Failures of external Tendons in Prestressed Concrete Bridges: Causes, Investigations, Remediation and Prevention.

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Abstract

In the early 1980’s, an evolution in the grouting operations took place with the use of increasingly fluid grouts to facilitate the injection of the prestress ducts. During a gammagraphy campaign carried out on a box girder bridge under construction in 1994, anomalies were detected at the upper point of the ducts of the external prestressing tendons. Observations carried out after opening of some ducts highlighted a lack of filling and the presence of a product having the consistency of a wet and soft white paste. After presenting several cases of external tendon failures that occurred in the past years in France, the article describes the mechanism leading to severe grouting defects resulting in failures of tendons by a rather rapid corrosion. Then it presents the development of an investigation device based on dielectric capacity measurement that was applied during the campaign of investigations launched on all box girder bridges of the French national road network.

Keywords: Post-tensioning; bridges; tendons; grouting; rupture; causes; investigations; capacitive probe; repair; replacement.

1 Introduction

From the mid-70s, a change was made with the use of more and more fluid grout to facilitate the injection of prestressing longer ducts. From the 80s, the search for a greater fluidity was accompanied with the widespread use of superplasticizers. This change in the grout formulation and the grouting methods prevailed without checking the actual filling of the ducts on the sites. This leads to the occurrence of failures in external prestressing tendons, and it was observed in various countries, especially United States [1], but also France.

2 Cases of external tendon failures

Between 1994 and 2005, 5 cases of rupture of external prestressing tendon protected by cement grout in direct contact with steel strands were observed in France. When they broke, the tendons were respectively 8, 10, 18, 19 and 21 years old, with a mean age of 15 years. In this article, three cases of rupture of prestressing tendons are presented; they occurred chronologically in the following box girder bridges: the Val-Durance bridge, the Saint Cloud viaduct and a bridge in La Réunion island.
2.1 The Val-Durance bridge case

The Val-Durance bridge is a prestressed concrete bridge that allows the A 51 to cross over the Durance. It was built by launching and commissioned in 1986. It has a total length of 288.60 m, comprises 6 spans with the following length: 41 m - 4x 51 m - 41 m, and consists of two parallel box girders. For each of them, the prestress which is entirely external, is composed of 32 tendons made of 19 strands T15 (diameter 15 mm). The bare steel strands are located within a HDPE duct injected with cement grout in direct contact with the steel.

![Figure 1. Failure of the external tendon](image)

In 1994, during an inspection, a team of the Regional Road and Bridge Laboratory (LRPC) of Aix-en-Provence discovered the rupture of a tendon that was about 250 meters long inside the downstream box girder (Fig. 1); the break occurred at an upper location, ahead of its anchorage, inside a crossbeam. The energy released during the rupture had projected the tendon toward its opposite end. The expertise conducted by the LRPC gave rise to the following conclusions:

- the rupture of the tendon was bevel-shaped (Fig. 2), and it corresponded to a break of the various strands in the same horizontal plane, a plane corresponding to that of a water level (Fig. 3);

![Figure 3. Scheme showing the position of the plane of rupture (air/water interface)](image)

- the duct was empty of grout and partially filled with water over a length of 2.50 m in front of the anchorage plate;
- among 109 analyzed wires, 21 presented a high corrosion dissolution and 88 had a striction and were thus broken during the final rupture;
- the pH measured on the reclaimed water in the anchor hood was high, suggesting that a hyper-basic medium corrosion could have occurred;
- the 33 gammagraphies performed on the broken tendon confirmed an absence of voids in the remainder of the duct;
- the RIMT method (Reflectometric Impulse Measurement Technology) applied for experimental purpose was inconclusive: areas announced as being defective proved to be in good condition during the opening of the duct.

A dismounting of the 64 anchor hoods of the downstream box girder was then made. The findings were the following:

- 31 % of the anchor heads were in satisfactory condition:
- 41 % of the hoods showed traces of oxidation;
- 12% of the hoods showed signs of corrosion;
- 16% of the anchor heads were very corroded;
- 5% of the anchor heads showed leaking oil or oil-water mixture.
A 3.8 mm diameter borescope was introduced through tiny holes of the anchor heads, when they were empty of grout. In six cases, a significant lack of grout, oxidation marks on some wires and even a reduction of the cross section of a tendon could be observed.

The broken tendon was replaced in 1996 and the bridge was highly monitored. After establishing a repair project, all the tendons of the downstream box girder were replaced in the year 2000. This was done by implementing a temporary extradosed prestress to support the weight of the deck. Each tendon was cut with a blowtorch through holes made in the walls of the box by hydrodemolition. The tendons were sectioned to be removed by pieces of 2 to 3 meters in length. After tensioning the new tendons, they were injected with wax, and then the provisional extradosed prestress was disassembled.

During disassembly, a whitish paste was found in the anchorage trumpets; this paste was sometimes associated with moisture and corroded wires. The last part of the tendon located between the last deviator and the anchor block buckled just after cutting, and this resulted in whipping and large lateral deformation. In areas where the sheath breaks out, the strands deform laterally and form a kind of mesh.

2.2 The Saint-Cloud viaduct case

The St. Cloud viaduct, commissioned in 1974, allows the A 13 motorway to cross over the Seine River in the west of Paris. Its length is about 1 km and it comprises spans from 67 to 102 m in length. It has a width of 20.40 m, a constant height and is made of a multicellular box girder with 4 webs; its prestressing is totally internal to the concrete. Joints between precast segments opened shortly after construction, and it was strengthened in 1979 by an external additional prestressing.

In 1998, one of the additional prestressing tendons that was in the North lateral cell and that was 300 m long was found broken in its middle; the failure was located at the lowest point, in a section between two deviators, near the lower slab and close to a reinjection hole. The 12 T15 tendon with bare steel strands of diameter 15.2 mm was injected with a cement grout incorporating an admixture. The energy suddenly released during the failure made “buckle” the tendon ends and eject one of the anchor heads of about 1 meter, while this one was supposed to be "non-removable". The autopsy of the broken end of the tendon showed that there was still a grout pocket having the consistency of a wet sandy paste with no cohesion; its pH was between 12 and 14. The appraisal conducted by LCPC showed that the prestressing wires were sensible to stress corrosion cracking and a majority of the wires exhibited this type of cracking.

2.3 The bridge case in La Reunion island

This box girder bridge was opened to traffic in 1991. It is a three-span bridge built by the balanced cantilever method. It is 150 meters long and includes a removable external prestressing passing through curved steel tubes installed in crossbeams and deviators.

The rupture of a 19 T15 tendon occurred in 2001 at an anchor located in the upper part of segment on pier. If this anchor did not move, the anchor head at the other end was expelled on a length of about 3 meters and hurt the wall of the pull chamber (Fig. 4). The tendon “buckled” in the end span, but also in the central span. The autopsy showed much whitish paste on the surface of the tendon and in the concerned anchor;
conglomerates of healthy grout and whitish paste were also observed in some areas of the tendon (Fig. 5). A lot of corrosion and some broken wires were detected; water was not found, but the whitish products were sometimes wet. The tendon failure process was similar to the bridge over the Durance: loss of cross section by dissolution, transfer of efforts to healthy wires and sudden break of healthy wires accompanied by striction.

**Figure 5: Observation of a whitish paste.**

### 3 Mechanism of defective grouting

It was during a radiography campaign of external prestressing tendons conducted on a box girder bridge in 1994 that anomalies were detected for the first time at the top of prestressing ducts that had been injected with a grout incorporating admixture. Observations made after opening of some ducts have shown a lack of grouting and the presence of a product having the consistency of a moist and soft paste that hardened thereafter in air. Controls carried out in 1995 on other bridges have shown that this phenomenon also existed in current structures like slab bridges and was more widespread than had been expected at first.

These anomalies could be reproduced in laboratory tests practiced on inclined transparent tubes. When certain conditions are met, the use of a superplasticizer promotes the migration of mineral species formed during the setting of the grout. There is a separation due to density between the cement in suspension (during hydration) and these lighter mineral species (particularly ettringite and portlandite). This creates a whitish product whose migration occurring along the tube is accompanied by a rise of air bubbles. At the end of the test, in the upper part of the tube, it appears a white paste layer surmounted by a more or less yellowish liquid, itself surmounted by an air gap. Mineralogical analyzes made by LCPC on the various products show that [2]:

- the white paste which hardens rapidly on contact with air, is mainly composed of ettringite (40%), portlandite (20%) and calcite (20%), the latter consisting mainly of carbonated portlandite. The remainder of the paste is enriched with admixture and sulfates;
- The supernatant liquid has a composition similar to the pore solution of a cement paste with a very high alkalinity (pH 13.8).

The analyses suggest that this is a bleeding phenomenon combined with a settlement of the grout and that this phenomenon is amplified by the presence of the superplasticizer, this admixture being able to present an incompatibility with the cement in some cases. The inadequacy of the couple cement/admixture causes instability of the grout during the dormant phase of the setting.

The coexistence of an air pocket and a liquid phase in a prestressing duct can cause a durability problem because of the long-term corrosion of the prestressing due to differential aeration. Indeed, the water-air interface in a confined environment means that the air is still saturated with water (100% relative humidity). Under the effect of temperature variations, a pure water condensation can occur on the interior wall of the duct or on the parts of the prestressing steels exposed to the air saturated with water. The conditions are then met for a steel corrosion to develop. In addition, the highly alkaline pH of the supernatant liquid may fear an alkaline corrosion of steel, as shown in the diagram of the Belgian engineer Pourbaix.

Thus, without a resumption of the grouting and even with a low-bleed grout (1%), an injection of long tendons (200 to 300 m long) may create air pockets on a cumulative length of 2 to 3 m. A study on grouting of translucent ducts at full scale [3] showed that the purge order at high points depends on the geometry of the duct, that the
filling mode of the duct depends on the thixotropy of the grout, and that the inclination of the ducts and the presence of the strands (filtration effect) amplify the volumes of air and water that appear at the top of the duct.

Figure 6: Visualization of the filling kinetics of the prestressing ducts during grouting.

The study showed that when the slope is quite pronounced and the grout is rather fluid, the grout collapses in descending parts and it appears a new front of grout progressing in the opposite direction. The purge is necessary to remove the air pocket rising back under pressure from the opposite front, but the purge order depends on order of arrival of each of the fronts (Fig. 6).

This is why a test on an inclined tube 5 m in length was developed and generalized to verify the stability of grout compositions in conditions representative of site construction. This test, which was described in an information note of Sétra [4], has been studied and validated in an experimental campaign launched by LCPC. This test was then taken over by the EN 445 standard [5]. Research conducted at LCPC has also verified the possibility of using a simplified test on vertical tubes with a length reduced to 1 meter [6].

4 Development of the 3CP capacitive probe

The principle of the capacitive method is known since long at LCPC [7], and it was used in particular for the measurement of water content variations in the unsaturated soil and for materials having a planar surface (concrete, masonry); it was the subject of a patent by Dupas from LCPC [8].

This method has been extended to the investigation of anomalies in the external prestressing ducts grouted with cement. Research to develop a device capable of diagnosing and locating grouting defects began in 2000 as part of a collaboration between the LRPC of Autun and LCPC. Then, a research operation was launched by LCPC to achieve the preparation of an operational prototype (called “second generation sensor”), based on the principle of measuring a capacity and capable of diagnosing the presence of voids and whitish paste above the grout in the external prestressing HDPE ducts [9]. These latter have a diameter between 90 and 110 mm and a thickness of 5 to 7 mm. The interpretation of the measures was done with the help of a modeling by F. Taillade [10].

Figure 7: Scheme of electrodes position.

The measurement principle is based on an oscillator whose frequency $f_{osc}$ varies as a function of an inductance $L$ and a capacitor $C$, formed by all the materials located between a pair of metal electrodes located at the duct surface (Fig. 7):

$$f_{osc} = \frac{1}{2\pi\sqrt{LC}}$$

with $C = \varepsilon_0\varepsilon_r\varepsilon$, where $\varepsilon_0$ is the absolute permittivity in vacuum and is equal to $8,854188 \times 10^{-12} F.m^{-1}$ (for a plane capacitor composed of two surface electrodes $S$ sandwiching a dielectric material of relative permittivity $\varepsilon_r$ and thickness $e$, $\varepsilon = \varepsilon_r \varepsilon_0$). This capacitor is formed by the various layers (duct, air, paste, slurry, steel) crossed by the field lines, according to the relative permittivity of the medium (1 for air, 5 to 15 for the grout, 2 to 3 for HDPE, 80 for water). The variation of permittivity between wetter materials and drier materials introduces a significant variation in the capacity.
and therefore the oscillator frequency that is measured.

In 2007, a project team was run by the Autun LRPC to design and manufacture a Capacitive Sensor for Prestressing Tendons (3CP), by improving the second generation capacitive sensor. This material produced by the Center for Study and Construction of Prototypes (CECP) was qualified as a “MLPC material” in September 2009. The 3CP (Fig. 8) can:

- detect and locate "precisely" injection defects of cement grout in external prestressing ducts: presence of voids or whitish paste above the grout (the depth investigation of the 3CP is about 30 mm);
- investigate external ducts with a diameter from 75 mm (7T15) to 140 mm (37T15);

![Figure 8: View of the 3CP capacitive sensor.](image)

5 Results of the campaign of investigations on bridges

After a circular of the Transportation Ministry was published in 2001 [11], the grout protection in direct contact with the strands was abandoned in the case of external prestressing tendons which are now overwhelmingly protected by a petroleum wax.

Therefore, structures potentially concerned by the rupture of external tendons are those built in the period going to the early 1980s to the early 2000s. Sixty structures at risk have been identified on the national road network. The total number of bridges concerned in France, regardless of the owners, has not been precisely identified but can be roughly estimated at about 150.

In order to have a better understanding of the phenomenon and of its extent, several phases of inquiries or investigations were conducted. Initially, for 45 of these bridges considered as particularly critical or strategic, visual inspection of the tendons and their anchorages were performed. These bridges had then a mean age of 16 years. In parallel, the tendons ducts were systematically tested with a hammer. This rustic approach allows to simply detect large grouting anomalies, but it does not test the high points of the tendons located in the deviators which are very problematic areas regarding this phenomenon as evidenced by the case of the Val de Durance bridge.

It is necessary to distinguish the case of ducts which present a hollow sound only in the upper part, which generally corresponds to a simple detachment between the grout and the duct, from the case of ducts that present a hollow sound along their periphery, which may reflect a significant lack of grout.

The main findings of this first phase were the following:
- no new failure of tendon or strand was observed;
- very roughly, it may be considered that the proportion of external prestressing tendons having presented a rupture is about 1/1000;
- only a small number of bridges, approximately 10%, had at least one area that "sounds hollow" over the entire periphery of the duct;
- the presence of poorly or not grouted areas does not systematically induce a corrosion of the reinforcement;
- no admixture is particularly suspected.

Depending on the results of this first phase, further investigations were carried out on 6 bridges. These investigations included:
- to open ducts in suspicious areas;
- to take grout and water samples and analyze them;
- to inspect the inside of the ducts with a borescope;
- to investigate the ducts with the 3CP capacitive probe.
This second phase showed that areas suspected of having a "total void" of grout after hammer testing may not be entirely empty of grout. Very few bridges have finally presented disturbing judged disorders judged as worrying to require interventions.

An information notice released by SETRA / LCPC (Cerema / IFSTTAR) [12] has been prepared to inform the various bridge owners and consultants on this phenomenon. This notice presents the state of knowledge on the subject, makes recommendations on the investigations that can be performed to assess the condition of an external prestress, gives safety instructions to apply and indicates what to do in case of doubt on a tendon or in case of a detected rupture.

6 Remediation

When the disorders in the tendons are considered important or very important after the investigations, the replacement of all or part of the tendons is necessary. This is the case of the three bridge examples presented previously. In the case of the Val Durance bridge and the bridge in La Reunion Island, the company cut the stranded tendon by means of a torch. This detensioning method is brutal because, as soon as 20 to 25% of the strands are cut, the tendon breaks suddenly releasing almost all the energy he had accumulated when its tensioning occurred. Some disorders resulting from shocks during detensioning were also observed in the Val Durance bridge.

It is therefore possible to proceed with the replacement of such tendons provided that on one hand, a minimum load bearing capacity is kept for the bridge (e.g., by setting up temporary tendons) and on the other hand, their detensioning is mastered to avoid collateral damages to the bridge or the utilities.

To limit the disorders caused by a tendon during its brutal rupture, shock absorbers were developed and tested on the long testing bench for cables at LCPC (now IFSTTAR) in Nantes (Fig. 9). These tests helped to develop shock absorbers capable of absorbing most of the energy released by the deliberate breaking of a tendon, thanks to the plastic deformations of their steel constitutive sheets. This new technique was successfully used when removing the external prestressing of the Saint-Cloud viaduct where the tendons were cut using a remote-controlled saw and where shock absorbers were firmly fixed on the existing tendons so as to abut against the crossbeams or deviators inside the box girder bridge (Fig. 10) [13] [14].

Figure 9: Test of a shock absorber at LCPC.

Figure 10: Shock absorbers after use during dismantling of tendons in the Saint-Cloud viaduct.

When the tendon disorders are considered minor or relatively local, and if the corroded wires show no sensitivity to stress corrosion cracking, then a re-grouting with the help of a vacuum technique is possible (well identified voids, drilled holes in the duct, etc.). Beforehand, it is advised to open the ducts in areas where water of wet paste are present and to remove them. Re-grouting with a cementitious grout allows to protect and stabilize
the strand corrosion. It must, if necessary, be supplemented by rehabilitation of sealings.

7 Conclusion
After having understood the causes of disorders and coped with existing structures a prevention strategy was launched in the various countries affected by the problem (see for example references [11] and [15]. Several solutions are adopted with the use of a thixotropic (anti-bleed) and low shrinkage grout, the use of wax or grease, the certification of the products employed and the implementation of a grouting certification procedure.

8 References


