CRITICAL INFRASTRUCTURES IN ITALY: STATE OF THE ART, CASE STUDIES, RATIONAL APPROACHES TO SELECT THE INTERVENTION PRIORITIES.

Marco di Prisco

Department of Civil and Environmental Engineering, Politecnico di Milano, Italy

Corresponding author email: marco.diprisco@polimi.it

Abstract

The collapse risk is a factor associated to the construction of any structure or infrastructure: maintenance and monitoring are actions aimed at reducing this risk, but they cannot reduce it to zero. The lack of a plan of maintenance procedures, established by the designer at the construction time, jointed to the neglecting of robustness principle in the conceptual design as well as of some possible extreme events correlated to the infrastructure far-field are the main causes of the collapses observed. The lack of a generalized consent of the technical and scientific community on the procedures to be pursued at the end of the expected life contribute also to increase the scattering of safety conditions in many infrastructures used in the road traffic. After a generalized discussion on the main causes of collapse, a specific analysis on Italian infrastructure situation aimed at highlighting the significant difference between the railway infrastructures from the road ones is proposed. An analysis of few collapse case studies like that one of Annone overpass, or that one on SP10 crossing the highway A14 near Ancona, as well as a discussion on the uncertainties in the diagnosis of historical bridges like Azzone bridge or on the critical aspects met in the design of intervention on relatively old bridges made of steel or post-tensioned reinforced concrete will be instrumental at giving a faceted overview of this complex problem that the next Model Code will try to deal with an organic vision. Finally, a brief nod on the main activities in progress to overcome this critical situation at both national and regional levels is outlined.

Keywords: bridge collapse; identification tests; priority intervention strategies, mechanical characterization; steel-bar oxidation measures; diagnostics techniques; structural robustness; safety indexes.

1. Introduction

The collapse of Polcevera bridge in August 2018 was the sixth collapse in the last 5 years in Italy after Carasco (2013), Annone (2016), Ancona (2017), Fossano (2017) and Bologna (2018) that occurred only one week before the Genoa one: it shocked the people all over the world for the huge loss of life, and the Civil Engineering community because it represented a masterpiece of reinforced concrete structure historical design. It also highlighted the need of an urgent therapy to manage the worldwide infrastructural heritage, mainly consisting in R/C and P/C structures.

Each bridge is always a unique prototype due to its boundary conditions, material adopted, execution procedure and traffic load applied. Service life expectance is regarded in the codes as a reference to evaluate the loads applied to the infrastructure according to a probabilistic approach, as well as to design the structure detailing aimed at improving the durability of the resistant mechanisms which guarantee both the functionality and the structural safety: it does not correspond to the real life of the infrastructure. Often media wonder why modern bridges appear less durable than ancient bridges, forgetting to compare the amount of resources employed in their construction, as well as the completely different geometries and boundary conditions which often characterize those bridges. In

the Italian infrastructure heritage, it is possible to detect roman bridges, middle age bridges, as well as steel and R/C bridges, more than one hundred years old, in very good shape.
The crucial point is the correct evolution of the infrastructure in the time, made by a consistent design correlated since from the beginning to realistic loads and boundary conditions, a careful maintenance of the structure in the time and a continuous survey to the consistency, in the time, of the acting loads with the designed ones. The need for modern infrastructures to reduce the costs, dosing the resources employed on the basis of a structural design able to take into account the safety requirements introduced in the Codes, implies a basic sustainability, but also could involve a larger risk hidden in a wrong evaluation of the real boundary conditions or of the applied loads, a poor care of the detailing, like the rainwater channelling, a bad execution, a wrong choice of the materials, a defective care in the time. Moreover, the ancient still standing bridges are the best built ones and they did not use any traction, because they were based on compression stress flows. On the contrary, modern engineering adopts steel to resist to tension stress flows, that allow much more daring geometries. This is obvious in steel structures where, if well-designed, the steel profiles could be easily protected in the time by suitable subsequent paintings, but it is true also for R/C and P/C structures where steel is usually embedded in a protective environment guaranteed by concrete pH, thus reducing the maintenance costs, but at the same time it is often hidden and where locally exposed to aggressive agents it needs careful treatments. Unfortunately, these critical points are not always easily to detect: this is the major risk of cement-based structures, aggravated by a lack of knowledge at the time of the economic boom constructions, gap that has nowadays practically filled. The design of durability has to be coupled with a careful respect of the detailing in the execution, as well as to the correct check of a good execution and a well-conceived maintenance user manual able to indicate, taking advantage from the knowledge of the original designer, the critical points which have to be monitored and surveyed along the time of the structure life. The main problems observed in the roadway bridges in Italy are motivated by the failing of this practice, as well as the good conditions of the railway bridges is due to the long-term observance of it.

In an invited lecture at Politecnico di Milano on March 2017, W. Philip Yen, chair of the International Association of Bridge Earthquake Engineering and former principal bridge Engineer of the U.S. Department of Transportation of the Federal Highway Administration (Tobias et al. 2014), analysing in detail the causes of bridge collapses occurred in thirty years from 1980 to 2012 on a total number of around six hundred thousand highway bridges, declared a total of 1062 collapses. The causes of these collapses (Fig.1) were due mainly to flood, collision and scour which alone count around 62% of the total amount of failures. It is worth to note that the loads usually taken into account by structural engineers, like wind, earthquake and conventional loads are responsible for only 4% (around forty collapses). This percentage is aligned to the expected failure probability, usually assumed in industrialized countries equal to 10^{-4} - 10^{-5}, if we start from a theoretical percentage of failure of 10^{-6} and then we take into account the safety reduction due to execution uncertainties. On the contrary, overloads, internal causes (i.e. mistakes at the design or at the execution level) and scour count 42 % over the total and appear too many, if compared with the expected values. This observation highlights as these causes are not adequately considered by designers; similar consideration could be extrapolated for environmental degradation (7%) and fire (3%).

In figure 1 it is also possible to recognise as the six last collapses occurred in Italy in the last five years are due to different causes and, taking into account a total number of about fifty thousands of bridges in Italy, they are less than those occurred in U.S. At the same time, the two failures mainly due to environmental degradation suggest an underestimation of maintenance care in the Italian roadway bridges, or an underestimation of the aggressive agents in the solution proposed.

Similar considerations are resumed in Wardhana, K., Hadipriono (2003), published more than fifteen years ago. In the following sections, first a general overview of Italian infrastructures is given, then two collapses are briefly discussed to highlight some weak points, which could be potentially responsible of disasters. The uncertainties and the critical aspects that can be met in the analyses of ancient and modern-aged bridges as well as the in-progress procedures to face in Italy this complex reality complete the overall picture drawn in this modest attempt aimed at representing the hard frame of the choices in which the civil engineering community is called to internationally operate.

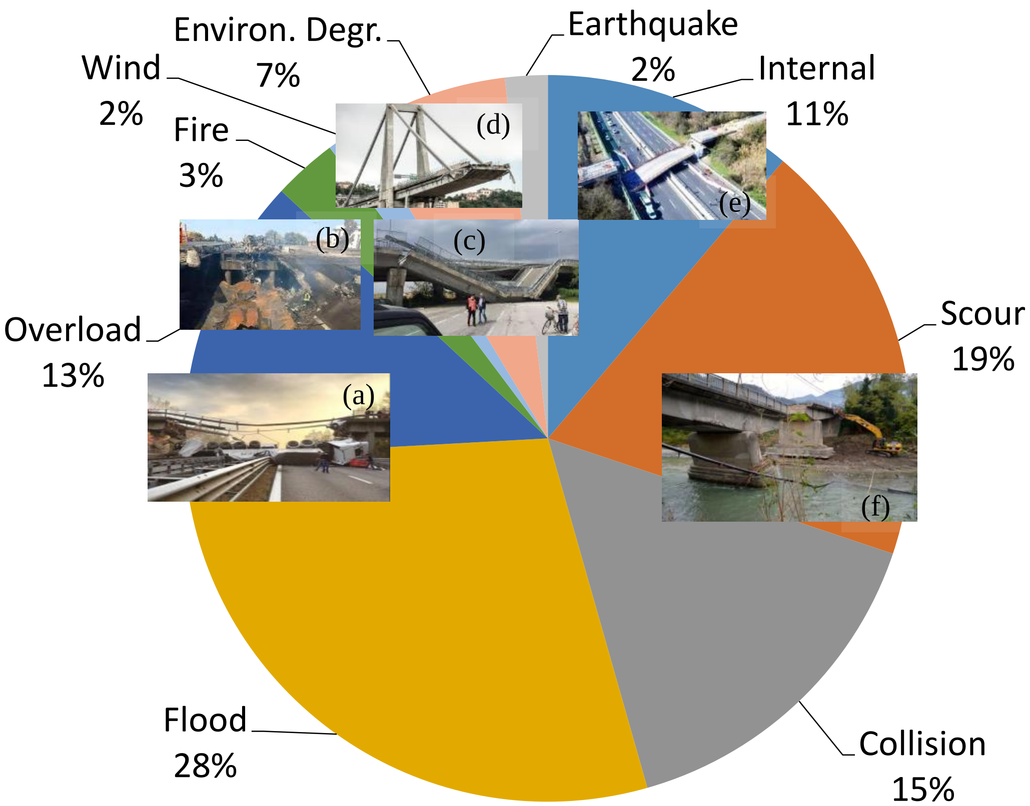


Figure 1. Bridge collapse causes according to W.P. Yen according to the data of the US Department of Transportation of FHA (Public lecture given at Politecnico di Milano in March, 2017). The collapse pictures refer to (a) Annone overpass (overload); (b) Bologna (fire & blast); (c,d) Fossano and Genova (environmental degradation); (e) Ancona (internal); (f) Carasco (scour).

2. Railway and road infrastructures in Italy

The Italian infrastructural heritage has been entrusted to several infrastructure management Companies: for the railway infrastructures we count 23 agencies, but there is only one dominant player, RFI that controls about 83% of the total railway length. Due to the morphology of Italy, we have about one bridge or viaduct every two kilometres (Table 1). In Italy the first railway line Napoli-Portici of about 7.25 km was built in 1839 in the kingdom of the two Sicilies. The history justifies a quite large variety of artefacts which considers masonry, steel, r/c and p/c structures (Fig.2). Even if RFI was created only in 2001, the control and the care of this heritage have been always oriented to durability in Italy: every practitioner involved in the design and in the maintenance of railway infrastructures knows the prudence and the severe requirements which were always requested in all the phases. The current procedures to inspect the artefacts (Fig.3) were recently introduced: the D.O.M.U.S. system was aimed at homogenizing the judgements, planning the optimization in the interventions, conserving and sharing the results. Besides the progressing digitalization, also the use of modern inspection techniques based on drones and automatic catalog of defect with relative weighting (Fig.4) are progressively substituting the more traditional human activities reducing often the cost of these operations.

Table 1. RFI bridge infrastructural heritage.

Total railway length (km)	Total artefacts n°	Viaducts n°	Bridges n°	Underpasses n°
17000	19000	1575	8085	10162

Figure 2. Bridges and viaducts maintained by RFI: several typologies made of masonry, r/c, p/c and steel (courtesy of ing. Andrea Vecchi shown in the Italian workshop organized by CTA, IIS, AICAP and CTE at Milan in 2019.

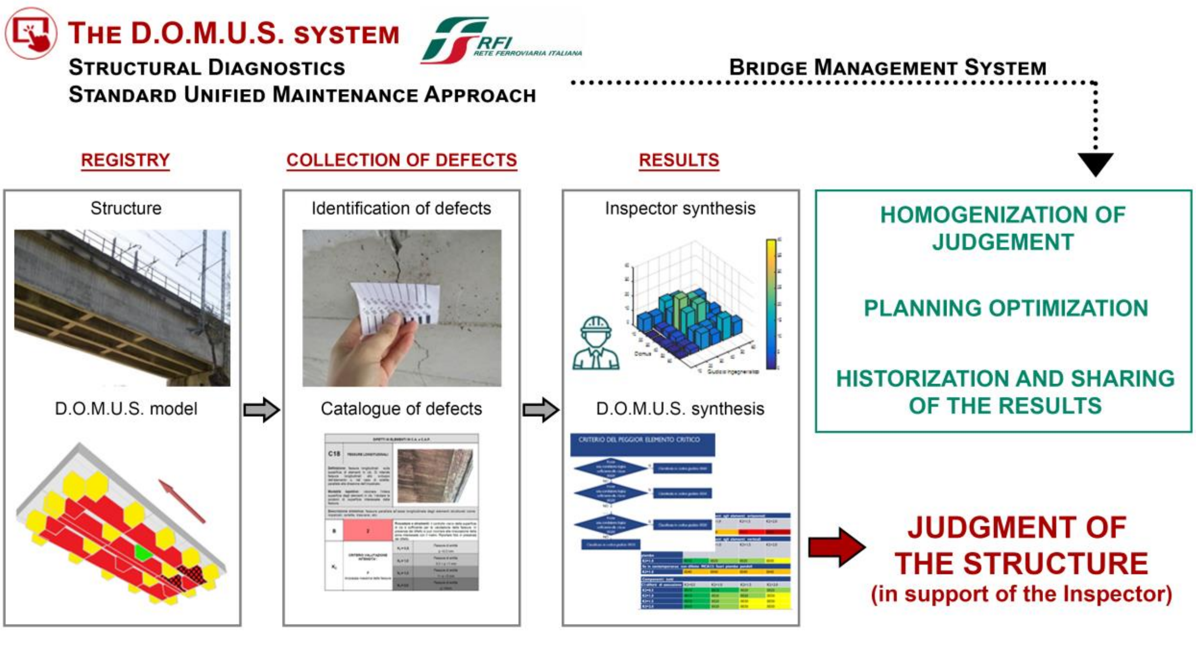


Figure 3. Maintenance control approach adopted by RFI: the D.O.M.U.S. system.

The roadway system in Italy counts around 837.493 km and is divided in highways (A), state (SS), regional (SR), provincial (SP) and municipal (SC) roads. ANAS, the National Autonomous Agency for the roads, is the main player (Tab.2). The change in the time of the owner and of the manager of the different road sections is often one of the reasons of possible degradation in the time of the infrastructure: it was the case of Annone overpass, because the Lecco province was convinced that the overpass structure would be managed by ANAS, while the documents confirmed that due to a not-

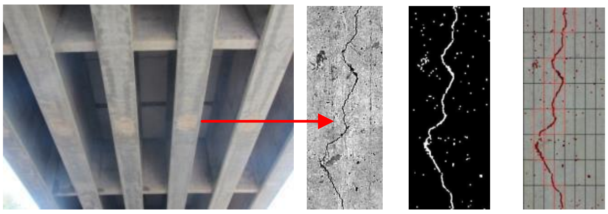
(a)

(b)

Reference Standard frame

Procedure DTC PSE 44 1 0 and Operational Methodology DPR MO SE 03 1 0

DTC PSE 44 1 0 *(since 06/06/2016)*
DPR MO SE 03 1 0 *(since 01/01/2018)* (c)



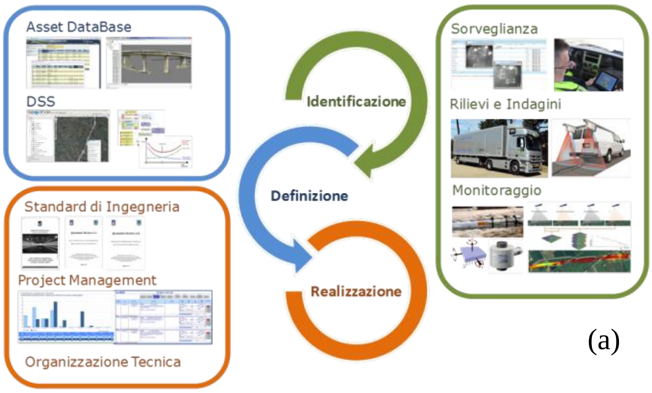
(d)

Figure 4. RFI procedures for control visits and relative recording: (a) use of drones; (b) operational drones; (c) reference standard procedures; (d) automatic catalog of defect and relative weighting.

regular free height of the overpass over SS 36, the artefact was never transferred to ANAS control and remained before to Como province and then, with the birth of Lecco province, it was transferred to this one, even if several accidents occurred on SS36 for the hitting of oversize vehicles against the intrados structures forced ANAS to manage the repairing operations. A recent investigation carried out in ANAS, highlighted that for 1425 overpasses over ANAS controlled roads the ownership is not clear: the huge number underlines, first of all, the need to overcome this unacceptable situation. Looking only to the highway system that counts 7472 km, it is controlled by 32 companies and ANAS controls only 12% of the overall road path. The amount of money of about 250 M€/year, given to the agency without any multi-year planning until the disaster of Annone overpass (2016), was able only to cover the most urgent critical issues and never allowed the Agency to elaborate a strategic plan for maintenance of the infrastructural heritage. Moreover the heterogeneous system of control favored a not fully-controlled design, manufacturing and conservation rules, giving rise to a most vulnerable system, if compared to the railway one.

Table 2. ANAS bridge infrastructural heritage.

Total roadway length (km)	Total artefacts n°	Viaducts n°	Bridges n°	Underpasses n°
30000	-	-	14603	-



(a)

(b)

Figure 5. ANAS Bridge Manage System: (a) scheme of the procedure; (b) geolocation of structures with higher degradation rank (IRD).

The inspection procedure until 2016 followed the Ministerial Circular n°6736/61/A1, dated 19 July 1967: the main points are the execution of a quarterly inspection, carried out by technicians and an annual inspection on the most important artefacts performed by engineers. The Circular illustrates the procedures for its execution and provides for the compilation of an inspection report and a form with the data of the product and its main characteristics. In July 2016 a new business multi-year plan was presented for the period 2016-2020 with around 23 Billion€ of financing: the maintenance could be based in 5 years on about ten times the yearly resources available before. For the bridges and the viaducts a new inspection procedure and a new Bridge Management System (BMS) were introduced.

The renewed vision of road management overcomes the logic of episodic or emergency intervention and thanks to a correct reading of the characteristics of the infrastructure and of the events that occur on it, or around it, intervenes programmatically preventing security criticalities, functionality or network comfort (Fig.5a). The local RAM model classifies the need for intervention for each Bridge / Viaduct by calculating a Degree Relevance Index (IRD) and a Future Degradation Index (IDF), combining different information: artefact degradation, its intrinsic vulnerability, environmental parameters and serviceability parameters.

Another source of criticality must be searched in the applied load evolution. A general increase can be observed all over the industrialized countries since the sixties. The Standards registered this evolution, but even if in 1980 a decree established the obligation to indicate the category and year of bridge construction, it was never respected. To appreciate the change in the load requirements until 2008, figure 6 shows for a two-line road (one for each direction of travel) what change in terms of bending moment, shear and torsion for the two categories and a simply supported span configuration.

The huge increase of the loads for an overpass with a span in the range between 15 and 20 m long can clearly justify the collapse of Annone bridge (Fig.7), that was designed in 1960-1962 for a II category bridge and was used for more than 10 years for exceptional loads up to 108t. In fact, in 2006, to reduce the number of circulating trucks with the aim to favour the environment, these kind of

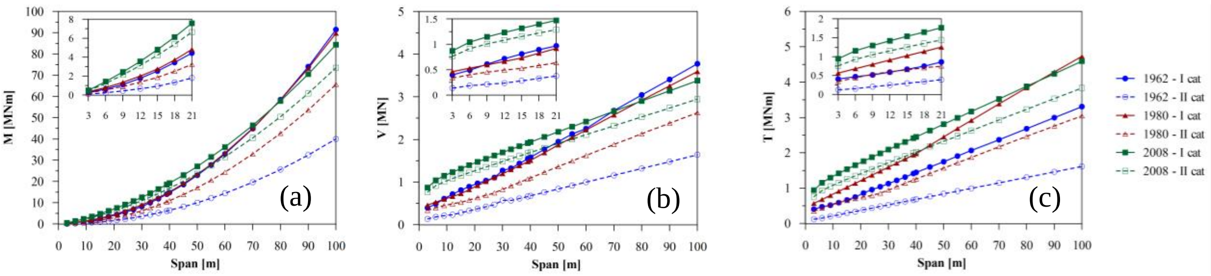


Figure 6. Load evolution for a simply supported span with one line for each direction of travel, according to Italian standards from 1962 to 2008: effects on (a) bending moment; (b) shear; (c) torsion.

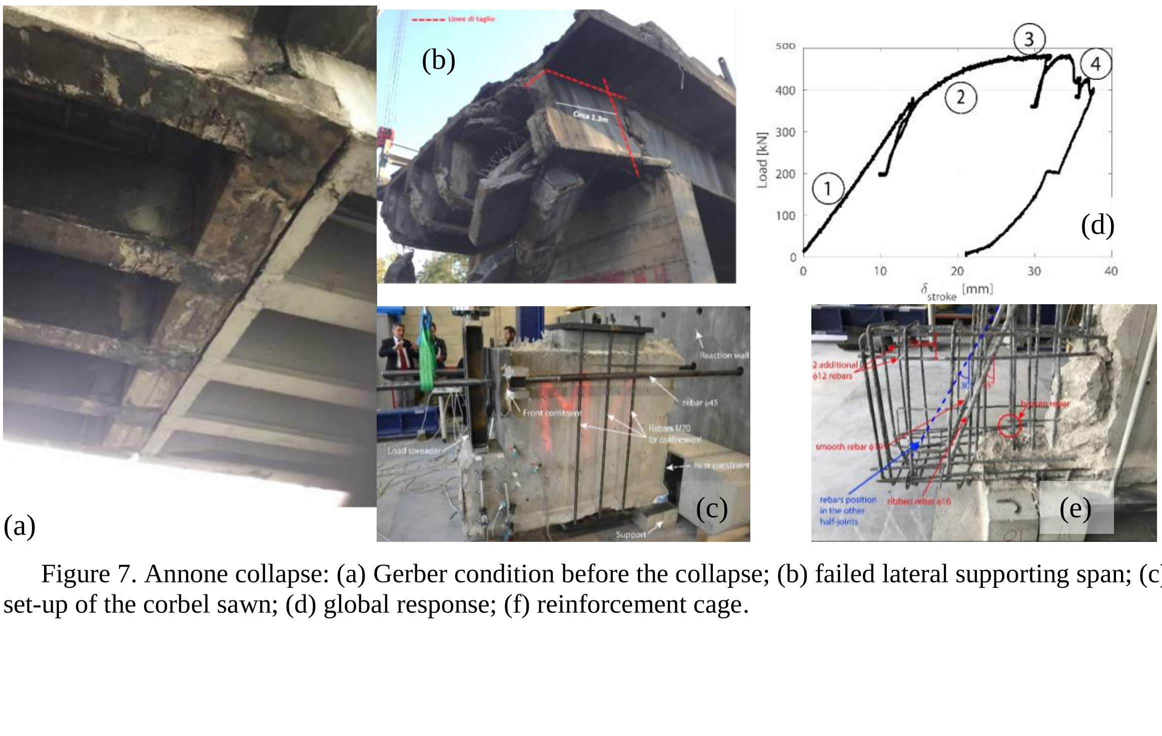


Figure 7. Annone collapse: (a) Gerber condition before the collapse; (b) failed lateral supporting span; (c) test set-up of the corbel sawn; (d) global response; (f) reinforcement cage.

vehicles were admitted to circulation with the need to request special periodic or occasional permissions, without having developed a robust identification of the bearing capacity for each artefact. The lab tests, carried out in the occasion of the inquiry ordered by the prosecutor (di Prisco et al., 2018), clearly showed that the bearing capacity of the dapped-ends which represented the weak point of the structure was significantly penalized by the environmental degradation, but the exceptional loads applied could not absolutely satisfy the required safety coefficients of the original design, even without any degradation and in the full respect of the prescriptions given in the released permission. As usual, the collapse was due to the combination of these circumstances. At the same time, the collapse occurred on the A14 (Fig.8) showed how dangerous could be to operate in a construction site with workers not sufficiently prepared: the lifting of a span to increase the free length of an overpass, carried out by using neoprene plates instead of steel plates, without the introduction of any retained system, even if specified in the design procedure, jointed to the lack of a clear procedure to manage any unpredictable event and the excessive speed of the vehicle caused the loss of two people. These two examples show as always a failure is justified by the contemporaneity of different causes, but clear and observed rules can strongly reduce the failure risk, even if it cannot be reduced to zero as some decision-making people have frequently declared in commenting these events.

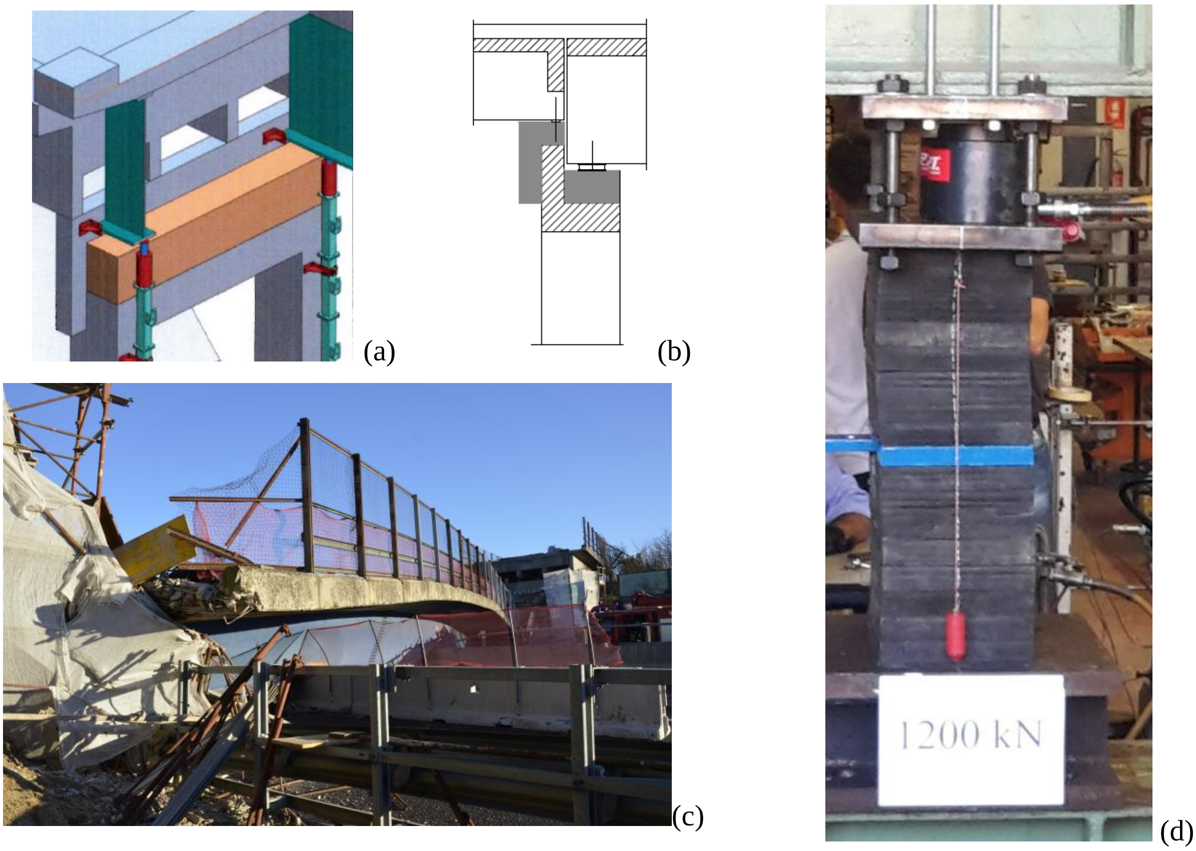


Figure 8. SP10 collapse at the intersection with A14: (a) design procedure adopted for the span lifting ; (b) concrete supports to be cast to increase the free height of the A14 highway; (c) collapse occurring during lifting procedure; (d) lab test with neoprene plates instead of steel plates.

4. **Uncertainties in the diagnosis of ancient bridges**

The experimental campaign carried out on Azzone bridge (Fig. 9a) erected in Lecco in 1338, was an occasion to face all the uncertainties in the assessment of the bearing capacity of an ancient bridge. As clarified in di Prisco et al. (2019) and Martinelli et al. (2018), the need of several expertise is required and only a careful historical research jointed with a patient identification of the materials and the techniques used in the centuries (Figs. 9c,f) to modify the original structure, a quite precise geometrical survey (Fig. 9b,d,e) and a multi-level structural model can help the engineer to estimate the residual bearing capacity of the bridge and eventually order retrofitting interventions. All the information collected on the bridge require a careful load test on site, driven by a well calibrated structural model, able to consider the geotechnical boundary conditions: the results of this test jointed to the identification of the frequency modes (Fig. 9g) can give the engineer the required confidence in calculating a reliable resistance of the ancient infrastructure.

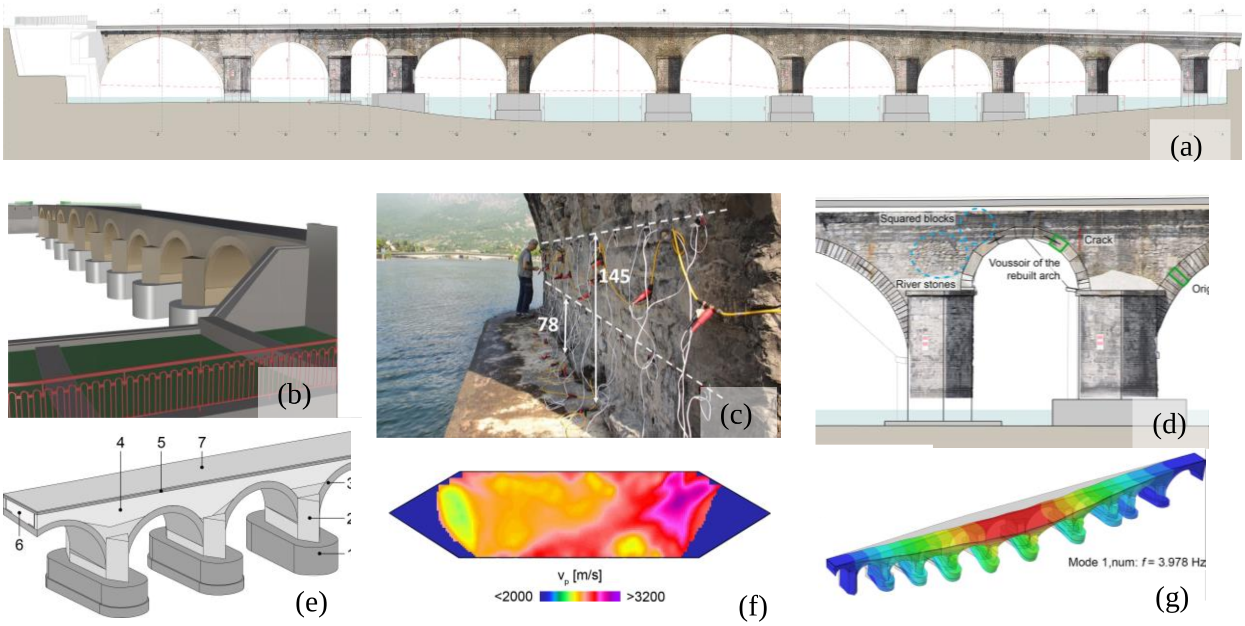


Figure 9. Azzone bridge in Lecco (1338): a) longitidinal view; b) 3D solid model; (c) pier tomography investigation; (d) UPV results; (e) dynamic analysis to identify mode frequencies.

5. **Critical aspects in the design of interventions on aged modern bridges**

The retrofitting design of modern-aged bridges presents many aspects that do not find a unique and clear answer in the taught civil engineering and in the scientific literature (Malerba, 2014). Looking for instance to two bridges located on Po river (Figs. 10a,b; 11a,b,c), analysed for the Public Work board in the last weeks, the following critical issues can be indicated: the choice of the confidence

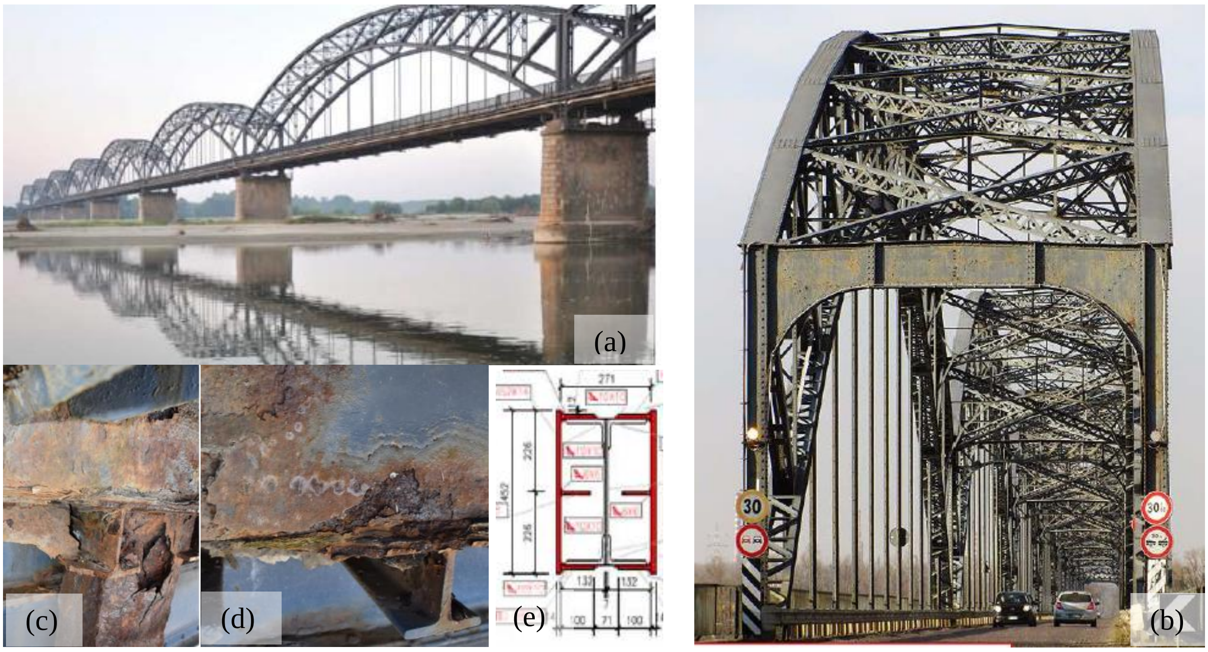


Figure 10. Gerola Bridge on Po river (1916) 755,8 m long: (a) side view; (b) end view; (c,d) corrosion of steel connections; (e) strengthening solution proposed for a profile.

Figure 11. Pieve Porto Morone Bridge on Po river (1967) 1265 m long: (a) side view; (b) critical dapped-end view; (c) corrosion of prestressed reinforcement at the intrados of the beams.

factors used for the materials, the definition of the reduced cross sections for the damaged portions (Figs. 9c,d), the prevention of details which could hide the steel connections and complicate the application of protection paintings (Fig. 9e), the introduction of additional reinforcement that could

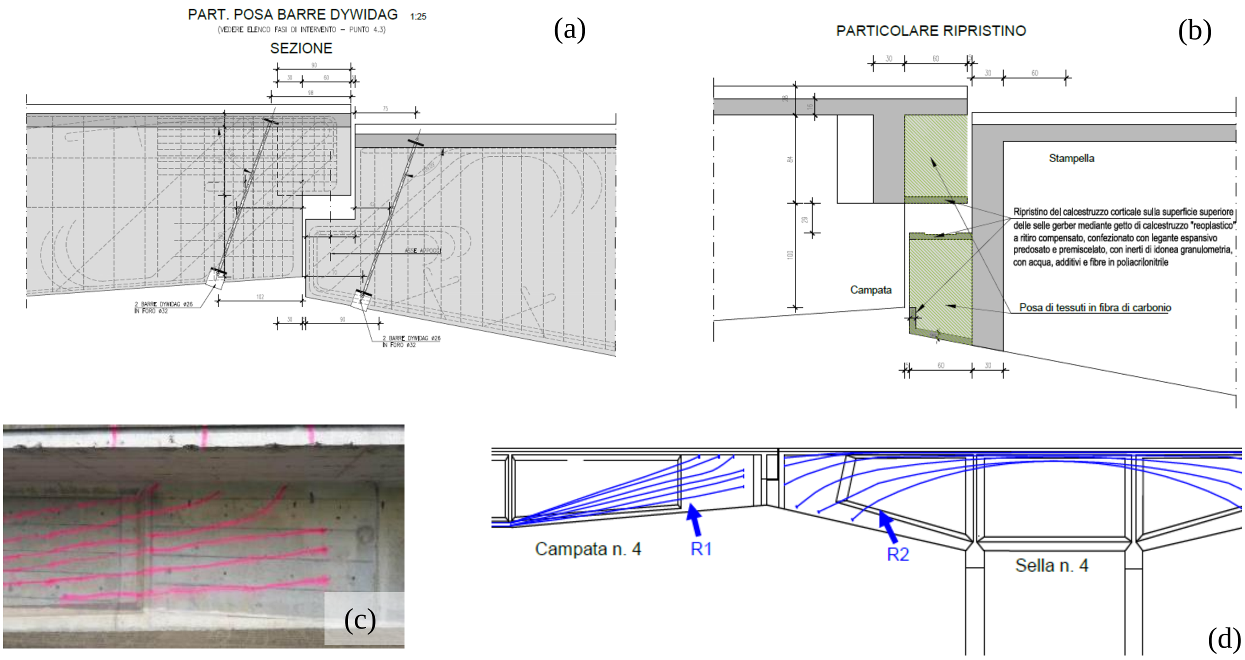


Figure 12. Pieve Porto Morone Bridge on Po river (1967) 1265 m long: (a) Prestressed bar to strengthen the dapped-end; (b) dapped-end restoration; (c,d) identification of the prestressed strand geometry by radar tecnique.

originate unexpected crack propagations (Fig. 12a); the choice of high-performance advanced cementitious materials to improve and protect the critical structural zones (Botros et al., 2017; Desnerck et al., 2017), the internal position and type identification of reinforcement (Figs.12c,d). All these issues require further research and a clear framework where to collect the consent of International Engineering community.

6. In progress procedures to manage the infrastructural heritage

Few months ago Lombardia Region started with Politecnico di Milano a research project aimed at proposing a rational approach to identify the intervention priorities for the large infrastructural heritage of the most industrialized region in Italy, that counts one sixth of the Italian population and around ten thousands of bridges. The research would consider a first step based only on existing data not related only to the actual safety conditions of the bridges, but also on the economic impact of each infrastructure in relation to the network served by each artefact. After a first clustering, a suitable monitoring on few bridges for each cluster will be suitably performed to analyze the structural conditions. A first database with about 75 main parameters is ready to be filled by the 12 provinces.

7. Conclusions

The brief analysis of the Italian infrastructural heritage has highlighted a significant difference between the railway and the roadway systems: the first appears smaller, more uniform and better organized in relation to maintenance. The lack of knowledge on durability for r/c and p/c constructions at the time of construction, the lack of planned resources devoted to the conservation jointed with the large market of civil engineering involved in the infrastructure artefacts construction and the applied load evolution are the most responsible actors of this critical situation. The companies involved in the current managing have the opportunity to use digitalized approaches like BIM and advanced monitor and survey systems to fill the gap between what we need and what we have. The government has to guarantee a right amount of resources in the next years to prevent at the national level an heterogeneous distribution of the safety coefficient correlated to this strategic source of development.

Acknowledgements

The author is in debt with Paolo Mannella (ANAS) and Andrea Vecchi (RFI) for their precious contributions exposed during the recent workshop organized by CTA, Aicap, CTE and IIS, Pietro Baratono for the discussion on existing bridges in the framework of the Public Works Board.

References

Botros, A.W., Klein, G.J., Lucier, G.W., Rizkalla, S.H., Zia, P., Dapped ends of prestressed concrete thin-stemmed members: Part 1, experimental testing and behavior (2017) PCI Journal, 62 (2), pp. 61-82.

Desnerck, P., Lees, J.M., Morley, C.T., The effect of local reinforcing bar reductions and anchorage zone cracking on the load capacity of RC half-joints (2017) Eng. Structures, 152, pp. 865-877.

di Prisco, M., Colombo, M., Martinelli, P., D. Coronelli, D., The technical causes of the collapse of Annone overpass on SS.36 (2018), Proc. of Italian Concrete Days, Lecco.

Martinelli, P., Galli, A., Barazzetti, L., Colombo, M., Felicetti, R., Previtali, M., Roncoroni, F., Scola, M., di Prisco, M., Bearing capacity assessment of a 14th century arch bridge in Lecco (Italy), (2018) International Journal of Architectural Heritage, 12 (2), pp. 237-256.

di Prisco, M., Scola, M., Zani, G., On site assessment of Azzone Visconti bridge in Lecco: Limits and reliability of current techniques (2019) Construction and Building Materials, 209, pp. 269-282.

Malerba, P.G., Inspecting and Repairing old bridges: experiences and lessons, (2014) Structure and Infrastructure Engineering, 10:4, 443-470.

Tobias, D.H., Bardow, A.K., Dekelbab, W., Kapur, J., Keever, M., Saiidi, M.S., Sletten, J.J., Yen, W.P., Multihazard extreme event design for accelerated bridge construction (2014) Practice Periodical on Structural Design and Construction, 19 (2), art. no. 02514001.

Wardhana, K., Hadipriono, F.C., Analysis of recent bridge failures in the United States, (2003) Journal of Performance of Constructed Facilities, 17 (3), pp. 144-150.