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Rehabilitation and modernization of the Monte Bianco Tunnel

G. Furlanetto & L. Ferretti Torricelli
Bridge Design Department SPEA Ingegneria Europea S.p.A., Milan, Italy

ABSTRACT: After the tragic event of the march 1999, in which the fire broken out from a truck destroyed a wide portion of the internal structures of the Monte Bianco Tunnel, an extensive plan of rehabilitation and modernization of this important link between Italy and France was started, in order both to repair the damages caused by the fire and to improve the safety of the tunnel. The tunnel carriageway runs onto a box prestressed concrete structure, laying on the bottom of the tunnel, that went irreparably destroyed in three distinct points of the upper slab, together with a wide portion of the vault. The paper, after an overview of the main features of the structure and of the modernization plan, which have strongly improved the safety standards of this important link, will show in detail the peculiarities of the structural interventions on the internal structure.

1 INTRODUCTION

The Monte Bianco tunnel was opened to traffic in 1965; with its 11.6 km, excavated under a medium cover of more than 2000.0 m in very hard geological conditions represented, more than the realization of a strategic link with Europe, a challenge that remained unequalled for many years.

Due to the complexity of the excavation conditions, compared with the equipment available at that time, the tunnel was designed in order to strictly allow a single two-lane carriageway 8.60 m wide, composed by two 3.50 m wide lanes and two sidewalks of approximately 0.8 m.

The carriageway runs on the top slab of a box concrete structure, whose internal cells are used as canalization of the ventilation system.

For the realization of this internal structure, two typologies have been adopted: for the segment under the competence of the Italian authority, from chainage 0.00 to 5800.00 a precast box section was used, whilst the portion under the competence of French authorities was realized for the greater part by a multiple arch cast-in place structure.

In correspondence of the border between the two portions the continuity of the ducts was successively interrupted closing the internal cell with a massive concrete diaphragm.

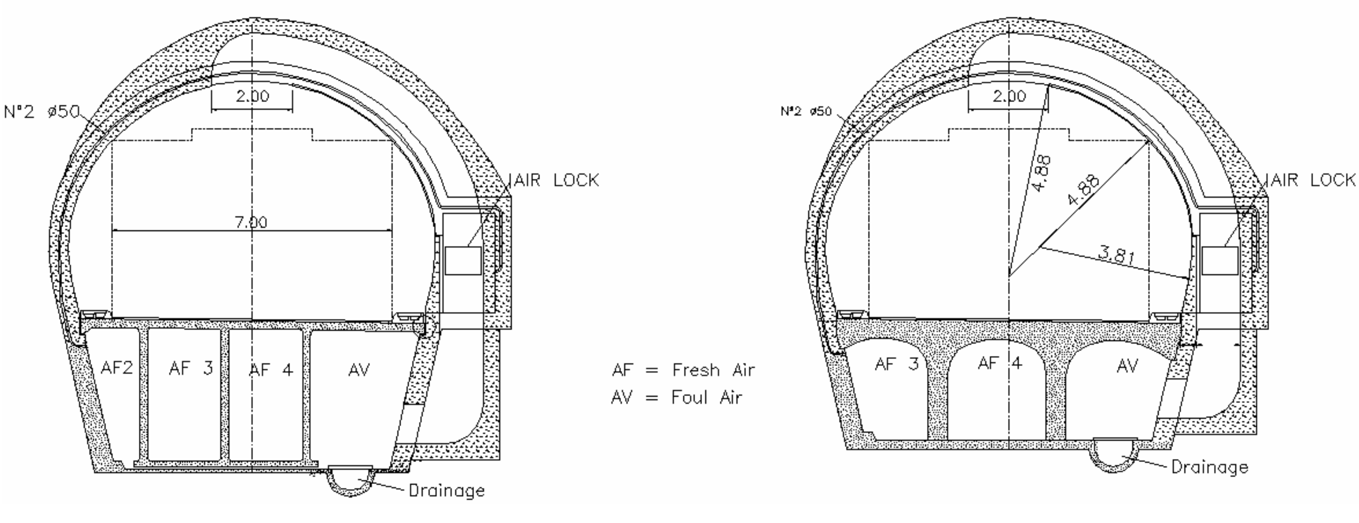

Figure 1. The two typologies of internal structure in correspondence of intake points

Along the "Italian" portion, the number of the cells varies from a maximum of five, near the entrance, to a minimum of three in the middle of the tunnel; one of the side cells is dedicated to the suction of foul air through intake points located every 300 m; the other cells are reserved to the injection of fresh air through inlets located every 10 m. For the "French" portion, the subdivision and use of the internal ducts is similar. The concrete structure is composed by precast box segments 10 m long; they rest on the bottom slab of the tunnel with the interposition of linear reinforced elastomeric bearings located under the web axes.

Figure 2. Archive photo: positioning of precast box segments and lateral haunces

The lateral haunches were installed in a second stage, rigidly fixed to the box with a cast-in-place junction, and simply supported on a longitudinal saddle provided on the lining of the tunnel. The air tightness is here ensured by means of continuous packing, which allows longitudinal movement to take place. Waterstops sealing were also provided in correspondence of the cast in place junction between lateral haunces and box structure.

Figure 3. Archive photo: the internal structure finished

Seen in cross section the structure appears as a box girder, completely independent from the lining, floating on the bottom slab of the tunnel. In the longitudinal direction, the "deck" is a continuous structure fixed at the ground in correspondence of three abutments provided at chainage 0.00, 2.900 and 5.800; the abutments were realized by anchoring special segments to the rock by means of vertical cables, subdividing the Italian portion into two segments having approximately equal length.

In transversal direction, in addition to traffic loads, the design required to account for the air pressure loads in the internal ducts, ranging from 7 to 12 kN/m^2 and the loads arising from the air temperature gradient between air in the tunnel and that in the ventilation ducts, giving rise to stresses of the same order as the traffic loads. The client organization decided to achieve the air tightness of the internal ducts without making use of either coating or painting, resorting to the prestressing of the structure. The prestress was obtained giving a permanent constraint compressive state through special "stressing sections" located every 180 m, using flat jacks uniformly distributed along the transversal section of the deck. The amount of prestress was determined in order to guarantee, accounting for the long term losses, a minimum compression stress of at least -1.5 MPa in presence of the lowest ambient temperature, during winter time; each abutment was designed to withstand a maximum design thrust of 77000.0 kN, determined on the basis of the initial prestress (without long term losses) and the maximum temperature rise. The prestressing was given following a long and complex cycle of stressing adjustment, set up in order to minimize the effect of long term losses, at the end of which the stressing sections were definitively sealed. In the service state, under the design seasonal temperature difference of 35°C, the longitudinal stress acting in the transversal deck sections could range from -1.5 to - 8.5 MPa.

1.1 *The damages*

On march 1999 the fire burst out from a truck broken down approximately in the middle of the tunnel. In this tragic event 39 people lost their lives, mainly due to the exceptionally dense smoke curtain that immediately invaded the tunnel, preventing the fire brigades from reaching the centre of the fire that was extinguished after more than 50 hours from its rise.

Figure 4. Vault and top slab damages

The most serious structural damages of the internal deck structure interested a portion about 800 m long; in this segment the concrete vault went almost completely destroyed, together with the top slab of the internal structure.

The deck structure suffered both for the presence of the vehicles burning on the top slab and for the extremely high temperatures of the air flowing into the ventilation tunnel, that caused the spalling of the concrete cover of the slab and webs in many points and the melting of the longitudinal rubber bearings supporting the lateral haunches.

Figure 5. Concrete spalling of the carriageway slab intrados

1.2 *The modernization and rehabilitation plan*

These heavy damages, in conjunction with minor damages due to the old age of the structure and, above all, the need to improve the safety standard of the infrastructure, induced the Italian and French managing firms (SITMB and ATMB) to start an intensive plan of rehabilitation and modernization.

On February 2000, the international call for tenders was won by the joint-venture SPEA Ingegneria Europea (Italy) - Scetaroute (France), whose designs were approved by an intergovernative supervising commission and, for Italy, by the National Authority for roads and highways A.N.A.S.

Here below are summarized the main works involved by the rehabilitation and modernization plan.

The first provides:

- The integral demolition and replacement of the box segments in three distinct zones, for a total length of 100 m (10 segments);
- The demolition and replacement of the concrete vault directly interested by the fire;
- The replacement of the bearings of the lateral haunces for the whole length of the tunnel;
- The repairing of the parts characterized by minor damages, with demolition and restoration of the concrete cover;

The most important structural works on the internal structure involved by the modernization plan, were related to the realization of a safety escape paths along the fresh air ducts, with:

- demolition of the diaphragm obstructing the abutment n. 3, located in correspondence of French-Italy border, which required the realization of a completely new abutment;
- realization of gaps through the prestressed box webs, fitted with air tight doors;
- improvement of the air tightness of the internal ducts, providing a special seal in correspondence of the continuous longitudinal bearing of the lateral haunces.

The other main works involved by the modernization plan, which interested the whole length of the structure, includes the realization of:

- layby's, located every 600 m, ensuring the easy U-turn of commercial vehicles;
- 37 pressurized shelters (one every 300 m), linked with the internal duct;
- fire places every 150 m, equipped with emergency telephone and fire extinguishers;
- additional smoke intakes;
- three water tanks located along the tunnel and dedicated to the fire extinguishing system
- a fire-brigade station, located in the middle of the tunnel;

In addition, the control system has been radically renewed, together with the alert-intervention procedures.

2 REHABILITATION OF THE INTERNAL STRUCTURE

The interventions provided for the rehabilitation of the internal structure consist in the repairing of the less damaged zone, where the deterioration affects generally only the concrete cover, and in the integral replacement of the precast segments characterized by damages whose repairing could have compromised the prestressing state originally provided.

2.1 *Replacement of damaged segments*

As previously mentioned, the damages suffered by the top slab and by the webs obliged to the integral replacement of the box segments in three distinct zones ("A", "B" and "C") located between the abutment "2" and abutment "3" in a range of about 800 m. In correspondence of these points the slab appeared buckled, and crossed by wide cracks through the thickness.

The sections were also tested by measuring the natural frequencies of the frame, which, compared with measures made on non-damaged sections confirmed an hard decay of the original properties. For this reason the complete replacement of the segments damaged was planned.

Due to its peculiarity, all the interventions provided along the internal box structure had to be planned in order to minimally disturb the design prestressing state imposed during the construction; in fact, the demolition of the segments, would have cause of the loss of prestress on a portion of length hardly to establish.

For this reason it was decided to "isolate" the portion under intervention, providing a provisional fixed point at chainage 4900.00, in order to preserve the restraint state due to the prestressing in the non-damaged portion. The restoring of the prestress should have been carried out acting through new "active" joints located along the replaced segments

The provisional abutment was conceived not only to guarantee the transferring of the resultant prestressing force to the rock without any slip, but also with the aim of making its realization and demolition as easy as possible. For this purpose was designed a sort of "clamping" structure, formed by an upper concrete plate, restraining the top slab, anchored to the rock with steel side cables, completed by an U-shaped concrete plate, which restrains the lower part of the deck, located into the central box and anchored to the rock with steel rods; the top and the internal concrete plates are anchored to the deck structure with steel prestressed pins. The interface between the existing structure and the "clamping" device were protected with steel plates provided in order to facilitate the removal of the elements at the end of the works.

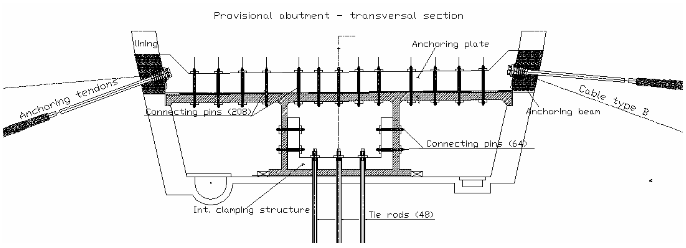

Figure 6. Provisional abutment at chainage 4900.00

The abutment was dimensioned on the basis of a maximum force of 30000 kN, evaluated accounting for the total maximum resultant force due to design prestressing force and temperature heating, plus the overstresses due to the friction losses occurring during the restressing stage of the isolated portion. The total length of the clamping structure was 24 m, needed to install the anchorages to the rock, for a total of 32 subhorizontal cables formed by 7 strands ϕ 0.6" and 48 vertical tie rods, and the anchorage of the clamping structure to the deck, for a total of 276 steel pins. The figure below shows the internal "U" shaped clamping structure before the casting. In the picture it can be appreciated the restriction characterizing the intervention conditions.

Figure 7. Provisional abutment - anchorage of the box

The demolition of the damaged segments was carried out using the hydro-demolition technology and interested a total of ten "original" segments (two segments respectively for zone "A" and "C", and six segments for zone "B") that were cut from the structure exactly in correspondence of the original joint sections. After this operation the "new" segments were cast in place in continuity with the existing, providing the accurate preparation of the joint between old and new structure, that was fitted with PVC waterstops. The demolition and casting was carried out for one segment per time.

One "active" joint was provided along each of the three interventions zones "A", "B" and "C", realized by a gap of 0.5 m, needed for the installation of the prestressing jacks. Preventive testing of the stress state of the structure carried out along the undamaged portion, gave evidence of the presence of a mean stress of -3.5/-4.0 MPa, value fairly agreeing with the original design previsions. The segment to prestress, which had a total length of 900.0 m, was instrumented providing four monitoring sections equipped with four strain gauges and seven thermometric sounds each one, in order to evaluate the actual stress during restressing for each of the four segments located between adjacent active joints and between the active joints and the abutments. Each stressing section was equipped with a total of 20 flat jacks having a maximum stroke of 100.0 mm and providing a maximum force of 1500.0 kN each.

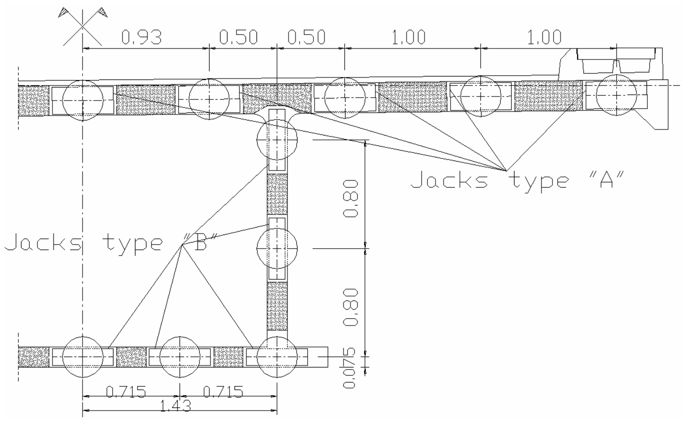

Figure 8. Stressing section

The mean target stress, depending from the mean temperature during the works, was about -4.0 MPa. The total resultant force to provided at the stressing section, reached 22000.0 kN.

Figure 9. Stressing jacks along slab and webs

The stressing operations were carried out under strain control, providing in every section a resultant force almost centered, acting cyclically on the three stressing sections. The stress was continuously adjusted until the end of the works in order to minimize the effect of long term loss affecting the new segments. At the end of restressing cycle, the jacks were replaced by steel striker devices, followed by the positioning of the reinforcement and the casting of the gap, made with low shrinkage concrete.

After the completion of the restressing operations that obviously followed the replacement of the abutment n. 3 (see the following chapter), the provisional abutment was removed by cutting the concrete plates with a diamond disk. The steel rods used for the anchoring of the bottom slab were completely removed in order to allow the restore the correct stress-strain flow between the adjacent sections.

2.2 *Repairing of the less damaged zones*

The zones characterized by minor damages, were preventively scarified with "selective" hydrodemolition; during this operation, the water pressure was accurately tuned in order to act only on the incoherent portion of concrete; after the passivation and, at the occurrence, substitution of the damaged reinforcing bars, the concrete was reconstituted operating for layers having thickness not more than 50 mm with a special low-shrinkage bi-component mortar reinforced with steel fibers.

3 REPLACEMENT OF THE ABUTMENT AT THE FRENCH-ITALY BORDER

For the restoration of the continuity of the internal ventilation ducts in correspondence of the French-Italy border, the demolition of the abutment n. 3, located at chainage 5800.00 was needed. This replacement was carried out contextually with the replacement of the damaged segments, taking advantage from the presence of the provisional abutment. The 37 m long abutment was replaced with a cast in place box segment. For the anchoring of the segment to the rock 36 sub-vertical cables made by 7 strand ϕ 0.6" were provided, located along the box webs. The design horizontal bearing capacity provided with prestressing was about 32000.0 kN, slightly greater than the maximum expected horizontal force transferred by the internal deck under the maximum temperature raising. Due to the presence of the fixed anchorage to the rock, this segment was prestressed independently, with longitudinal post-tensioned tendons providing an almost centroidal resultant. The longitudinal prestressing was realized with a total of six tendons formed by four strands each one (respectively 4 tendons and two tendons in the top and bottom slab), ensuring a residual compressive stress of about -1.0 MPa under the worst temperature condition. The stressing of these cables was carried out before the stressing of the anchorages in order to allow the free longitudinal strain of the element.

Figure 10. Replacement of abutment 3 - transition between box structure and arch structure at chainage 5.800.00

4 REALIZATION OF OPENINGS ALONG THE DECK WEBS

The accident dramatically highlighted the need to provide alternative escape paths located safe from fire and smoke. For this purpose, the pressurized shelters were linked with the fresh air ventilation ducts through appropriate escape paths.

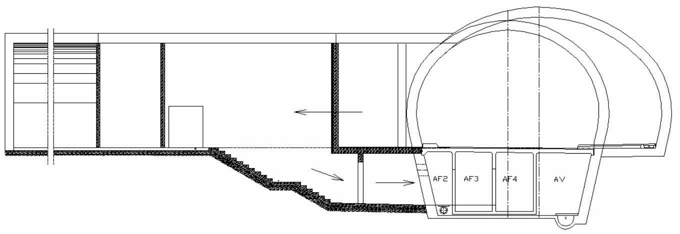

Figure 11. Evacuation path from a fire shelter

The realization of the openings along the webs of the prestressed structure required the design of special steel frames capable to resist and to properly spread the longitudinal compression stress flow of prestress acting in the webs after the realization of the opening.

The openings are of various typology, dependently from the deck cross section into which are located; they have constant height of 2.0m and length form 0.9 to 1.80 m.

As shown in the following figure, the frames are realized with large steel plates 15 mm thick forming an inverted "U", positioned outside and inside the web and connected at the base by a steel beam. The frames are connected together by 125 pretensioned pins crossing the web, dimensioned in order to ensure the transmission of the compressive force from the concrete web to the steel frame by friction.

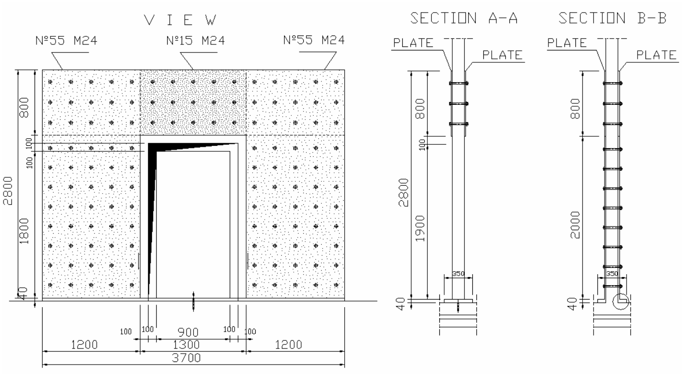

Figure 12. Steel frames for realization of web openings

The adequacy of the frame has been verified with a non linear finite element model, modeling also the interface between web and steel plate.

The sequence of realization of the opening provides was rather complicate because the frame had to be positioned and completely fixed to the web before the cutting of the opening, to avoid the formation of shear cracks due to the heavy perturbation caused by the opening and the loss of prestress the adjacent zones of the web.

The work sequence was as follows:

- preparation of the concrete surfaces;
- positioning of the inward steel plates;
- realization of the hole across webs;
- positioning of the outward steel plates;
- injection of resin through steel concrete interface;
- positioning and tensioning of the bolts.
- realization of the opening with concrete cutting using a diamond disk.

Afterwards, the frame was fitted with special airtight doors.

Figure 13. Emergency escape path from shelter - doors through the ventilation ducts

5 CONCLUSIONS

This paper describes the main interventions carried out for the rehabilitation of the internal structures of the Monte Bianco Tunnel after the tragic fire of march 1999. The originally adopted design solution provides an internal prestressed structure similar to a box girder, whose internal cells are used for canalization of fresh and foul air.

The replacement of the damaged portions of this structure, and the realization of the escape facilities, required the set up of a special intervention strategy aimed at the preservation of the original imposed prestressing state needed to ensure the air tightness of the ventilation system.

These interventions belong to the extensive modernization plan that started after the accident and whose works were completed in an extremely short period of time, which allowed the reopening of the infrastructure on February 2001.

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