Analysis of cracking in tunnel lining segments

A. Focaracci
Prometeoengineering.it srl, Rome, Italy

SUMMARY: The article describes the study carried out with the purpose to seek the probable causes that have provoked an overall systematic description of the cracks in the works of covering for the tunnel dug with TBM and covered throw prefabricated structures in armed concrete. First of all, it is analysed carefully the overall systematic description of the cracks and in addition the operating methods of excavation and covering. This analysis allows to underline that the reasons for the cracking phenomenon are to return several factors connected to ground conditions and to the presence of layer, to work conditions and to static aspects of the covering. In underground works realized with cutter, these factors are closely related and strongly linked together and lead to undesired effects, in the adverse coincidence

1 INTRODUCTION

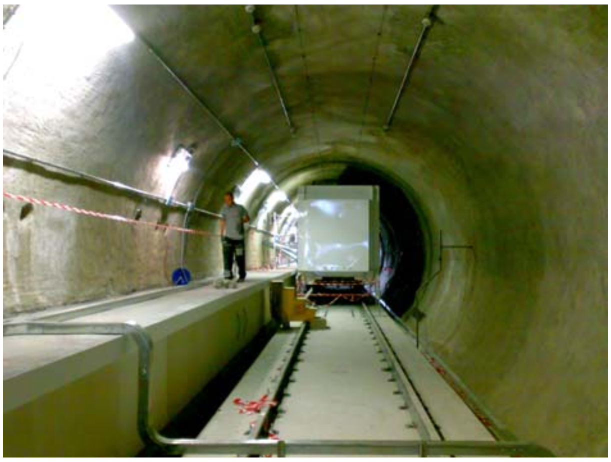

Figure 1 Fire experiments at Montelibretti – A test tunnel with the body of a carriage from Line C of the Rome Metro

The safety design for a road or rail tunnel must take full consideration of studies of thermal fluid dynamic phenomena resulting from an accident in a tunnel in order to understand the possible effects on people exposed to danger within the tunnel over a determined period of time as a result of vehicles flowing through it.

The formulation of safety designs for many new or existing tunnels has led to the development of a large number of innovative solutions. Work has been done in many fields, but mainly with a view to providing solutions for priorities set by regulations which, following a totally prescriptive approach, had been completely forgotten in the past. I refer in particular to systems to facilitate evacuation, to improvements in the fire resistance of structures and to fire fighting systems. Some of these design solutions are illustrated here.

Passive measures for the evacuation of persons from a tunnel include the fundamental role played by structural considerations and by the resistance of structures to fire in particular.

Figure 2 Longitudinal cracks in the prefabricated segments of TBM driven tunnels

A study was conducted to find the probable causes which often lead to cracking phenomena in tunnels excavated by TBMs and lined with prefabricated rc segments (a system employed mainly in the construction of underground works near the surface in urban contexts such as those for metropolitan railways) .

The phenomenon of cracking is complex and in all probability is the combined result of geomechanical factors, the methods used to place concrete and also of the statics. These aspects are common in the construction of tunnels using full face tunnel boring machines with and without earth pressure at the face.

The analysis was then broadened to include the possibility of reducing cracking phenomena by using materials such as fibres, both metallic and synthetic. At the same time the response of concrete segments to fire was studied using data acquired from specially designed models.

Figure 3 Cracks in the prefabricated concrete segments of TBM driven tunnel

Concretes reinforced with both metallic and polypropylene fibres, termed fibre reinforced concrete (FRC) are innovative products developed in the nineteen seventies. They can increase the fire resistance of concretes in conditions where there is a danger of fire.

The idea of inserting fibre reinforcement in a material to improve its properties dates back a long time. The use of short discontinuous fibres distributed evenly within a concrete matrix confers greater strength to the concrete to withstand cracking and as a consequence improved performance in terms of durability, even when subject to high temperatures.

These characteristics of fibre reinforced concrete have been used in a study on prefabricated segments for the construction of tunnels using TBMs under all the load conditions to which the prefabricated components are subject during their normal life.

Italian safety regulations for road tunnels are contained in Legislative Decree No. 264 of 5th October 2006 entitled "The implementation of EC Directive 2004/54/EC concerning the safety of tunnels in the trans European road network", which implements that directive. The legislation governing the rail network is the Decree of the Ministry of Infrastructures and Transport of 28/10/2005 in Italy and the EC Directive 2008/163/EC entitled "safety in rail tunnels in the conventional and high speed trans European rail network" in Europe.

These regulations identify fire as an initiating event and set the following objectives to be achieved by the infrastructure: "*The integrity of a structure must be maintained in the event of fire for a sufficiently long period to allow first-aid to be given and passengers and personnel to be evacuated and rescue teams to operate without the risk of structural collapse.*

The fire experiment on the body of a vehicle from Line C of the Rome Metro at the fire fighting school at Montelibretti was conducted in this context. It allowed information on all the necessary factors concerning structure, systems, plant and thermal fluid dynamics to be acquired for the formulation of a specific and innovative design for structures in tunnels and for prefabricated segments in particular, because it was obtained directly from full scale tests.

2 STRESS-STRAIN ANALYSIS OF PREFABRICATED CONCRETE SEGMENTS FOR TUNNELS

2.1 Background

A study was conducted on the structural behaviour of prefabricated concrete segments used in the construction of tunnels with reinforcement distributed throughout the entire volume. Finite element analysis (FEM) was performed on the stress-strain state under the different load conditions to which the prefabricated components are subject during their normal life.

The forces exerted on the segments in a tunnel are the result of both transitory conditions such as those of the transport, placing and thrust of the jacks and permanent forces such as the earth pressure when in service or the fire load generated as the result of an accident.

The assumptions made to construct the model simulate the geometry of the curve of the segment and the constraint conditions, even for faults in assembly, where a yielding support was modelled to simulate an imperfect joint between one ring of segments and the next. As concerns earth pressure, it was decided to apply a load distributed on the edge of the segment by studying the effect of a change in this load resulting from corrections to the direction of the cutter.

The model constructed was designed to identify possible concentrations of stresses and to understand the possible improvements that changes to the normal reinforcement used in these structures might have on the distribution of the stress state in the lining rings.

An analysis of the operations connected with the service stage found that conventional reinforcement distributed evenly within prefabricated segments does not withstand the stress state that is generated as well as it might. The stress state in the operations for the removal of the forms, handling, storage and transport is typical of simple bending with minimal loads compared to those encountered during assembly and service. The strength of the conventionally reinforced section is much higher than the performance actually required of it.

One of the particularly onerous load conditions is generated by the thrust of the jacks for TBM advance. In this situation the concrete segments are subject to very strong loads which are borne under poorly defined conditions due to inevitable irregularities in the plane in which they bear against the previous ring and to possible assembly faults already mentioned.

It is clear from the analysis performed that one of the main causes of cracks which are often found in the concrete segments of tunnels excavated using TBMs, as already mentioned, is faulty assembly when the fit with the previous ring, especially with regard to the key segment, is not implemented properly leaving it raised (the key segment is slightly higher than the other segments in the ring) or depressed (more likely when the key segment sinks too deeply into the ring). In addition, frequent changes of direction are required to follow changes in the alignment of the tunnel and to maintain the shield on the alignment and these are effected by adjusting the hydraulic pressure in the jacks which are divided into four groups each of which with four jacking units.

Various analyses were therefore conducted to simulate the imperfect alignment of the key segments by reducing the elastic modulus of the bearing surface, limited to one part of the elements into which it was divided.

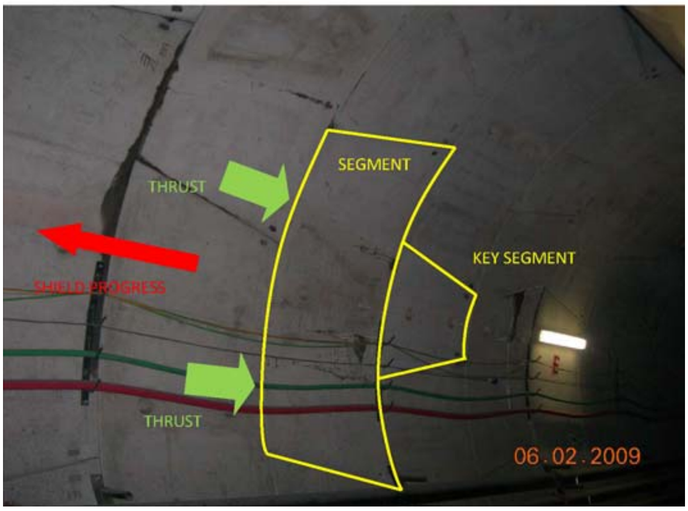

Figure 4 Diagram of the conditions analysed

The strong forces of friction that must be overcome may depend basically on two factors, the fact that the pozzolana that is excavated, ground to a powder and mixed with foam tends to grip around the shield and that the machine fits very tightly in the excavated tunnel.

The considerations made led to the conclusion that three courses of action needed to be taken to solve the problem of cracking:

– reduction of the thrust, which can be achieved by increasing the foam injections through the nozzles at the cutter head, injecting bentonite along the shield and increasing the excavation diameter of outermost tool accompanied by an increase in the bi-component mortar injection to limit the increase in the loss of volume due to over break;
– greater care in the erection of the rings, with attention paid to see that the face of the ring to which the thrust is applied is free from sunken and raised segments;
– reinforcement of the edge of the concrete segments on the side opposite to that which bears the thrust, by increasing the existing reinforcement to withstand the tendency of cracks to form more effectively.

Finite element method (FEM) analysis of the thrust phase under theoretical and therefore optimum conditions shows that the stresses along the tunnel alignment are all compressive stresses, while those perpendicular to it are generated in the tensile zones concentrated on the side on which the thrust is applied.

In the absence of assembly defects, the stress values produced are generally compatible with the strength characteristics of the materials employed, even when the pressure is greater than that of the design specifications. The compressive stresses fall within the limits of the class of concrete employed and the tensile stresses, which are always lower than those specified by regulations, can be easily withstood by the reinforcement.

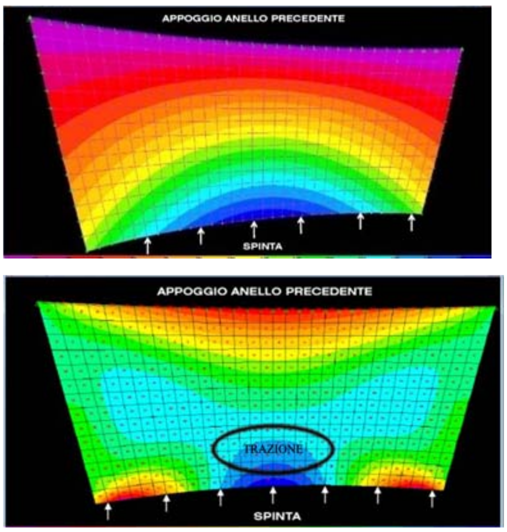

Figure 5 Ideal thrust conditions – Deformation a stress perpendicular to the direction of thrust

In the presence of “assembly defects” and/or exceptionally high thrust values, the compressive and tensile stresses on the surface bearing against the previous ring rise to adjust the stress conditions to the absence of an area on which to bear and to absorb the excess thrust. The stress peaks generated on the edges of the zone where the support is missing, and that is opposite those of the thrust, can cause the origin and propagation of cracks.

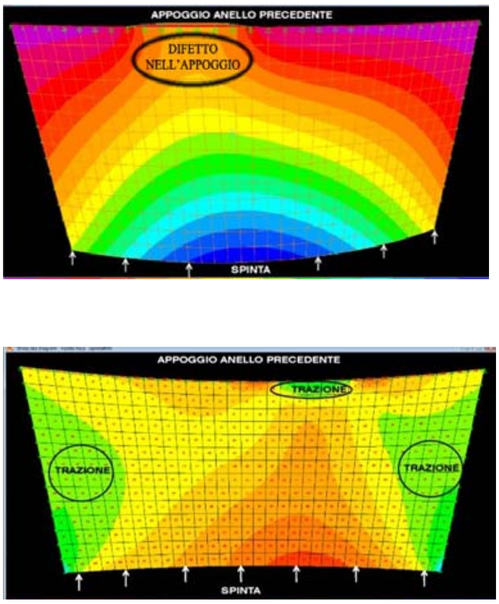

Figure 7 Thrust conditions with assembly defects – Deformation and stress perpendicular to the direction of thrust

These considerations lead to the conclusion that reinforcement should be placed on the side opposite that of the thrust to withstand the stresses resulting from the ring assembly operations.

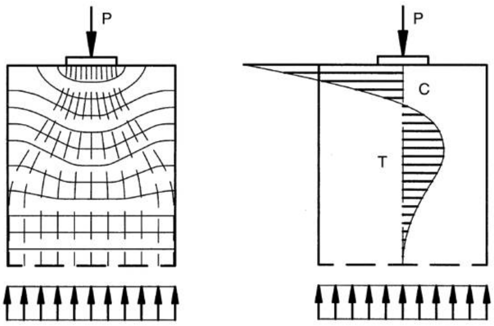

Figure 6 Stress state due to the concentration of a compressive force

One further aspect analysed during the thrust operation is that of the concentration of the compressive stress on a reduced area consisting of the thrust distribution plate of the jacks.

The compressive force in this area spreads into the concrete to produce a linear distribution of the stresses on the cross section. The compressive stresses deviate from the direction parallel to stress as they spread and this produces high transverse compressive stresses immediately after the anchor plate and subsequently transverse tensile stresses.

These stresses, termed "bursting stresses" are caused by the diffusion of the concentrated force and are attributable to the curve in the trajectory of the compressive stresses. They normally act in the direction in which the load is applied and reach a maximum at a short distance from the surface loaded.

These types of stresses inside a concrete segment act by means of a three dimensional stress state which can be countered by placing longitudinal and transverse reinforcement (i.e. tied bars which also generate a beneficial confinement effect on the concrete) designed to "sew together" the zones in which cracks form.

Subsequently, on the basis of the data considered so far, the Montelibretti fire experiment was used to study the possibility of improving the conventional reinforcement with the addition of steel and polypropylene fibres to withstand both structural loads and those resulting from fire.

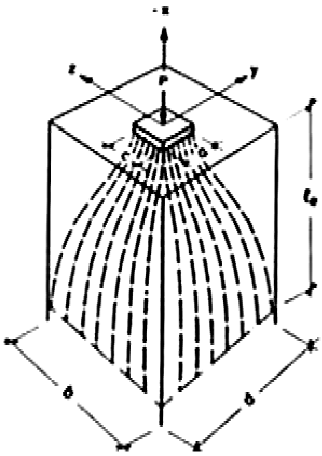

Figure 7 Bursting stresses - 3D stress state

The addition of steel fibres distributed in a concrete matrix modifies its mechanical properties. It improves the tensile behaviour and counters the progressive opening of cracks.

The fibres make their contribution once the matrix has begun to crack, by conferring a post-cracking strength on the composite material which is absent in matrices without fibres.

The strongly degenerative behaviour, typical of a mono-axial tensile test on concrete, can be significantly modified by the addition of fibres, as the percentage volume is increased. The fibres also improve the tensile behaviour of the matrix during cracking, conferring residual strength capacity on it.

The use of short discontinuous steel fibres uniformly distributed inside the concrete matrix confers greater resistance to cracking on the material and improves performance in terms of durability as a consequence.

These properties suggested that steel fibre reinforced concrete (SFRC) should be used for prefabricated concrete segments in TBM driven tunnels to partially replace the use of conventional reinforcement. As concerns polypropylene fibres on the other hand, their low resistance to fire can be exploited as an advantage to reduce the problem of spalling in high strength concretes.

In fact high strength concretes have little permeability and therefore the water vapour that develops inside the material at high temperatures cannot escape from the concrete until concrete material itself is expelled by the pressure of the water vapour.

When the fibres dissolve, vacuoles are created in the matrix of the concrete which allow the water vapour under pressure to escape through them thereby preventing the concrete from exploding and shattering.

An experiment was conducted at the Montelibretti school for fire-fighters designed to seek the best solution from the viewpoint of fire resistance and consequently of safety for tunnel users in cases of emergency. A test tunnel was therefore designed in which different types of concrete segment were employed, both prefabricated and cast *in situ*, with and without the addition of steel and polypropylene fibres in varying amounts.

2.1 *Fire experiment with the body of a carriage from Line C of the Rome Metro*

The main feature of the future Line "C" of the Rome metro is that is an automatic metro with no train drivers on board and with platform doors installed in the stations.

Figure 8 A three dimensional model of the body of a carriage from Line C of the Rome Metro

While on the one hand, the new operating configuration tends to increase the intrinsic safety of the transport system, on the other hand there are problems concerning knowledge of the consequences of possible fires in tunnels. In fact the platform doors constitute a true and genuine longitudinal continuity with regard to fluid dynamic models and they require careful assessment of the input data, such as the heating power produced, the time taken for fire to develop, the emissions produced and flashover phenomena.

The experiments programmed inside the test tunnel with a "sacrificial vehicle" allowed sufficient data to be acquired for subsequent simulations to be performed using physical and mathematical models.

Passenger safety in the event of a fire on a train in a metro tunnel was one of the most carefully studied subjects in the design of Line "C" of the Rome Metro. A memorandum of intent was signed between Roma Metropolitane S.r.l., Metro C S.c.p.A, the Fastigi Consortium, Ansaldo Trasporti Sistemi Ferroviari S.p.A., Ansaldo Breda S.p.A. and the Train Consortium to study the issues and to conduct a fire experiment on the body of a carriage from Line "C" of the Rome Metro.

Figure 9 Partners involved in the experiment

The assumptions adopted in the design needed to be confirmed and the system choices and structural behaviour needed to be verified with a real fire experiment in which one of the carriages to be used on the line in service was burnt, with the creation of an environment as similar as possible to that of a real tunnel on the metro line.

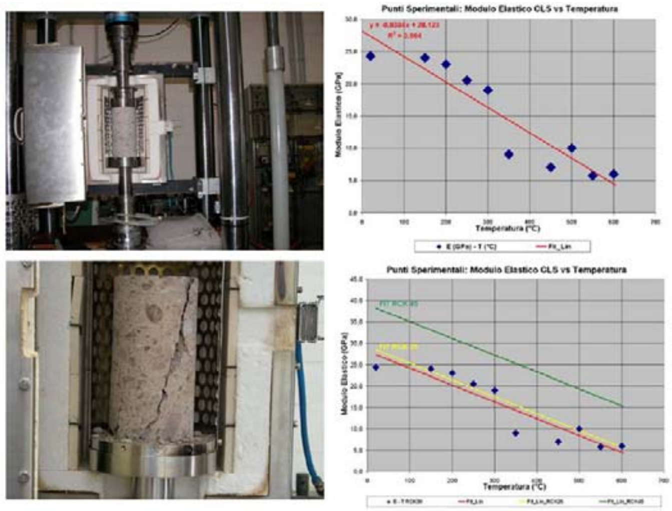

Figure 10 Experimental tests – Changes in the strength characteristics of the materials with temperature

Performing the experiment made it possible to test and validate on a final basis the simulations carried out at the design stage. This constituted a unique case of national and international value which will provide unconfutable data not only for Line "C", but also for all other metropolitan railways, for better formulation of fire prevention and protection strategies and for passenger evacuation strategies.

The site selected to perform the test was the Firefighters Operational Training School at Montelibretti after a tunnel 110 metres long was constructed inside the school with the same dimensions and functions as that of Line "C".

Figure 11 Test tunnel at the Montelibretti school for fire-fighters

Figure 12 The constructio n of the test tunnel at the Montelibretti school for fire-fighters

This tunnel was constructed according to the design, partly using prefabricated concrete segments (the same as those used to line the TBM tunnels of line "C"), some of which containing fibre additives, and partly using segments cast *in situ* in order to test different lining combinations.

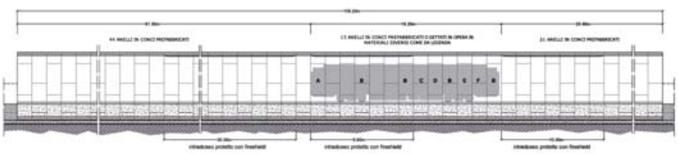

Figure 13 Detail of the rings where the carriage to be sacrificed was positioned according to the design

The design specifications for the part of the tunnel (14 segment rings) in which the carriage body to be sacrificed was positioned were as follows:

– 6 rings with completion of the upper half-ring cast in situ;
– 8 rings constructed using different types of concrete containing metal and/or polypropylene fibre additives;
– 7 rings starting from the centre protected with "fireshield" fire resistant mortar.

The composition of the rings is shown in the figure below.

While the general design remained unaltered, the following were constructed:

– 5 rings with completion of the upper half-ring cast in situ of which 4 with concrete containing steel and polypropylene fibre additives (type C* solution) and one ring with concrete containing no additives;
– 1 ring with normal concrete according to the design;
– 1 ring with prefabricated concrete segments constructed with the addition of steel fibre reinforcement according to the design (type A solution);
– 1 ring with prefabricated concrete segments constructed with the addition of steel fibre reinforcement optimised according to the procedures illustrated in the calculation report (type B solution);
– 1 ring with prefabricated concrete segments constructed with the addition of steel fibre reinforcement according to the design and with polypropylene fibre reinforcement (type C solution);
– 1 ring with prefabricated concrete segments constructed with the addition of steel fibre reinforcement optimised according to the procedures illustrated in the calculation report and with the addition of polypropylene fibres (type D solution);
– 4 rings with conventional prefabricated concrete segments according to the design.

The test was performed by recreating the conditions specified in the design for Line "C" and therefore the configuration of the site and the materials used were maintained as similar as possible to that design.

The objectives achieved by the test were as follows:

– to measure the curve of the heating power emitted by the vehicle, the maximum power developed, the critical velocity of expansion of the fumes and the fire load of the vehicle;
– to monitor the parameters of the combustion products and of the substances released, the temperatures, the visibility following the concentration of the fumes, etc.;
– to verify the system choices for the design of Line "C", with particular attention paid to the safety measures;
– to test the structures of the tunnel following the fire.

The experiment made it possible to acquire all the elements needed to formulate a specific and innovative design for structures in tunnels, because obtained directly from full scale tests.

It is clear from the first results that the addition of steel fibres can lead to a reduction in the use of conventional reinforcement of more than 40% and at the same time results in greater efficiency at high temperatures, assisted by the introduction of polypropylene fibres.

These considerations led to the proposal of a design for prefabricated concrete segments which involves abandoning the use of conventional reinforcement distributed throughout the volume in favour of prefabricated structures with steel and polypropylene fibres added to the entire volume with the addition of an edge in conventionally reinforced concrete, which runs along the outer perimeter where the finite element analysis and experimental results showed that stresses were concentrated.

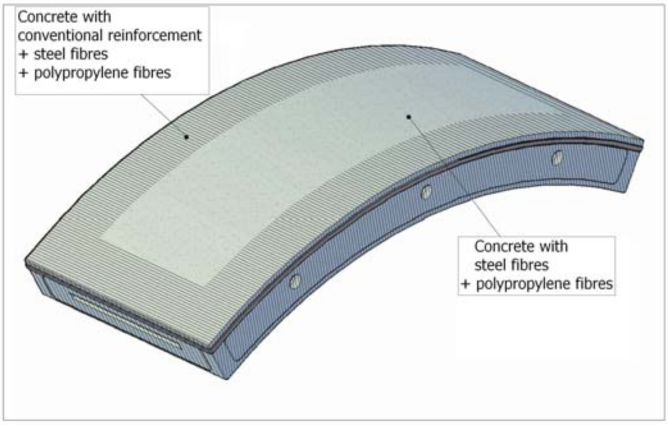

Figure 14 Design solution for segments with optimised conventional + fibre reinforcement

Verification of this type of solution showed that optimised conventional plus fibre reinforcement, as illustrated in the figure above, produces a configuration of strength to the section capable of withstanding all the load combinations generated by the ground in the short and long term.

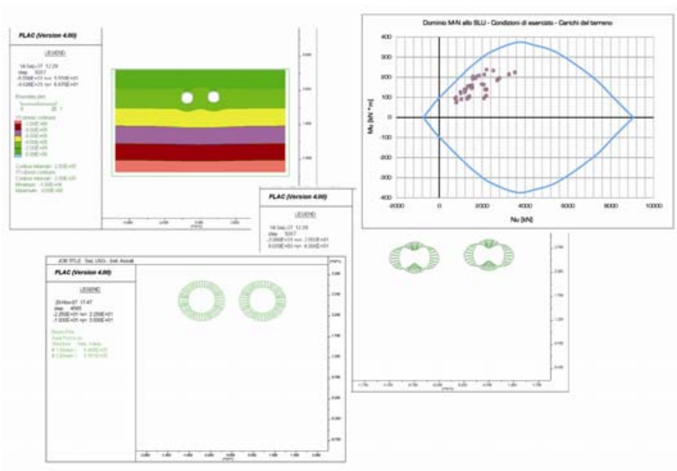

Figure 15 Verification of a section of concrete segment with reinforcement optimised for loads from the ground

At the same time the configuration is also capable of preventing possible cracking phenomena due to transitory conditions such as handling and assembly with the thrust of the TBM.

3 CONCLUSIONS

A correct engineering approach involves both developing design solutions with a passenger safety orientation by improving evacuation processes and also in-depth study of the response of a tunnel to fire by using mathematical models.

The most effective measures, as demonstrated by the application of the Italian Risk Analysis Method (IRAM) on more than 300 km of road and motorway tunnels, are those given in paragraph 2.3 and those that follow of Legislative Decree No. 264/06: escape routes and emergency exits; access for first aid and rescue services; parking places; drainage, resistance of structures to fire, etc. This study on the structural behaviour of prefabricated concrete segments for TBM driven tunnels, performed using finite element method analysis of the stress state and deformation under different load conditions to which the prefabricated components are subject during their normal life falls within this context.

Careful examination of cracking phenomena by means of the analysis performed here resulted in the generation of FEM models that were used to study the probable causes of the phenomenon from a structural viewpoint and therefore to seek possible solutions in terms of both construction measures and the characteristics of the structural components of the concrete segment linings. It was clearly found that action needed to be taken in a number of directions to prevent the manifestation of the cracking encountered by adopting one or more of the following approaches:

– reducing the values of the forces applied;
– adopting specific measures during assembly;
– introducing extra reinforcement additives.

The experiment of a fire in a carriage from Line “C” of the Rome Metro in a test tunnel at the Montelibretti school for fire-fighters constituted a natural continuation of that work. Its objective was to furnish data on the response to fire of the systems and structures of the future Line “C” of the metro, i.e. those dedicated to the safety of tunnel users.

These data were used to formulate a specific and innovative design for structures in tunnels and for prefabricated segments in particular, because they were obtained directly from full scale tests.

4 REFERENCES

Focaracci A. 1999. Gestione progettuale dei preconsolidamenti III *Sessione delle Conferenze Permanenti sull’Alta Velocità, Bologna, 24 giugno 1999*

Focaracci A. 2005. La Gestione progettuale e costruttiva delle Gallerie, *Gallerie e Grandi Opere sotterranee*, n 76 Bologna, agosto 2005 Patron Editore

Focaracci A.,Mattei M. 2007. Le gallerie oggi e nella storia, *Le Strade*, n.6, Milano giugno 2007 La Fiaccola srl

Focaracci A. 1991 - Interventi conservativi: aspetti riguardanti l'impresa specializzata. *Convegno su il consolidamento del suolo e delle rocce nelle realizzazioni in sotterraneo, Milano - Marzo 1991*

Focaracci A. 2007. Utilizzo del sottosuolo in area urbana, *Le Strade*, n.9, Milano settembre 2007 La Fiaccola srl

Focaracci A. 2008. Il preconsolidamento del fronte, *Le Strade* 3/2008 Milano La Fiaccola srl

Focaracci A. 2008 .La galleria Frena, *Le Strade* , 12/2008 Milano La Fiaccola srl

Lunardi P., Bindi R., Focaracci A. 1989. Nouvelles orientations pour le Project et la construction des tunnels dans des terrainsmeubles. Etudes et expériences sur le preconfinement de la cavité et la preconsolidation dunoyau au front. *Colloque International "Tunnels et micro-tunnels en terrain meuble - Parigi 7-10 Febbraio1989*

Lunardi P., Focaracci A 1998. Mechanical pre-cutting for the construction of the 21.5 m span arch of the “Baldo degli Ubaldi” Station on the Rome Underground *Atti del Convegno Internazionale su "Tunnels and Metropolises”, São Paulo, 25-30 aprile 1998*

Lunardi P., Focaracci A.1998. Quality Assurance in the Design and Construction of Underground Works *Convegno Internazionale su "Underground Construction in Modern Infrastructure" - Stockholm 7-9 Giugno 1998*

Lunardi P., Focaracci A.. 2000 - Modern Tunnelling in Italy for High Speed Railway Line, *Bauma 2001 Munich, zud to 8 th*

EU Directive 2004/54/EC concerning the safety of tunnels in the trans European road network”

EU Directive 2008/163/EC entitled “safety in rail tunnels in the conventional and high speed trans European rail network