The Reinforced Arch Method for the life of the ancient bridge of Omegna

L. Jurina

Politecnico di Milano, Milan, Italy

E. O. Radaelli

JURINA e RADAELLI Studio Associato, Milan, Italy

D. Coronelli

Politecnico di Milano, Milan, Italy

ABSTRACT: Extending the life of historic masonry bridges frequently requires strengthening of arches showing damage or limited load bearing capacity. The "Reinforced Arch Method" (RAM) uses a cable on the extrados and/or the intrados, prestressing the blocks. A recent application is the xv century bridge (Ponte Antico) in Omegna (Verbania, IT) along a route of an historic quarrying district. Originally formed of two stone arches, today a damaged structure with one arch remains after a 20th century collapse. The structure is modelled numerically and assessed in the present condition and with the strengthening by four extrados cables, comparing the results of a linear elastic finite element model and limit state verifications, and static limit analyses with optimization of the thrust line and limit load. The strengthening and the intervention proposed for the collapsed arch are discussed, in relation to their new life as a footbridge on a touristic route.

1 INTRODUCTION

The necessity of interventions on arch structures is frequent in the field of the strengthening of historic masonry bridges showing damage conditions or limited load bearing capacity for live loads. The damage is generally related to the limited tensile and flexural strength of masonry, particularly in the presence of non-symmetrical gravity loading, horizontal seismic actions or, as in the case considered in this paper the effects of water pressure during a flood.

Historic bridges suffer from the environmental actions along centuries of life, and the lack of maintenance. Climate change causes flooding and extreme flow conditions causing increasing threats for these systems (Drdacky and Slizkova. 2012).

A strengthening technique denominated "Reinforced Arch Method" (RAM) has been proposed by the first author (Jurina, 2012). The method consists in the laying of a tension cable on the extrados and/or the intrados of the arch, in order to prestress the blocks thus providing flexural strengthening. The cable tension brings the system in action by applying a set of radial forces on the arch, leading to a reduction of the thrust-line eccentricity, thus avoiding or anyway delaying the formation of flexural hinges. The over 500 experimental tests carried out on scale models have demonstrated the validity of this method, using arches with different geometries: roman, pointed and segmental arches.

A recent application of the RAM method, with ongoing worksite activities, has been the historic bridge on the Strona torrent in Omegna (Verbania, IT). This construction which dates back to the xv century was originally formed of two stone arches, each measuring 13.30 metres, along a route of an historic quarrying district. Today a damaged system with only one arch remains after a collapse at the start of the 20th century. Restoration and strengthening activities have been undertaken. Within the structural assessment and design, the structure has been modelled numerically both in the present condition and with the strengthening by way of four extrados cables, pre-tensioned by 30KN each. The paper shows the assessment results obtained by a linear elastic finite element method, and limit analyses with a static approach to calculate the collapse load multiplier, using a recently developed calculation model.

The intervention proposed for the masonry arch of the bridge that collapsed is discussed, in relation to its compatibility with the surviving structure and its new life as a footbridge on a touristic route.

2 BRIDGE DESCRIPTION AND CONDITIONS

The bridge over the Strona torrent is located in the municipality of Omegna (VB). The construction dates back to the 15th century, by the will of Duke Gian Galeazzo Sforza, and consisted of two stone arches. The eastern bank humped back arch collapsed at the beginning of the 20th century.

(a) (b) (c) (d)

Figure 1. Life of the bridge (a) in the early 20th century (left); (b) in 1952 after the collapse (right) of the eastern span; (c) conditions prior to the restoration works; (d) rendering of the restoration project.

The arch span is 13.6m, the cross section thickness 0.4m and width 2.1m. The standing Western wing walls extend 6m on the bank. The central support is on rock elevating above the water flow. The collapsed span to the East corresponded to a lower elevation above water flow; the collapse was related to erosion of the foundation on this bank side with the torrent in full spate. Fig.1a shows the conditions prior to the collapse. Fig.1b-c show the conditions in recent times, after the collapse and prior to the start of restoration works. Further damage of the walls and parapet above the standing arch is visible. Fig.1d shows a rendering of the restoration project described in the next section.

3 INTERVENTION AND RECONSTRUCTION

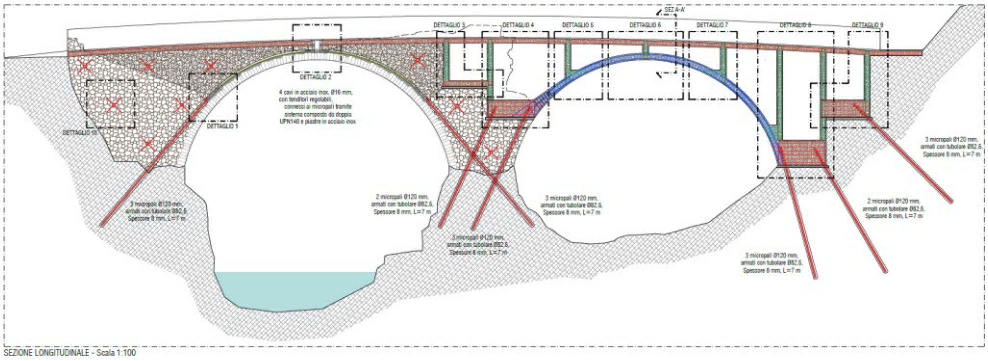


Figure 2. Structural restoration with cable layout and anchoring, and new bridge span.

The intervention (Fig. 2) includes foundation strengthening by piles reaching rock at 4.5m depth, strengthening of the stone arch (RAM), spandrel and wing walls ties, reinforced concrete arch construction and a reinforced concrete slab for the whole length of the bridge roadway. The missing span is replaced with a reinforced concrete arch structure faced with stone. This choice, approved by the Ministry of Cultural Heritage, was the fruit of the comparison of different alternative solutions (see section 6).

4 THE REINFORCED ARCH METHOD (RAM)

The main purpose of the "RAM – Reinforced Arch Method" is to modify the distribution of loads, acting on the arch, vault or dome so that the combination of the old loads plus the new loads can be the "right one" for the given and known geometry of the masonry structure. It's worth to mention that cables can be applied with similar effects either on the extrados or the intrados of the arch, obtaining the same consolidation results. In the first case (i.e. at the extrados) cables can be simply laid down on the masonry or, if need-ed, a thin layer of fiber reinforced mortar can be in-terposed to regularized the surface. In the second case (i.e. at the intrados) some connection devices are needed to transfer the loads between cables and masonry.
Experimental and numerical results showed a linear relationship between the load multiplier factor μ and the tension force N applied to the cables.
The Reinforced Arch Method, in its several variations, is an innovative solution that adjusts many different geometries, with acceptable aesthetic results and other important advantages, such as: necessity, lightweight, minimally invasive, removability.

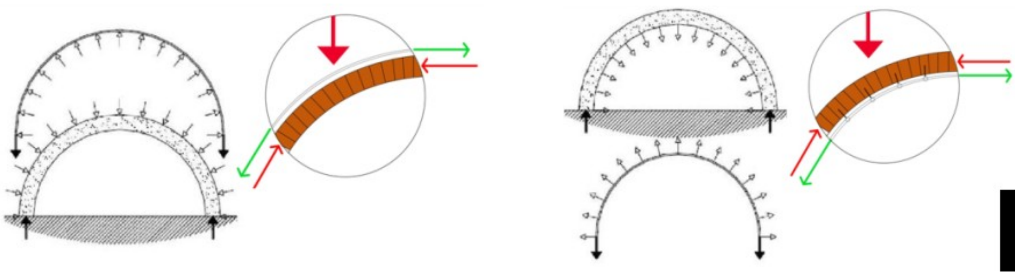


Fig.3. Radial forces applied on the arch by means of RAM (extrados and intrados)

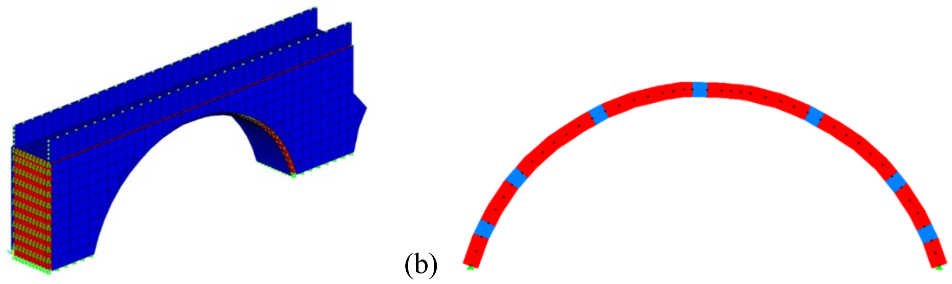
5 MODELS FOR ASSESSMENT AND DESIGN

5.1 *Materials*

The arches, spandrels and abutments are made of roughly cut stone masonry. The fill is made of rubble with an estimated unit weight of 10 KN/m^3. Material properties were determined with the Italian Code NTC2018. The characteristic compression strength is 3.2 N/mm2 and the factored strength for ultimate limit state verifications is 0.95N/mm2. For shear the friction coefficient is equal to 0.4 and the characteristic cohesive bond strength 0.065 N/mm2 (factored 0.02 N/mm2). The strengthening ties are made of stainless steel INOX AISI 316, diameter Φ16 mm with 222 wires, grade 1470 MPa.

5.2 *Finite Element analysis and verifications*

The design and verifications were carried out based on the Italian code NTC 2018. Four linear elastic FEM models were set up using SAP2000 (CSI, 2019) – see Fig.4:
1) 3D model with plane shell elements for the existing arch and spandrel and wing walls, for static loading; this corresponds to the as built configuration prior to the intervention.
2) 3D model with the addition of brick elements for the fill; this corresponds to the strengthened existing stone masonry structure;
3) 2D model with one-dimensional frame elements for the new RC arch span, for static loading;
4) 3D model of the whole bridge for seismic verifications.



(a) (b)

Fig.4. Finite element model: (a) the western span (model n.2); (b) the arch barrel and reference sections.

Flexural resistance verifications were based on the eccentricity *e* calculation, from the calculated axial force and moment in the arch cross-section; cracking occurs for e >t/6 and loss of resistance for e > t/2 (t = cross-section depth).
The strengthening effect is considered by an increase of the axial force in each cross section, equal to the tension in the cables.
The load conditions were the gravity loading ultimate limit state and the seismic actions; the latter are low and are not discussed in the following.

Table 1 - FEM analyses, internal forces and normal stress

A) Non-reinforced bridge.

Section	Comb.	N (KN)	M (KNm)	e=M/N (m)	condition	Stress σ_{N+M} * (MPa)	Strength f_d (MPa)	σ_{N+M} / f_d
1	A	182	27	15	Cracked	1.39	0.95	1.46
	B	260	29	11	Cracked	1.09	0.95	1.15
2	A	163	39	24	e > h/2		0.95	
	B	221	41	19	Cracked	5.37	0.95	5.65

3	A	147	1	1	e < h/6	0.21	0.95	0.22
	B	156	1	1	e < h/6	0.21	0.95	0.22
4	A	111	30	27	e > h/2		0.95	
	B	157	31	20	Cracked	20.10	0.95	21.16
5	A	144	2	1	e < h/6	0.21	0.95	0.22
	B	203	5	1	e < h/6	0.33	0.95	0.35
6	A	158	34	10	e > h/2		0.95	
	B	231	35	10	Cracked	1.61	0.95	1.69
7	A	242	29	12	Cracked	1.09	0.95	1.15
	B	176	28	16	Cracked	1.63	0.95	1.72

B) RAM reinforced bridge.

Section	Comb.	N (KN)	M (KNm)	e=M/N (m)	condition	Stress σ_{N+M} * (MPa)	Strength f_d (MPa)	σ_{N+M} / f_d
1	A	272	27	10	Cracked	0.99	0.95	1.46
	B	350	29	8	Cracked	1.06	0.95	1.15
2	A	253	39	15	Cracked	1.92	0.95	
	B	311	41	13	Cracked	1.56	0.95	5.65
3	A	237	1	0	No cracking	0.31	0.95	0.22
	B	246	1	0	No cracking	0.32	0.95	0.22
4	A	201	30	15	Cracked	1.28	0.95	
	B	247	31	13	Cracked	1.07	0.95	21.16
5	A	234	2	1	No cracking	0.32	0.95	0.22
	B	293	5	2	No cracking	0.44	0.95	0.35
6	A	248	34	14	Cracked	1.33	0.95	
	B	321	35	11	Cracked	1.17	0.95	1.69
7	A	332	29	9	Cracked	1.03	0.95	1.15
	B	266	28	11	Cracked	1.00	0.95	1.72

A = combination for maximum flexural stress; B = combination for maximum axial force effect.

(*) calculated with no tension assumption, linear stress distribution

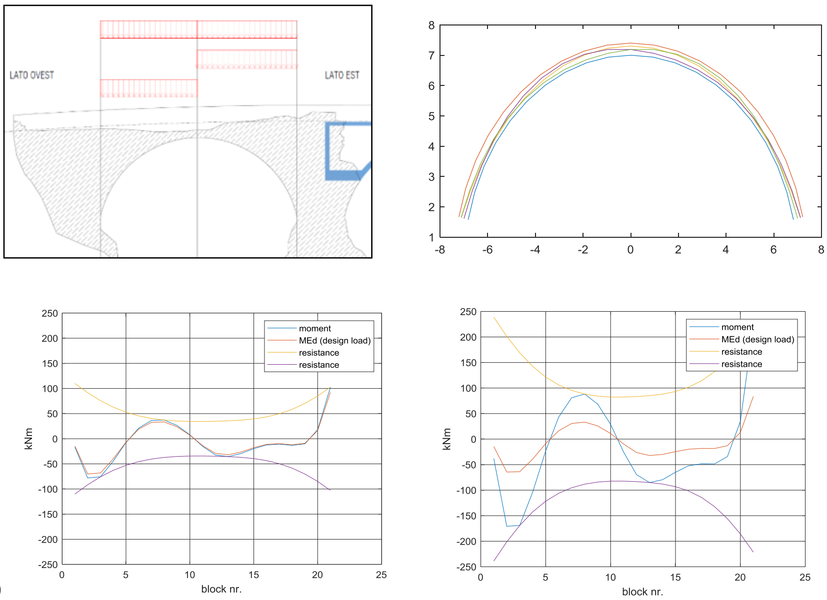
5.3 *Limit analysis*

A 2D limit analysis model has been developed. The arch is divided into rigid blocks separated by interfaces where flexural and sliding verifications are carried out. No-tension interfaces are used. Finite compression strength is considered, limiting the thrust line position within a band interior to the block depth. For the shear interface a constant friction coefficient equal to 0.4 is used. A linear program is solved obtaining the maximum static multiplier, corresponding to the limit load and the optimized thrust line position.

The effect of the RAM strengthening is modelled as resultant radial forces on each block, calculated as components of the tie tension forces along the extrados with a circular shape.

The model is set up with 20 blocks for the arch; the remaining parts are modelled as loads:

- Case 1: arch weight (20 KN/m3), fill weight (10 KN/m3), spandrel walls (18 KN/m3) and live load.
- Case 2: the same as Case 1, with the addition of radial forces transferred by RAM ties.



(a) (b) (c) (d)

Fig.5. (a) Variable load distributions and (b) strengthened arch lines of thrust for limit loads. Comparison of moment load effects for arch (c) without strengthening (combination 1, limit multiplier = 1.1) and (d) with RAM strengthening (combination 1, limit multiplier = 2.64).

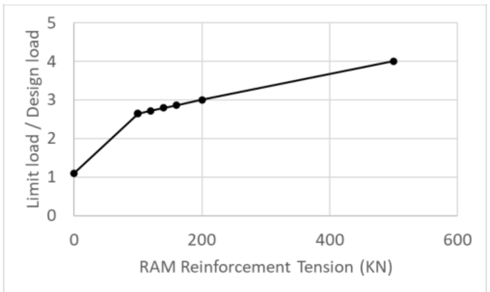


Fig.6 Increase of the limit load relative to design load as a function of RAM reinforcement tension.

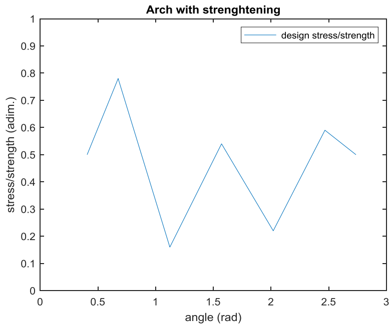
Fig.5 shows the comparison of design moments in combination 2 and cross-section resistance for the non-reinforced and reinforced configurations; in addition the moment distribution for the limit load is shown. Fig.6 shows the increase of the limit load relative to the design load, for increasing tension of the reinforcement. The masonry strength increase given by bed-joint repointing and injections is considered as well, in the passage from non strengthened (tension = 0) to strengthened cases.

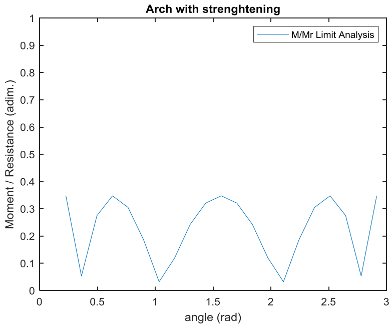
5.4 *Comparison of results*

The project allows the comparison of different analysis and verification methods. Elastic finite element analysis sets up a model with geometrical features closely related to the survey results for arch vault, spandrel walls and fill. With a choice of elastic material properties the model furnishes an equilibrium solution for selected load distributions. This can be used for the structural verifications prescribed by codes, such as the Italian national specifications, under the assumptions of no-tension and limited compression and shear strength. The assumed elastic behavior highlights critical structural conditions by elevated eccentricity of the normal force in the arch sections, resulting in very high compression stress or even eccentricity beyond the section limits.

Limit analysis model considers only the arch as load bearing element. The cross section limit moments are calculated with finite compression and no tension strength, without the possibility of exceeding the cross-section resistance with a model closer to the masonry arch mechanical response.

Fig.7 shows the comparison of the ratio of maximum compression stresses and strength in the FEM based design (section 5.2) with the ratio of the design moments to the resistance for the limit analysis (section 5.3). The design moments are obtained dividing the limit moments by the maxmum load multiplier obtained. The two models are based on different assumptions. The limit state verification are carried out for the maximum compression and shear stresses compared to the corresponding strength. The stress distribution is linear in the compression zone. This leads to determine more critical conditions, particularly for the non-reinforced arch (see Table 1) and for the reinforced arch as well.

(a)




(b)

Fig.7. Comparison of assessment results for the resistance of the RAM reinforced arch, full load combination 1 (a) ratio of design stress and strength (from elastic analysis); (b) ratio of design load moments to moment resistance (limit analysis).

6 DISCUSSION

The life of the bridge started in the XV century in relation to mining and quarrying activities of the Strona valley. The intervention was urgent because of the risk of collapse of the remaining span, damaged by the flow of the Strona torrent. A new phase will start with the restoration and strengthening of the bridge, aiming at providing a path for pedestrians within a cultural and touristic project.

The solution chosen for the span that collapsed was the result of a multidisciplinary work in collaboration with the Ministry of Cultural Heritage. The structural and the architectural designers, evaluated multiple solutions relating to the method of reconstruction of the collapsed span; examples of projects in the practice were taken into consideration (Fig.8). In fact, different structural materials were considered, including masonry, steel and concrete, analyzing their advantages and disadvantages in terms of ease of execution, durability, maintenance and, last but not least, costs. The final choice was the use of reinforced concrete, finished with roughly cut stones.



Fig.8 - Study of alternative solutions: examples of projects: a) medieval bridge in Su Ponti Ecciu - Allai (Oristano) b) Pont Trencat (Catalunya); c) Roman bridge in Sogliano al Rubicone (www.jurina.it).

7 CONCLUSIONS

The following conclusions can be drawn, based on the case study shown, concerning the RAM strengthening system, analytical methods for verification and design solutions to extend the life of the historic bridge in Omegna.

The strengthening system provides an increase in resistance proved by two different verification methods, maintaining the features of the original construction where this was still standing.

Thus the project allows the comparison of different analysis and verification methods. Finite element analysis provides a good geometric model with relative ease, using available commercial packages. The elastic solution with equilibrium, though different from the real behavior of a masonry structure, gives indications for design based on a lower bound approach. These can be integrated with a limit analysis lower bound model, with a more simple geometry but assumptions closer to masonry response. Thrust line analysis with limits for eccentricity can be easily set up e.g. using a spread sheet, predicting the limit load. Developments considering limited compression strength and shear sliding within an optimization solution have been shown in the paper.

The solution chosen to reconstruct the part that collapsed was the result of a comparative study considering different configuration and materials. The elements in favor of a reinforced concrete system with a stone facing were the structural stability and cost of this solution.

ACKNOWLEDGEMENTS

The authors acknowledge the role of the project committee coordinated by Don Gianfranco Lanfranchini, the financial support provided by CARIPLO, 2019 “Interventi emblematici”, the construction works carried out by Panizza 1914 srl (Trenzano, BS), and architects A. Baldioli and G. Ciuffo

REFERENCES

CSI (2019) CSI Analysis Reference Manual – SAP 2000 Advanced Research, Computers and Structures Inc.

Drdácký M. , Slížková Z. (2012) “Structural strategies and measures reducing flood action on architectural heritage” www.witpress.com, ISSN 1743-3517 (on-line) WIT Transactions on Information and Communicatio n Technologies, Vol 44, © 2012 W IT Press doi:10.2495/RISK120221

Jurina, L. (2012) "Strengthening of masonry arch bridges with RAM - Reinforced Arch Method", Bridge Maintenance, Safety, Management, Resilience and Sustainability - Proceedings of the Sixth International Conference on Bridge Maintenance, Safety and Management, p.1063-1070

Ministero degli Interni (2018) NTC2018 - Norme Tecniche per le Costruzioni. D.M.17 Gennaio 2018