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Short communication

Damage and collapse mode of existing post tensioned precast concrete bridge: The case of Petrulla viaduct

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ABSTRACT

This paper describes an investigation into the collapse mode of a single-span, segmental post-tensioned concrete bridge caused both by the effect of chloride induced corrosion in Prestressed Post Tensioned Bridge and by some initial faults during tendons design. Collapse was determined by the breakage of the tendons and the wires inside the tendons appear completely rusted.

A numerical investigation was also carried out in order to determine the local mechanisms that led to the collapse of a segment of the Petrulla Viaduct in the south of Italy (Sicily) after a widespread beam damage was found. The main damage is the consequence of both an inadequate grout cementitious mortar filling, capable of introducing chemicals by which corrosion travelled along the tendons, and an inadequate distance among the ducts employed. The latter produces rotation of the wings around a point in the transversal section.

1. Introduction

Many of the bridges built in Italy are Prestressed or Post Tensioned (PT) concrete girders where the tendons are the main load-carrying elements. The advantages of PT bridges compared to bridges constructed using conventional reinforcement include greater span length, structural efficiency, reduced materials, and a more streamlined appearance. Although prestressed concrete members were generally manufactured with concrete of relatively higher strength, time has shown that they are subject to the same adverse effects of reinforcement corrosion as reinforced concrete members are. Corrosion can take many forms beyond that which occurs with a great loss of material; for example corrosion may occur by the interaction of corrosion and mechanical stress to produce a failure by cracking. This type of failure is known as stress corrosion cracking, often abbreviated to SCC [1,2]. SCC is an insidious form of corrosion; it produces a marked loss of mechanical strength with little metal loss; the damage is not obvious to casual inspection and the stress corrosion cracks can trigger mechanical fast fracture and catastrophic failure of components and structures.

Besides, when cracking is clearly a result of hydrogen embrittlement, is called as hydrogen attack. In fact, hydrogen dissolves in all metals to a moderate extent. It is a very small atom that fits in between the metal atoms in the crystals of the metal [4]. Consequently it can diffuse much more rapidly than larger atoms.

Hydrogen tends to be attracted to regions of high triaxial tensile stress where the metal structure is dilated as the regions ahead of cracks or notches that are under stress. The dissolved hydrogen then assists in the fracture of the metal.

Documented cases of prestressed tension members failure as a result of corrosion make this a most pressing problem. Since prestressed concrete members rely on the tensile strength of the prestressing steels to resist loads, loss of even few wires or strands per member [3] could result catastrophic.

Damage during service, frequently appearing after several years or decades of exploitation, is usually most consequential. The lacking or insufficiently alkaline protection already from the beginning or its loss due to carbonation and/or depassivation after chloride attack are the major causes of later damage or even of a failure. Responsible for that are usually the failures caused by shortcomings in planning and/or execution as well as inaccurate or inefficient structural measures. Execution faults and construction errors concern e.g. the injection of the ducts with mortar in case of post tensioned concrete (a mortar-free section of tendons is exposed to the risk of corrosion, when penetration of moisture is possible and oxygen can enter the duct space), the concrete technology (too small concrete cover and too low concrete quality, under certain conditions not protect. The prestressing tendons, the procedure (technology) of the production of the structural elements, as well as waterproof sealing (not present or damaged) and drainage (damaged), can strongly affect the durability of PT elements.

The use of poor quality materials and poor construction practices accelerate and aggravate the problem of corrosion, so that actually, the annual cost of corrosion was estimated to be very high [5–8].

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So, a brittle collapse of the bridge deck may be caused by a number of design deficiencies (individually or combined), namely: (i) inadequate duct venting, (ii) incomplete duct filling, (iii) strands pressing against the duct interior surface, (iv) strand congestion, (v) subsidence, or (vi) poor consistency with segregation [13,14].

In Italy, research on steel corrosion [9] is more focused on reinforced concrete (RC) structures than on Post tensioned concrete structures. PT structures adequately designed and constructed have been generally considered highly durable because the prestressing tendons would be protected from corrosion by the duct filling. But, some deterioration problems due to corrosion have been discovered in some existing bridges, raising serious concerns about the long-term durability [10] of PT bridges. In this kind of concrete structures, the high stress level in the tendons strongly modifies the steel corrosion process [11,12].

Macrocell corrosion with a local anode and a large cathode frequently occurs in chloride induced corrosion of rebars in concrete and is responsible for very high local corrosion attacks and reduction in cross-section. In PT beam with inadequate grout and protection of the tendonds, the process is equal to the mild reinforcement corrosion: in fact, the mild reinforcing in concrete is normally protected from corrosion by the passive film formed at the steel/concrete interface inside the alkaline cementitious matrix. But, if the passivity is compromised, than active corrosion may occur at an unacceptable rate. For instance, this passivation can be eliminated either by a decrease in the pH value ($pH < 9$) due to carbonation, or by the presence of chloride salts, which initiate an expansive corrosion of the reinforcing steel and eventually damage the surrounding concrete.

The importance of chloride ion in the corrosion of steel in concrete has been developed into the concept of chloride threshold level. Chloride threshold level is defined as the chloride content at steel depth which is necessary to sustain local passive film breakdown and to initiate corrosion process [15–17]. So, chloride threshold level can represent a key element in predicting the life service of structures exposed to environmental conditions [18].

Concrete structures such as bridges, buildings and other reinforced concrete structures might suffer severe damages due to macrocell corrosion [19–21].

2. The case studied: Petrulla bridge collapse

The case studied is a forensic analysis for the collapse of the Petrulla viaduct. The viaduct is constituted by n. 13 simple supported deck with span variable from 35 to 50 m long. It is located in south of Italy, in in a city, Licata, of Sicily island at both 'Salso river' and sea proximity. The name of the river derived by the Italian word 'salsedine' that means saltiness. The environmental condition can be considered as aggressive. The viaduct was built in the early '80s. The original as-built project were approved in 1985. It was designed according to the Italian Code in force at the time of the executive project (D.M. 1980) [28]. The viaduct was mainly devoted to vehicular traffic concerning to the transport of raw materials for agriculture as fertilizers and similar. In fact, it is in countryside, far away from urban center. The Fig. 1 shows the global aerial view of the bridge and its location to the river proximity.

So this viaduct is constituted by multiple bridge span. Each single span is made up of four longitudinal post tensioned double tee beams. The superstructure of the viaduct is supported by ten piers. The schematization of the typical deck span is represented in Fig. 2. Concrete slab completes the bridge deck.

In August 2014, a span of the viaduct suddenly collapsed. The collapse mode consisted in forming a plastic hinge in the mid-span of a bridge beam as shown in Figs. 3 and 4.

3. On site inspection of Petrulla viaduct

The inspection, after collapsing, revealed fractured strands and failure of the prestressing tendons as a consequence of their deterioration through corrosion (Figs. 5 and 6). In the mid span of the collapsed span, the complete dissolution of some strands in tendons numbered as No. (number) 4 and 5 can be observed. But the collapse was due also to some design lacks in the PT beam (i.e.: no gap presence among the ducts and inappropriate grout for prestressed concrete tendons). As reported in Fig. 5 the tendon numbered as 4 and 5 and originally composed by 12 strands, now present only 7 strands. The breakage of the tendons produced the expulsion of the ducts anchorages at the head beam due to the release of elastic energy (Figs. 7 and 8).

4. Analysis of Petrulla viaduct executive project

According to the original project, the single longitudinal beam was pre-stressed by means of five tendons realized by twelve strands of 0.6 in. each. So according to Standard Production Italian Specifications Law Act 1086-1971 and Following Revisions for the 7 wire strands, the strand nominal diameter and the nominal area will be 15.20 mm and 140 mm^2 respectively. Then, each tendon exhibits a cross section (or equivalent diameter) of 1680 mm^2. The tendons layout is derived from the original executive project and represented in Fig. 9 in which the position of each tendon (in figure called '*cavo*' according to the Italian language) and the corresponding anchor-head regions are represented. It's worth to note that for the "cavo 4" and "cavo 5" (called tendon No.4 and tendon No. 5 in the following) the anchor-head region is on the extrados of the deck beam. Fig. 10, shows the strand disposition in the mid span. The pretension of the tendons was applied in progressive steps i.e. No. 1–3, tendons were fully tensioned at the beginning, before the bridge erection, while No. 5–6 tendons were tensioned up to 35% of the specified tensile strength after the transversal beams construction. The other 65% of the specified pretension was applied after the casting and hardening of the deck slab.

During the construction, tendons no. 4 and no. 5 of Fig. 10 were tensioned at the end, to achieve 100% of the specified pre-stress to be applied in the tendons. To this aim some slots at the extrados of the deck slab had to be filled by grout after tensioning (Fig. 11). Thus, a volume of potential accumulation of water for saturation of the concrete, is created and this allows the entrance of aggressive ions.

This is partly due to the shrinkage during the curing of the concrete used to fill the holes, which results in the formation of cold joints at the interface between the old and new concrete. This is necessary to complete the existing slab, from which bleed water infiltrates and percolates, accumulating in the tank arranged in the prefabricated beam in the cap, up to the saturation of the mortar injection of the cables.

From the original project, in the cross section at the mid span of the PT beam, the tendons, placed in a duct of 70 mm in diameter, converge into a narrow space (Fig. 10), which does not meet the minimum gap required by the international codes (ACI 318 – R 18.16, Grout for bonding prestressed tendons) [24]. Therefore, a right constipation of the concrete during the cast is not ensured. This is unable to develop and disseminate the tangential stresses due to the adherence [22,23]. According to Eurocode 2 [25], in fact, for ducts of 70 mm, the required gap among the tendons must not be less than the duct diameter. In the case studied, no gap was found among the tendons and this caused the formation of voids as shown in Figs. 12 and 13. As will be explained and shown in detail in the section devoted to the FEM analysis, these gaps caused the implosion of the cross section of the deck, with inward rotation of the lower flanges, resulting in expulsion for tensile of the mild reinforcement placed along the section web. A uniform rust distribution can be noted along both the tendons and the duct.

The internal tendons located inside the structural concrete section, are housed in corrugated metal ducts, and bonded to the structural concrete by means of cementitious grout. In the past, there have been no problems due to using grout, capable of filling the interstitial spaces between tendons and ducts for the bonding of prestressing tendons, with portland cement as the cementing material capable of preventing