The partial collapse of the Bridge Galeria dos Estados in Brasília, DF, Brazil

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1 Abstract

The partial collapse of the Bridge *Galeria dos Estados* occurred on February 6th, 2018, in Brasília, Brazil when blocked the strategic traffic of downtown. Accessing the central bus station came to a complete stop, vitally impacting the commercial, banking and hospital sectors, and Government Administration District of the capital. The viaduct was built for the inauguration of Brasília, in February 1960, exactly 58 years ago. With 5,000 m², the viaduct has 8 spans with dimensions of 21.70 m and 27.0 m. The partial collapse of the viaduct suddenly occurred without large deformations, or other evidence visible to the naked eye, which could indicate, in advance, the fragility of the structure. The investigations indicated stress-corrosion on all prestressed cable the cap beam. The corrosion is systematic damage that occurs in all seven bent of the bridge. The structural retrofit of the bridge makes removals and reconstruction of the cap beam, easy for maintenance. Finally, the partial collapse could have been avoided if there was any visual inspection possibility, of reasonable cost, which would allow repairs before the collapse.

Keywords: bridge collapse, detailing, durability, forensic study, Prestress corrosion

2 Introduction

The bridge *Galeria dos Estados* is a relevant public equipment of the main road system and the Central Bus Station of Brasilia, Brazil. Because of that, the partial collapse, on February 6th 2018 at 11:45 AM, extremely impacted the city's population.

The equipment (bridge) was built in 50 days, for the inauguration of Brasilia, which took place on April 21th, 1960. It has been 58 years since any structural maintenance has been executed until now.

The partial collapse of the viaduct suddenly occurred without large deformations, or other evidence visible to the naked eye, which could indicate, in advance, the fragility of the structure and enable measures to avoid the collapse of the viaduct.

The collapse of the of the deck, approximately 7.0 m away, of the stretch supported on columns P6 and P7, on the east side, Figure 1.

3 The structure of the bridge

3.1 Structural system

The structural system of the bridge, it is described in Figure 1, and is based on a prestressed slab.

The viaduct was built with a structural system consisting of 8 alveolar slabs, with prestressed, isolated by expansion joints, over seven intermediate bents and two abutments E1 (south) and E2 (north). The support of the alveolar slabs in the encounters E1 and E2 are formed by GERBER beam, as the intermediate supports, Figure 2. The Intermediate supports are formed by 7 massive walled columns in the form of a "hang glider", with a wingspan of 27.0 m. The viaduct has a length between axles of bent approximately 22.1 m and 193.49 m length.

The deck is an alveolar slab with three transversal beams, whose dimensions are 1.05 m depth and 28 circular hollows of 80 cm in diameter, Figure 1.

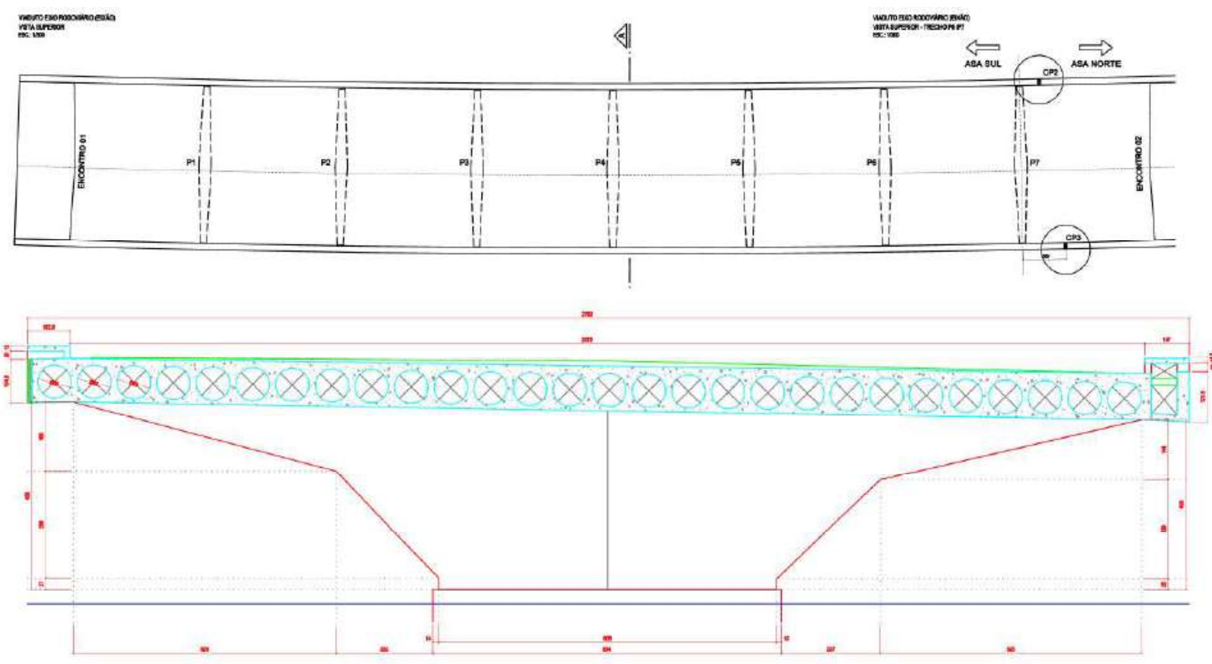

Figure 1. Top View and cross-section of viaduct, Source: NOVACAP, 2013

In this way, the identification of a crack on the cap beam is only possible after removing the concrete part over the cap beam that was used to fill this region.

The cap beam has a width of 1.58 m, and the support of the deck has 37.5 cm on each side. With this, the distance between the "edges of the slabs" (faces of the transverse ends) on the cap beams, results in a free space of 83cm on the top of the column (158 cm-37.5 cm * 2 = 83 cm). This distance must have been idealized (projected) during original construction to be used in the installation of prestressing jacks of longitudinal prestressing of the alveoli slabs' ribs.

Therefore, the staged construction was identified after the collapse may have been: (a) construction of the columns and decks on the wood formwork; (b) Prestressing of the caps beam; (c) Prestressing all the webs of the decks (part between hallow) and the 3 transverse beam.

Then this space between the slabs, of 83cm, was filled with simple concrete, forming a prismatic bar with a cross-section of 54x83 cm, which occurred 7 times along the viaduct, figure 2. Therefore, in the upper view, the bridge formed a finished and continuous surface with a slightly curved axis. It can be verified that the pictures were taken after the collapse.

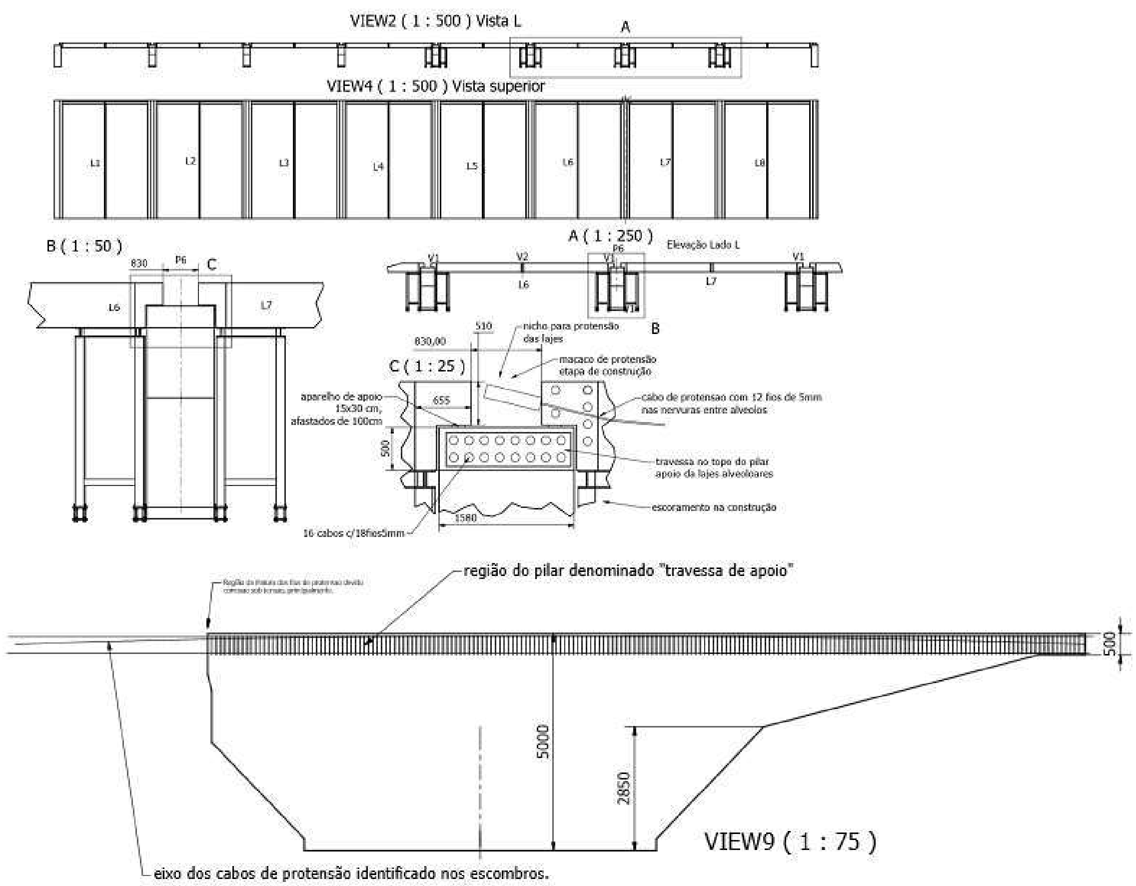

Figure 2 Design developed after dissection of the parts of the collapse, aiming to clarify aspects of the system of prestressing structure, Source: Authors

The cap beam was prestressed with 16 cables, consisting of 18 wires of 5 mm each, CP150 (150kgf/mm^2). They are parabolic cables, anchored at the ends of the cap beam, forming two layers of 8 cables in each line, spaced at the height of ≈ 16cm between the two lines (rectangular cross-section (158x50 cm). Then these cables are all raised to the top of the column, tangents to the stirrups, aiming to increase theirs.

The cap beam was constructed with a reinforcement of 16 mm-diameter stirrups, spaced every 8 cm, with an estimated average distance. It was difficult to determine when elements was dissected after the partial collapse.

During dissection, no reinforcement bar was found with the column wing, according to Figure 1.

3.2 Aspect of the conservation of the bridge

It is verified that under the spans of the bridge, between the columns P5 and P6; P6 and P7, there was a restaurant installation that it blocked the vision of damage to the structure.

In addition, the P7-P6 section was used for public parking. In this way, 4 vehicles were crushed when part of the structure collapsed and fell on them, Figure 3.

Figure 3 - Situation of the spaces underneath the viaduct, Source: public

4 Visual inspections after collapse

4.1 Aspects of the structure shortly after the collapse

The photographs were taken immediately after the collapse to allow the expediting identification of the partial mechanism that occurred on the bridge, as described below.

It is observed in Figures 4 and 5, that there was partial collapse delimited by the fractures of the wingspan of the columns P7 and P6, in this order, which resulted in a well-delimited cutout of the bridge bearing track, Figure 4, of them. In this case, it is relevant to consider the danger that the vehicles were subjected in those moments followed by partial collapse.

Figure 4 - Upper view of the viaduct instants after partial collapse, source: public

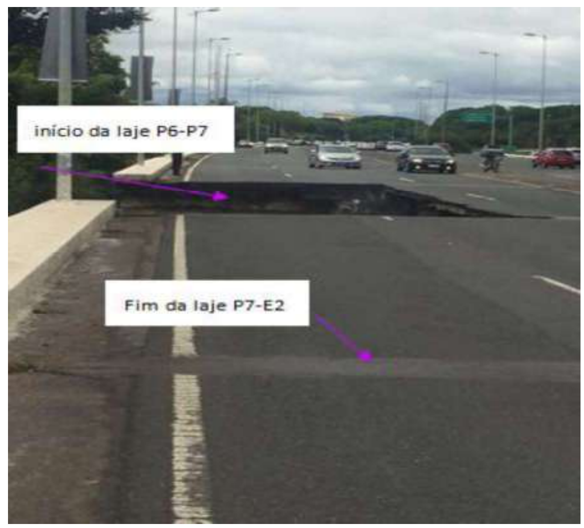

Figure 5 - Partial collapse of the deck, Source: public

4.2 Analysis of the fracture of the column wing

The shear reinforcement occurs only in the support of the "slabs", cap beam, with a limited height of 50cm. It is armed by stirrups, involving the 16 prestressing cables. In the case of the P6 pillar, the fracture process occurs in various plans., figure 6.

Figure 6 - Lateral view of the collapsed part, Source: Public

The resistance of the support was initially ensured by the presence of the 16 cables, until the beginning of the stress corrosion. When the behavior of the corbels is modified, with the opening of cracks in the region of 7.3 m from the edge of the slab, side L and W side. However, it is noteworthy that these cracks would only become visible after completely crossing the cap beam at 50 cm high when it was possible to identify on the free lateral face of the columns. The visualization of the initial cracks was hidden by the articulation of the Gerber beam of the slab. These cracks grown without being able to be identified in time to avoid the partial collapse of the wing of the pillar. It is noteworthy that there are not projects of these structures in NOVACAP.

These images show the bearings with 150x300x30 mm (it was estimated 3 cm thick due to the advanced state of degradation of the device) that were installed on the upper face of the prestressed cap beam at 15 cm from the end.

Along the entire bridge were identified process of corrosion in the prestressed cap beams and in many cables of prestressing of the slabs (in the middle of the spans).

When the investigation of the collapsed part was initiated, it was possible to identify a large part of the reinforcement of the parts. It was also possible to investigate the crossbeams of the slab at the ends and in the middle of the span, V1 and V2, respectively, figure 7.

The schematic drawings of the relevant parts of the fractured column are in figure 10.

The corrosion was aggressive in the cables of the prestressed cap beam, mainly in the region of the ends, where they were aligned to increase the efficiency of the prestressing reinforcement, i.e. Seeking greater eccentricity of the cable, has showed in the Figure 9, where the cables tangent to the stapes of the fractured section are found.

At the ends of the prestressed cap beam, the anchorages are distributed in two lines, apart from approximately 160 mm.

From the end, the cables are raised to approximately 10 cm from the top of the face of the cap beam. This can be seen in the photographs of the fractured section of this chapter.

Figure 7 - Cap beam, bent P6, where it can be Identified the slab bearing device, source: Authors

Figure 8 - P6-P7 span sheaths photo, where it can be Identified sheath without injection, Source: Authors

Figure 9 - Detail of the cable anchors in the end section of the cap beam, P7, with 16 cables, with 18 wires of 5 mm in each, Source: Authors

5 Mechanisms of collapse

To identify the mechanism of the bridge partial collapse, the investigation took as reference the set of photographs taken at the site of the collapse and the geometric specifications of the "project of forms" resulting from the topographic survey of 2013, available at NOVACAP.

This information was amplified with the pictures, Figure 10, which were developed from the identifications of the parts of the structure after the dissection of fragments. The picture revealed relevant details of the broken parts in the collapse of viaduct.

Partial collapse can be described in 3 stages.

1. Stage I, the degradation of the cables that occurred before the cracks (by relaxation of the cables, fluency of the concrete, shrinkage, injection defects and reinforcement deficiencies) that allowed the infiltration of water penetrating the wires of the prestressing cables (here was not considered the resistance reinforcing grid of the prestressing, that are still being identified for the final version of the report).

2. Stage II, considered the intermediate phase when cracks occurred in the prestressed parts of the deck, figure 9.

3. Stage III, at this final stage, the deficiency of the corbel to resist vertical loads caused the behavior of the deck (slab) to be a shell (due to its 3 prestressed crossbeams, 2 of the ends and 1 of the middle), seeking its balance in the prestressed crossbeams. In this case, the crossbeam support in the P7 partially resisted transferring part of the vertical force to the corbel of the P7, which has a weak flexural strength due to the lack of typical armor of corbel.

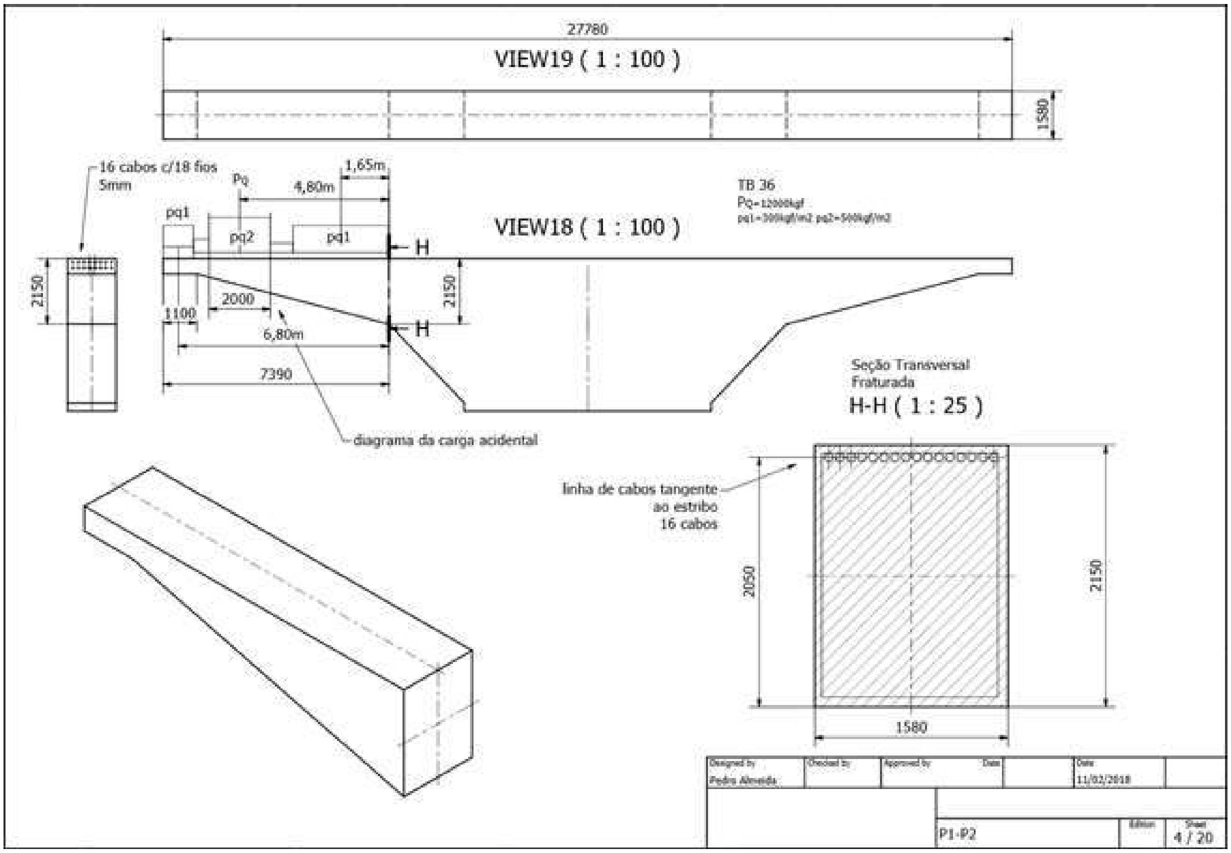

Figure 10 - Lateral view of the P7 column, after fraction (schematic drawings), Source: Authors

Finally, the process is finished with the rupture of the cap beam of the wings span that propagated along the slab until the AP6.

It should be considered that the durability of the cantilever of the prestressed cap beam were helped by good efficiency of the crossbeam at the end of the slabs, because the transfer the efforts to the strongest region of the column (central part of the column). The plate behavior predominated of the alveolar slab.

The original detailing of the structure in this region employed a simple concrete filling, without plastic joints or gaskets that prevented the infiltrations in the interfaces of the slabs on the column. This infiltration was aggressive to the active reinforcement at the top of the column (of the cap beam). It should be emphasized that the prestressed parts have tension declines due to the relaxation of the steel (in this case, it is inferred that normal relaxation steel was used). Losses due to concrete retraction and losses by fluency of the concrete all occur in a way inherent to the actions that lead over time the cracking of the parts. Thus allowing the direct penetration of water to the armor.

The active reinforcement is formed by small diameter wires of high-strength steels with low corrosion resistance, working at 75% of its strength. Active reinforcement is permanently (in much of its useful life), susceptible to fracturing by any corrosion point (pit corrosion) that quickly hosts on the surface of the wires. This was largely found in the rubble of the collapse, in the cables of the top of the Column (crossbeam).

In the evaluation of the balance resistance, wires with diameter d = 5 mm, CP150, with FPK = 147 were considered 1kN/cm², WITH AP area = 19.63 mm².

Therefore, each of the cables were estimated for prestressing strength given by the equation: FPi =

18 * 19.63 mm² * 147.1 kN/cm² = 519.8 kN. The resistance of the wires was confirmed by the University of Brasilia after mechanical traction tests.

The action of the permanent load in this cross-section without the presence of the balance's weight corresponds to MG = 11.583 MN * m for 20 loads 98 kN/m², actuating in the length of 7. 3m of the cantilever from the end.

The accidental load was considered the train type TB36, with 3 axes of 120,000 kgf, 1.5 m, between each other, 0.5 m from the lateral of the theoretical vehicle, and a projection in the plant of 3mx6m. The vehicle is also accompanied, in the front and rear band with the distributed load of PQ2 = 500 kgf/m² and on the lateral bands of pq1 = 300 kgf/m².

For the calculation of the stresses at the upper edges of the crosswise and bottom of the cross-section, it has combinations of tensile stresses at the upper edge of the order at 14.4 MPa and compressive stresses at the bottom edge of the order at 5.9 MPa. These values would require concrete with resistance above FCK = 15 MPa and complementary reinforcement on the upper edge of the support rail to resist tensile stresses at maximum load.

These values should be revised in the final version of the report, where the effective values of the resistances of the materials extracted from the structure will be considered. The results of the analysis of stresses resulting from the model of SAP (Structural Analysis Program), Figure 11.

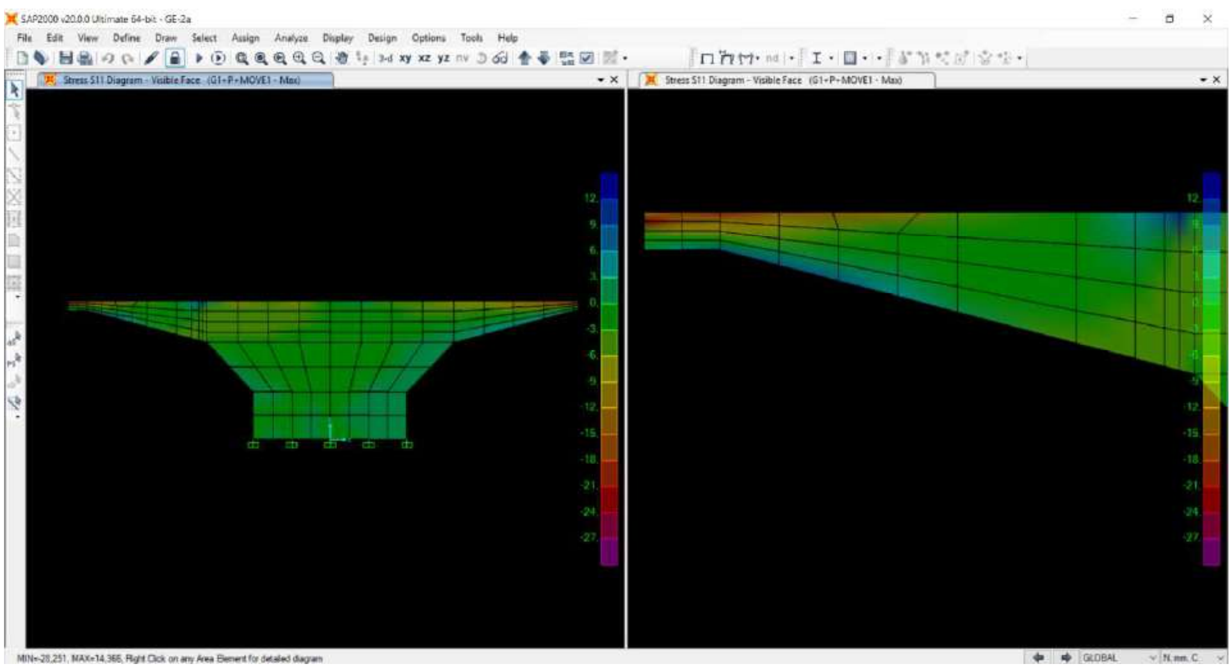

Figure 11 - Results of finite element analysis, with prestressing P, permanent load G and accidental load vehicle Q TB36, voltage S11 = + 14.37 MPa at the top edge of the rail and S11 =-5.97 MPa at the bottom edge of the Corbel, Source: Authors

6 Conclusions

We conclude from the assessment carried out in the wreckage of the collapse that there was an unwarned collapse of the P6-P7 section of the deck by a process of stress-corrosion contributed by the prestressing of the cap beams of the alveolar slabs of the deck, and the top of the walled columns.

It is noteworthy that this is systematic damage, that occurs in all 14 wings (cantilevers) of the 7 walled columns of the viaduct.

The fragile nature of the partial collapse stems from the lack of warning capacity of the column balance, because of the failure of the active armor through an accelerated process of corrosion under tension.

Through inspections carried out in the rubble and the structure of the bridge, it is concluded that the alveolar slabs of the deck are robust, with quality concrete and satisfactory mechanical resistance. All of can be utilized in the structural recovery of the bridge, with some prestressing repairs and reinforcements.

Finally, the accident of partial collapse could have been avoided if there was a possibility of inspections at reasonable cost and if it were built with a structural system with the ability to warn of danger in the face of damages arising from unexpected situations of use, or maintenance, or arising from the constructive system, which would allow repair prior to collapse.

Moreover, it is recommended that in the recovery projects the assumptions of structural design should be considered: "1. During the useful life, the structure must ensure the permanence of the characteristics of the construction at a reasonable cost of maintenance; 2. Under normal conditions of use, the construction shall not have an appearance that causes concern to users or the general public, neither it presents false alarm signals that release suspicions about their safety, and 3. In unforeseen situations of use or maintenance, the structure would present visible signs of any dangerous states ".

7 References

[1] Franz Knoll; Thomas Vogel. Design for Robustness – Structural Engineering Documents 11. IABSE, 2009.

[2] FIB-Bulletin 86 – Safety and Performance concepts. Guide to good practice.Task Group 2.8, 2018.