 1898 years for the evaluation of the seismic design actions for the ULS for life safety assessment.

Considering that the reference PGA on soil Category A for the considered site is 0.309 g and taking into account the presence of masonry arches, the behavior factors has been set to 1.0 both for vertical and horizontal component of the response spectra. Therefore, the dynamic linear seismic analysis has been carried out considering the horizontal and vertical elastic response spectra represented in Fig. 13.

Thanks to the full integration of the functions between new parts and existing structure, static and seismic assessment where satisfactory, confirming the effectiveness of the proposed solutions.

It must be highlighted that the adoption of variable thickness for the continuous reinforced concrete slab supporting the carriageway executed on arches not affected by the collapse, allowed also to reduce the effects of the temperature variations, so allowing eliminating expansion joints not only along the bridge, but also at the embankments.

As already said, the concrete deck transfers the loads to the existing structure only at the piers; with this aim, the deck was executed casting in situ prefabricated reinforced concrete predalles (Fig. 14), supported by intermediate sheets of soft material, polystyrene, 30 mm thick, already shown in Fig.10, previously placed above the filling of the arches of the bridge, so limitating the interactions between the new concrete deck and the existing arches (see also Fig 15).

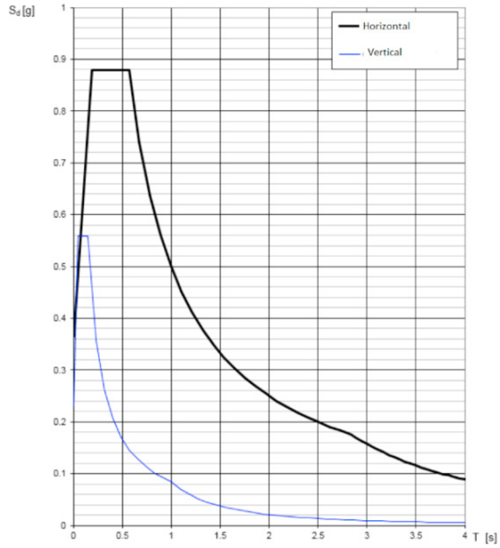

Fig. 13. Design (elastic) response spectra for bridge

Fig. 14. Preparation of the new r.c. cast in situ deck

The intervention has been carried out according to the following phases:

- Phase 1: strengthening of the external body of existing piers by means of steel bars ϕ24, spaced 0.8 m vertically and 1.0 m horizontally, duly injected, strengthening of the foundations of the existing piers with external micropiles connected to the existing foundations and protected from scour by means of stone barrier (Fig. 16) (in this phase light traffic was permitted);
- Phase 2: erection of foundation and body of the new concrete pier (light traffic permitted on the bridge);
- Phase 3: setup of alternative routes to mitigate the effects of the closure of the bridge;
- Phase 4: dismantling of prefabricated beams in c.a.p. put in place in 1961 to widen the carriageway (fig. 17) and restoration of the external surfaces (Fig. 18);
- Phase 5: disassembly of the Bailey bridge;
- Phase 6: erection of the two new spans in c.a. cast in place (Fig. 19);
- Phase 7: strengthening of the remaining part of the bridge (6 arches);
- Phase 8: erection of the new r.c. concrete deck slab (Fig. 19);
- Phase 9: finishes.

The total cost of the intervention, including the execution of the temporary pedestrian bypass, was about 1.1 M€, for a unit cost, referred to the total deck surface, of around 800 €/m^2.

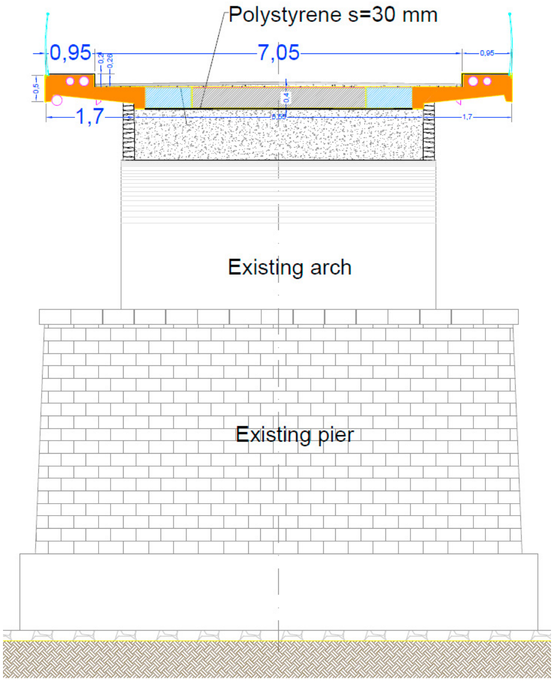

Fig. 15. Cross section of the deck

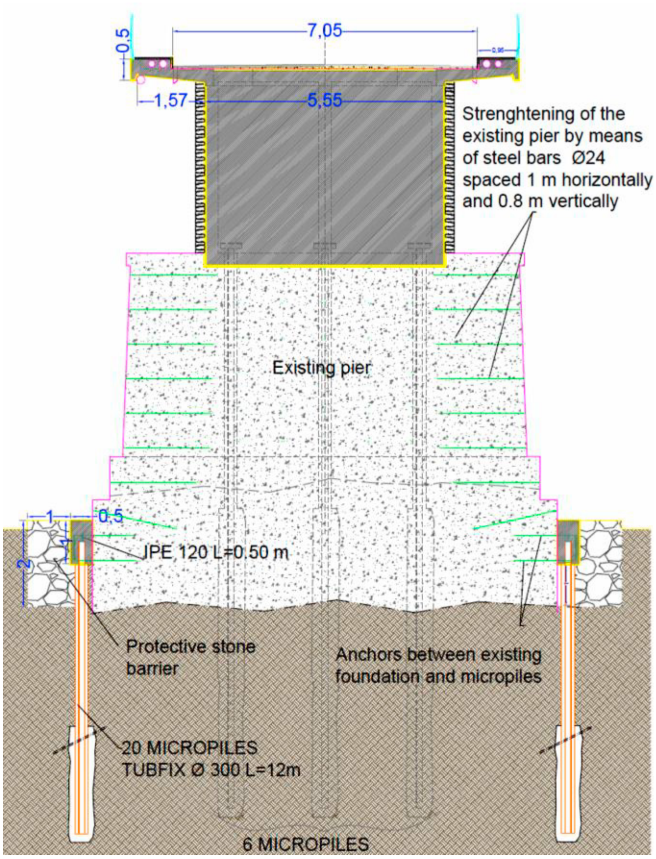

Fig. 16. Strengthening of the existing piers and foundations

Fig. 17. The bridge after the dismantling of the prefabricated r.c. beams

Fig. 18. Restoration of the external surface

Fig. 19. Preparatory works for execution of the continuous r.c. slab

3. Conclusions

In the paper, the reconstruction of the collapsed arches and the rehabilitation, strengthening and seismic upgrading of the Villafranca bridge on Magra river, has been shortly discussed.

The design of interventions aimed not only to repair the collapsed arches, but also to widen the carriageway, fulfilling at the same time severe requirements in terms of static and seismic performances. In fact the bridge is now able to withstand traffic loads and seismic actions foreseen for new bridges.

In particular, due to strategic needs, seismic actions with return period of 1898 years have been adopted, considering a soil Category E and a refence PGA on soil Category A of 0.309 g. Nonetheless, the assessment was very satisfactory confirming the effectiveness of the proposed solutions.

It must be also highlighted that the interventions have been conceived in order to preserve as much as possible the historical and cultural value of the bridge, adopting were possible reversible solutions, like for the new concrete deck, and recovering the original aspect of the bridge, anyhow not hiding the unavoidable additions, linked with the reconstruction of the collapsed parts (Fig. 20).

Fig. 20. A fisheye photo of the Villafranca bridge at the end of works

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