The anatomy of a collapse: forensic analyses, monitoring and restoration attempts of the Fossano Bridge

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ABSTRACT: The collapse of the Fossano bridge (Italy) occurred on April 18th, 2017 and it put high pressure on the Italian society for infrastructural risk perception. First of all, this collapse was the third in the last sixteen months. Then, the bridge was relatively young, being erected in 2001. Additionally, this bridge was just one of the 108 spans that composed the entire viaduct of the Fossano bypass road. In this scenario, the italian road authority (A.N.A.S.) conducted an in-depth investigation over the causes of the collapse and its implications on the existing remaining span. Moreover, study for monitoring and restorations were encouraged and supported. In this paper, we present the results of the forensic analyses, the studies over the entire infrastructure and the management of the data over a one year monitoring with and Artificial Intelligence framework for vulnerability assessment and risk prediction. Furthermore, we present study over the investigated structural solutions for safety refurbishment. We believe that this work will be significantly useful for both researchers and technicians employed in bridge management.

1 INTRODUCTION

On the early afternoon of 18th of April 2017, one of 108 spans that constituted the Fossano bypass viaduct collapsed abruptly on the street below (Figure 1a). Luckily, the incident did non involved any person or moving vehicle, apart from a parked empty car under the bridge. At the time, this collapse represented the third in a row for the Italian infrastructure network on a time span of sixteen months (Bazzucchi, Restuccia, & Ferro 2018). The level of pressure affixed to the system by the civil society and road authorities concerning the safety of whole system was particularly high after the event, and it skyrocketed when the iconic Morandi bridge on the Polcevera river collapsed on August 2018.

Scientific and technical community is facing an emergency, dealing with a numerous and vulnerable patrimony of infrastructures. On one hand, a high percentage of these artifacts have been built in the same years (1950s and 1960s), when there were both no sufficient informations about durability of concrete and no automatic calculation tools for hyperstatic systems (then redundancy was discouraged). On the other hand, due to the Italian orography and urbanization, the number of these structures is huge, one of the vastest of the world. Present challenges concern a feasible, fast and scalable approach to assess the safety of these kind of infrastructure.

Structural Health Monitoring (SHM) methods panorama is extremely fragmented and it lacks of an organic interpretation scheme. The vast set of methods varies among dynamic to static regime, passive to active stimulation, and remote to field sensing. To mention some techniques, we have Acoustic Emission, Fiber Optic Network, Piezoelectric Active Sensors,Accelerometers Modal Correlation, Guided Wave Sensing, Tomography, LIDAR Displacement Detection and so on. As recently criticized by several authors ((Sohn, Farrar, Hemez, Shunk, Stinemates, Nadler, & Czarnecki 2003), (Deraemaeker & Worden 2018)), even each available method has a huge number of different patented technologies behind. Moreover, accuracy is strictly dependent on the prior knowledge of the monitored structure. Using again a medical analogy, it is like having a disorganized number of specialized clinics without a general diagnostician that performs a fast screening with limited number of symptoms.

In this paper, we share the unique experience of the research sides of a forensic investigation that we had the luck and honor to conduct about the collapse of the above mentioned structure: from the main causes, investigation methods and consequent monitoring to the concept of a restoration system will be presented in the following sections. Anyway, several information can not be given at the moment due to secrecy related to the running investigations.

Figure 1: a) collapsed structure. b) in-situ casted intact joint.

Figure 2: Collapsed joint.

2 THE COLLAPSE

2.0.1 *The mechanical failure*

The collapsed bridge was constituted by a simply supported beam, $30.80m$ long and $8.90m$ wide, made by a multiple-box post-tensioned beam and by a in-situ casted slab. The section was realized by connecting two concrete precast U-elements by a shear-key casted in situ. In the longitudinal direction, the bridge was built in 3 segments, the central one $11.50m$ long and the lateral ones $9.35m$ long. The connection between the segments was realized by an in-situ casted concrete joint $0.5m$ wide (Figure 1b). Post-tensioning system constituted in 8 parabolic cables, each of them made by 19 $0.8''$ strands ($934cm^2$). Total weight of the artifact was about $400t$. The collapsed structure evidenced an intact joint and a damaged one, together with an evident shear failure where the bridge impacted the ground.

Visual inspections consented to affirm that the collapse mechanism was triggered by a shear failure in one of the joint due to the absence of the equilibrating action of the prestressing. Same inspections immediately evidenced the lacking of the sufficient grout protection in the opened joint area (Figure 2). Corresponding level of cable oxidation was not compatible with such a *young* structure (20 years old) concrete structure damage scenario, where, above all the external overall condition appeared healthy. The collapse had a sudden and fragile nature, with an insignificant process zone and volume of debris. The kinematic was practically vertical with no out-of-plane displacements. Only a modest slip in the longitudinal axis direction occurred in the pinned bearings side.

2.0.2 *The main causes*

All the immediate evidences lead to a failure of the prestressing action. Considering the total number of the cables and of the bearing systems, the fear of a systematic bias and the unusual type of failure brought to an extensive and detailed field analyses campaign: simulated rain tests to locate water gateways, chemical tests for crystallized residuals and molds, mechanical properties of the materials, extraction and scanning of each cable. Moreover, the entire bridge has been dissected carefully to check the position and the condition of every component of the structural skeleton.

Figure 3a,b exhibits the oxidation pattern of the longitudinal trend of the cables. Compared to the smaller diameter ones (precasted inside the central segment (Figure 3c)), it can be seen how important is the protection and passivization role played by the grout to the steel. In Figure 3d, the extraction of the main lateral cables is shown from the side of the intact joint. Also in this case, state of conservation was considerably high. As a last act of the dissection, Figure 3e shows the detachment of the slab from the deck to examine the presence and the position of the connecting longitudinal stirrups.

Final results, in terms of vulnerabilities ((Zheng, Chen, Zhuang, Ma, & Zhang 2013)), can be summarizes as follows:

- absence of ductility and structural robustness due to the lack of any redundancy in the prestressing device and shear keys ((Starossek & Haber-

Figure 3: a,b) oxidated cables. c) in situ casted cable. d) dissection and extraction of one of the main cables. e) extracted stirrups

land 2011), (Ghosn, Moses, & Frangopol 2010), (Cavaco, Casas, Neves, & Huespe 2013));

- inadequate grout injection inside the cables;
- complete non-accessibility for structural inspections of the deck beams.

Because of the investigation, only the major detail can be produced to date, but they represents a good set of interesting facts and when the legal action will be closed there will be more to learn from the new data.

3 STRUCTURAL MONITORING AND TESTING

3.0.1 *Load tests*

After the collapse of the above mentioned span, the road authority launched an investigation campaign to the whole viaduct to asses the elastic reserve of every constituting bridge. After the closure of the road, a loading system with four trucks with the magnitude comparable to the design check-load, has been applied to every span. Both longitudinal and transversal behavior has been assessed, to sustain the validity of the successive estimations. Because of the elastic-fragile nature of the collapse, the elastic reserve has been evaluated assuming the failure load as the corresponding one to the minimum amount of prestressing reinforcement that causes the activation of the opening of the joint. Working this way, it was also possible to summarily assess the guaranteed degree of corrosion inside the cable to support the test loads. Unfortunately, no numerical details can be divulged at this stage but the safety factor were compatible with the ones for an existing structure subjected to reduced traffic lanes.

3.0.2 *Monitoring*

The forensic investigations evidenced a concise correlation between the external presence of a pattern of superficial stains and the expected level of damage of the cables. As evidenced in Figure 4a, crystallized matter accumulated along the cable trajectory by the absolving action affecting the grout of the infiltrated and pressurized water in the sheatings. Depending on the extension and the dimension of these superficial stains, two ascending levels of damage have been established (lv. 2 and lv. 3). A maximum level of damage (lv. 4, Figure 4b) has been created for red-brown stains along the cable trajectory, meaning that the oxidation is acting without any presence of the grout (unbonded cables). Obviously, no evident sign of degradation has been classified as level 1. Results of this preliminary classification are reported in Figure 4c. These results have been used as ground truth for the building of the image layer of a Deep Convolutional

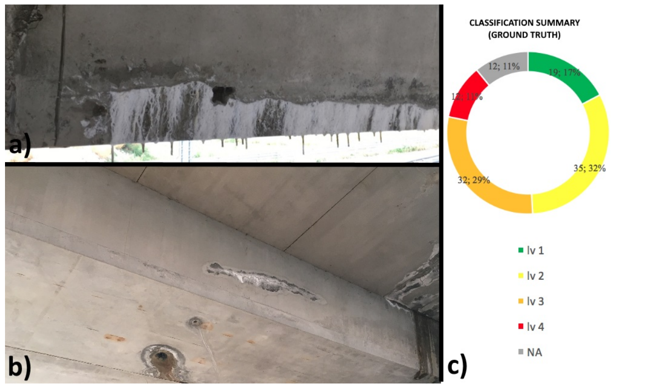

Figure 4: a,b) lv. 3 and lv. 4 stains classification standards. c) Entire classification summary.

Neural Network (DCNN) Computer Vision (CV) detector. The set has been split in $65\% - 35\%$ for training and validation. Before training, each picture has been filtered for red-contrast enhancement. A random set of 200 images from Kaggle has been used as false test. Training lasted 21 hours on a 2014 MacBook Pro. DCNN has been implemented with Pytorch and Anaconda 3.5.2.0. Other two layers have been implemented in the net, one based on the results of the load tests and one on the dynamic properties of the bridge, both computed by a FEM tuned model.

Four photographic campaigns have been carried out (tablet-based) as reported in Table **??**, and every picture was geolocalized for an automatic processing. Figure 5a shows the results of the application of the DCNN on the bridge n. 48. The system correctly spotted a red stain and classified the bridge as a Lv.3. Analogously, for bridge n. 52 (Figure 5b), a Lv.4 classification has been successfully matched. Regarding instead span n. 85, classified Lv.3 manually, the DCNN detected a Lv.2. damage degree Figure 5c. To date, 73% of accuracy has been encountered, and after the second campaign no evolution from previous damage degree has been noticed. Incrementation of this accuracy is strictly dependent on the number of input data. Apart from the collecting of a larger set of images (work in progress) we are testing in the lab the possibility to create a collaborative system with a fiber optic device across the joints (Bragg's nets based).

4 A PROTOTYPE FOR A REFURBISHMENT SYSTEM

To replenish the safety of the structure, two main actions must take place:

- stop the oxidation of the cables by injecting the sheatings and restore an high level of waterproofing;
- installing a ductile device that protect the structure from a fragile collapse due to the cobined action of flexural and shear failure at the joint section.

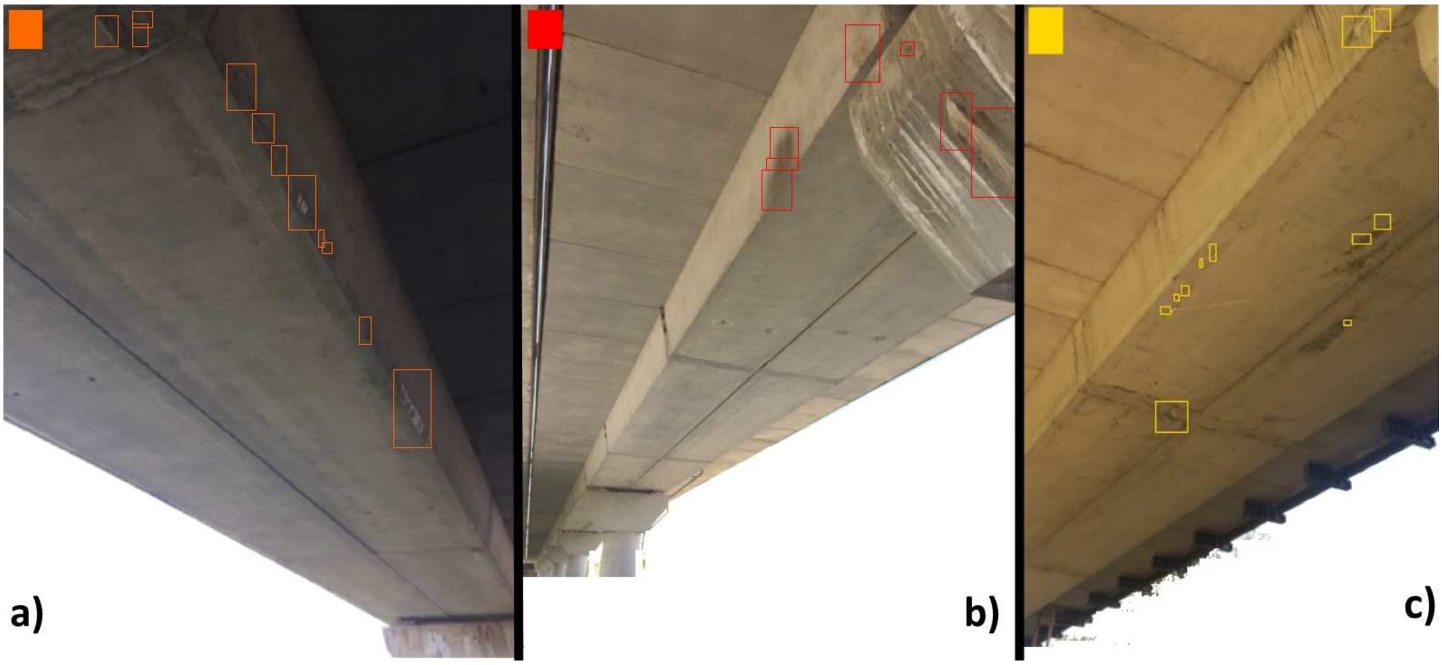

Figure 5: a,b) lv. 3 and lv. 2 correctly classified decks. c) Incorrect lv. 2 classification.

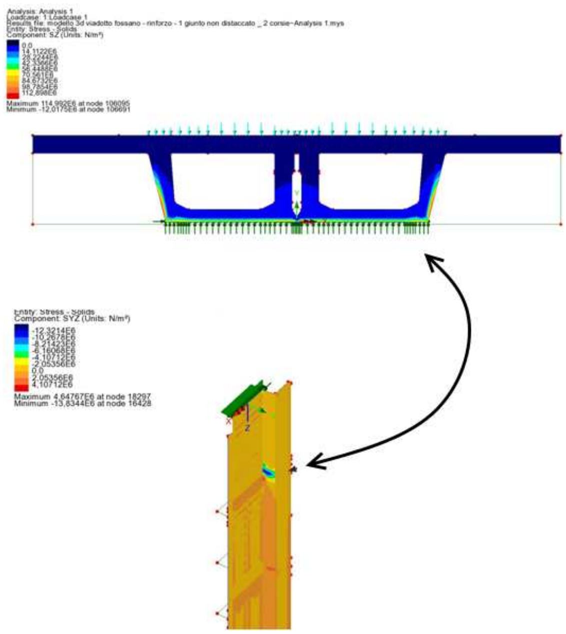

Figure 6: Numerical simulation of the steel U sleeve to attach at the deck.

While the first operation is now undergoing with epoxy resins injections and waterproofing pavement layers restorations, the second issue can be tackled only by the application of a structural component. In this case, a U steel sleeve has been designed to be attached across the joint to sustain both the shear and the flexural tensile force at the bottom. Connection has been designed with 56 M22 bolts per side. Each sleeve is designed with an embedded monitoring system for deformation to check if the prestressing force is diminishing by the progressive loading od the sleeve. Numerical simulations, i.e. reported in Figure 6, suggested that the system is able to bear the ultimate load with no operational limit state guaranteed.

5 CONCLUSIONS

The complete autopsy of a collapsed bridge has been shared and presented in the paper. Above the many lessons we learned, it has been highlighted how much the prestressing system must be carefully cared and maintained. When it comes for simple structures as supported segment beam, there is no possibility to count on some additional (off the design calculation records) reserve that structure may exhibit due to plasticity or redistribution. Safety of the infrastructure has been monitored while waiting for restoration and refurbishment works. An innovative method based on a DCNN CV detector has been presented to check the external damage of the deck and correlate it to the internal degree of degradation. Lastly, the structural propertied and analyses of a prototype for the restoration/monitoring device has been presented.

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