A new approach in the design of first lining steel rib

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ABSTRACT

In recent years considerable advances have been taking place worldwide in the design and construction of first tunnel linings. Included in these advances, there is a tendency to move away from traditional support that includes heavy open profiles of rolled steel arches, to a lighter solution with the use of an optimize tubular steel cross section rib, and shotcrete reinforced with steel mesh and/or steel fibers, providing a continuous support (Lunardi, 1982). The development of tubular ribs has provided to engineers and contractors greater design options, increasing flexibility and bringing an efficient construction cost effective method

In this paper the authors describe numerical and experimental investigation on this, suggesting a new first lining steel arch design approach by using tubular ribs cross section as new technical solution for first lining underground support.

1 INTRODUCTION

Ground-lining interaction control is one of the most critical processes during a tunnelling project implementation. Some of the design and construction decisions during a tunnel project are very critical to reduce the ground movements around the excavated tunnel.
These movements have a direct effect on the tunnel stability and the design load of the lining system (Lunardi et al., 1994).

Tunnel linings are structural systems installed during and/or after excavation to provide ground support, to maintain the tunnel opening, to limit the ground water inflow, to support appurtenances and to provide a base for the final finished exposed surface of the tunnel. Tunnel linings can be used for initial stabilization of the excavation, permanent ground support or a combination of both (Hoek E. et al, 1981).

Tunnel linings are structural systems, but differ from other structural systems in their interaction with the surrounding ground, which is an integral aspect of their behavior, stability and overall load carrying capacity. The loss or lack of support provided by the surrounding ground can lead to a failure of the lining. The ability of the lining to deform under load is a function of the lining relative stiffness and the surrounding ground (Beiniawski, 1984). Frequently, a tunnel lining is more flexible than the surrounding ground. This flexibility allows the lining to deform as the surrounding ground deforms during and after tunnel excavation. This deformation allows the surrounding ground to develop strength and stability. The tunnel lining deformation allows the moments in the tunnel lining to redistribute the main load inside the lining which are axial or eccentric load. The most efficient tunnel lining is one that has high flexibility and ductility.

Open steel profiles (IPE, HE, IPN) typically used as first lining support, show performance weakness in their static structural properties in directions different than the normal and central position. In reference to particular local conditions a closed circular profile

will bring a better performance conditions compare to an open profile. As an example of particular local condition there is a non homogeneous contact between the profile and the soil, which may occur during the tunnel excavation progress and not always found a plane strain state. It is also acceptable to assume the worst performance conditions for a double "T" profile in the presence of a horizontal load component (see Figure 1.a). These problems can be solved using a symmetrical axial cross, like a tubular rib. Substituting the open profile with the circular profile, with the same area, you get a better stress redistribution, which ensures to the resistant cross section, the ability to take control of axial and eccentric loads, acting along any direction (Bringiotti, 2003).

2 NUMERICAL ANALYSIS

Some numerical analyses have been made prior to the experimental activity. Those focussed to find the correct profiles to compare.

The numerical evaluations started to consider cross section area, moments of inertia and resistance modulus. This first assessment has been made to define which profiles to compare. The different sections have been evaluated considering the behaviour of composite section in terms of diagrams N-M (Axial Force and Bending Moment, see Figure 1.b). The calculation is in compliance with the requirements of Eurocode 4 and NTC 2008 (Italian Standard Reference).
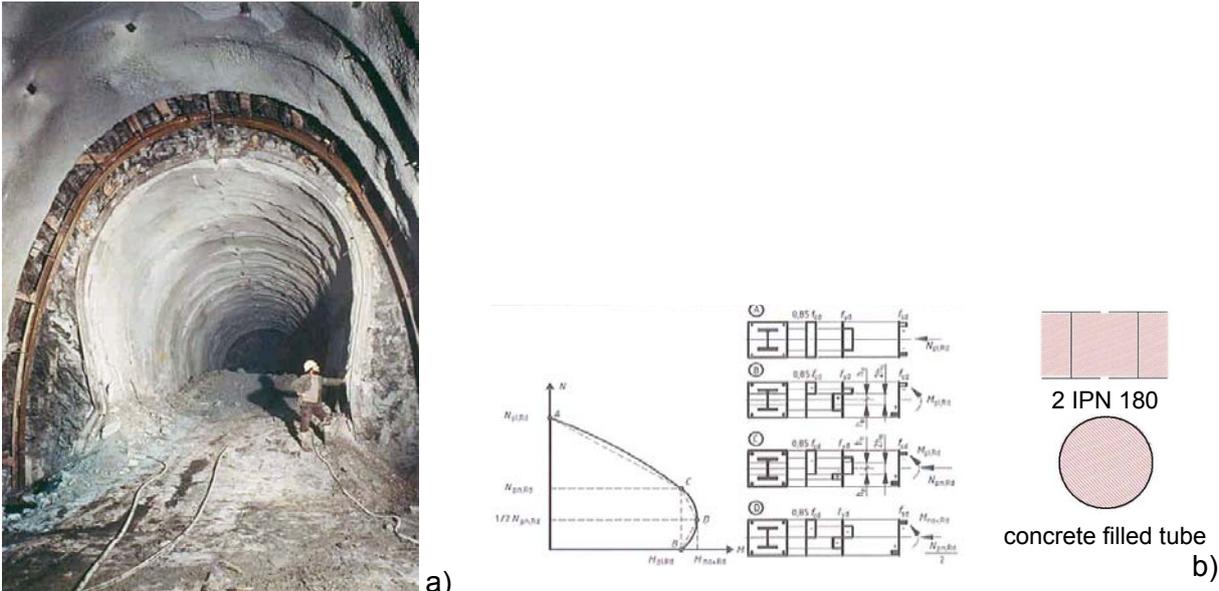
Figure 1 – a) Example of open profile buckling; b) Calculation of the N-M domains for the two steel section types considered collaborating with the concrete filling (Eurocode 4, 2004)

Some assumptions have been introduced in the calculation:
- It is not considered progressive damage of the section. This hypothesis turns out to be an improvement in the expected behavior of the standard rib. This assumption neglects the change of position of the neutral axis, caused by progressive damage of the concrete filling, considering this, one the main cause of instability of open profiles ribs.
- Tube ductility capability due to its geometry is not given. The circular profile uses gradually its own ductility capability, allowing their full exploitation. This is basically the worst condition for the tubular rib, which deliberately neglects its geometrical advantage.

These choices have been made to be sure to determine, in a preliminary phase, the circular profiles which certainly would have matched the performance of open profiles.

One of the most important causes of a rib instability of is the presence of eccentric loads, which cause horizontal load components. This fact generates high bending moments

which the geometry of the standard ribs, made by open profiles, is not able to take control. The consequence is the necessity to use largest profiles.

Referring to the diagrams propose in Figure 2.a), which represent all the resistance domains analyzed, it is possible to see a resistance domain of steel-concrete section wider for circular section characterized by a diameter of 224,5 mm with a thickness changing from 6 to 10mm. This provides an increased resistance in compression and bending stresses. The numerical analysis shows also the different behaviour of Standard Rib along "x" and "y"axis.

As a consequence of the assumption adopted during numerical analysis it have been decided to compare the *Standard Rib* with two different *Tubular Ribs*, the ones which reach the maximum bending moment of *Standard Rib* along "x" and "y" directions (Figure 3.b).This decision have been taken because the real behaviour of *Standard Rib* is something in between the ones along x and y axis.

The laboratory experimental activity compared three different types of ribs:
- <u>TSH-T5</u>: *Tubolar Rib* - hollow profile circular section Φ 244.5 thickness = 5mm - S275;
- <u>TSH-T6</u>: *Tubolar Rib* - hollow profile circular section Φ 244.5 thickness = 6mm - S275;
- <u>2 IPN 180</u>: *Standard Rib* - 2 profile IPN 180 connected by 25cm IPN 160 – S275.

It is chosen as *Standard Rib* one of the most common profiles used in Italy.
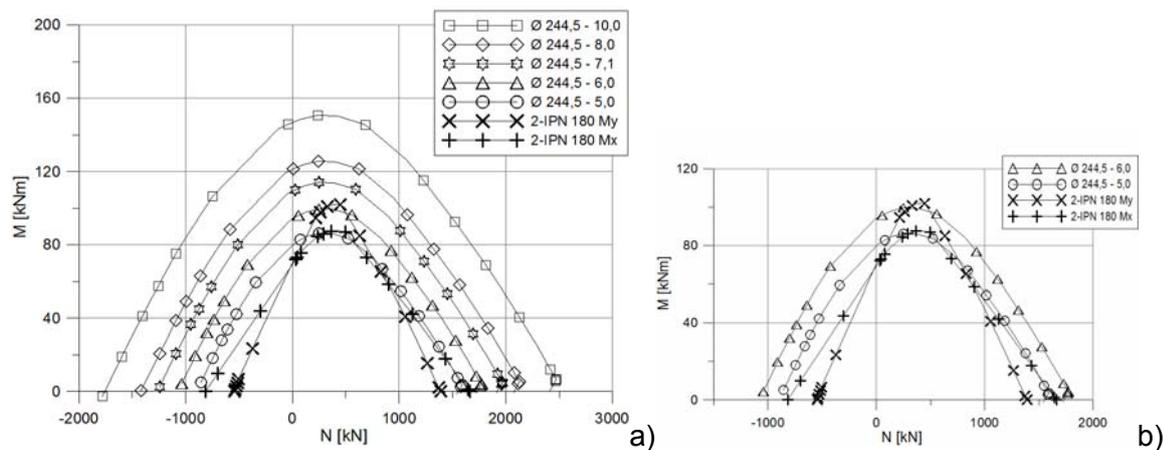
Figure 2 - Resistance Domain Comparison: a) all profiles analyzed; b) profiles selected for experimental activity (convention: positive compression strength);

3 EXPERIMENTAL ACTIVITY

The experimental work was carried out in two phases. The first, conducted in the laboratory, necessary for the validation of numerical analysis. The second, conducted on site in order to compare the structural response of the two types of ribs, the standard one and tubular one.

3.1 Laboratory Test

Laboratory Tests were carried out at Politecnico of Milan. For each type of rib <u>4 samples</u> have been prepared, two to be tested at 24 hours and two to be tested 48 hours after filling.

The samples were prepared in a job site in Milan. The filling concrete wasn't prepare in laboratory because it is our interest to use one typically used in a job site and fill the sample with a sprayed concrete machine. The filling operation of the tubular hollow section was really simple. The filling operation of Standard Rib was not so simple, and the necessity to have a complete filled sample let brought to obtain a trapezoidal sample instead of the desire rectangular section, as showed in Figure 3.a) and b). The samples have not been adjusted to avoid their damage but it was necessary to study by a new numerical analysis the trapezoidal sample resistance domain, Figure 3.c). The calculations highlight more than 15%

strength increase in terms of maximum bending moment, which changes its value from 87.7 kN-m to 104.9 kN-m.

Figure 4 shows the static scheme used during the tests, it is referred to a 4-point flexure test. This test condition represents the ideal load condition for standard ribs. It have been chosen to demonstrate that in the ideal conditions for the standard rib, the tubular rib can match the same performance. If this happens there are "n" load conditions in which the tubular rib has a better performance than the standard one. For example it enough to introduce a small eccentricity in the load to cause the instability of traditional rib, while in the case of the tubular this does not cause any effect since it is an symmetrical axial profile.
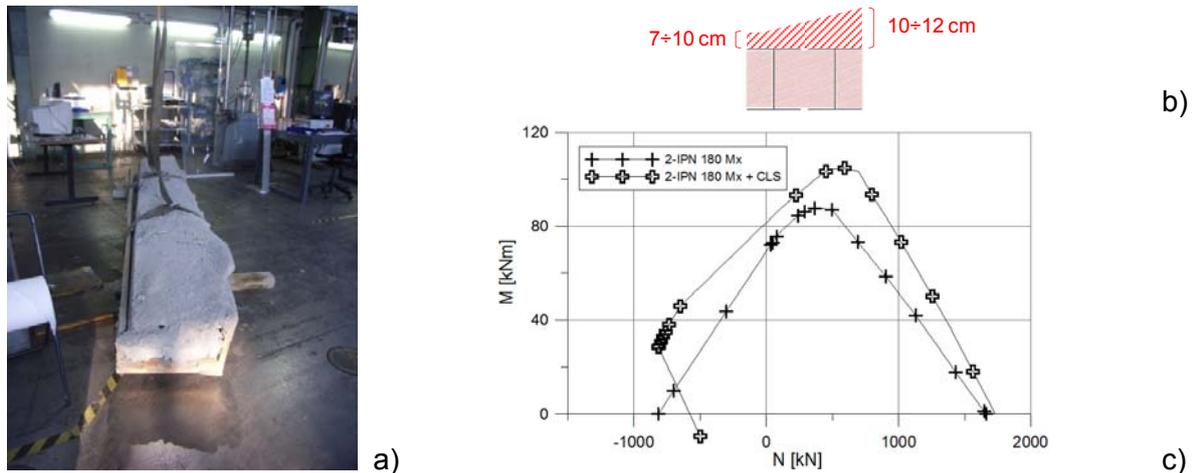
Figure 3 – Standard Rib sample: a) Photo; b) Geometrical scheme; c) Resistance Domain evaluation.
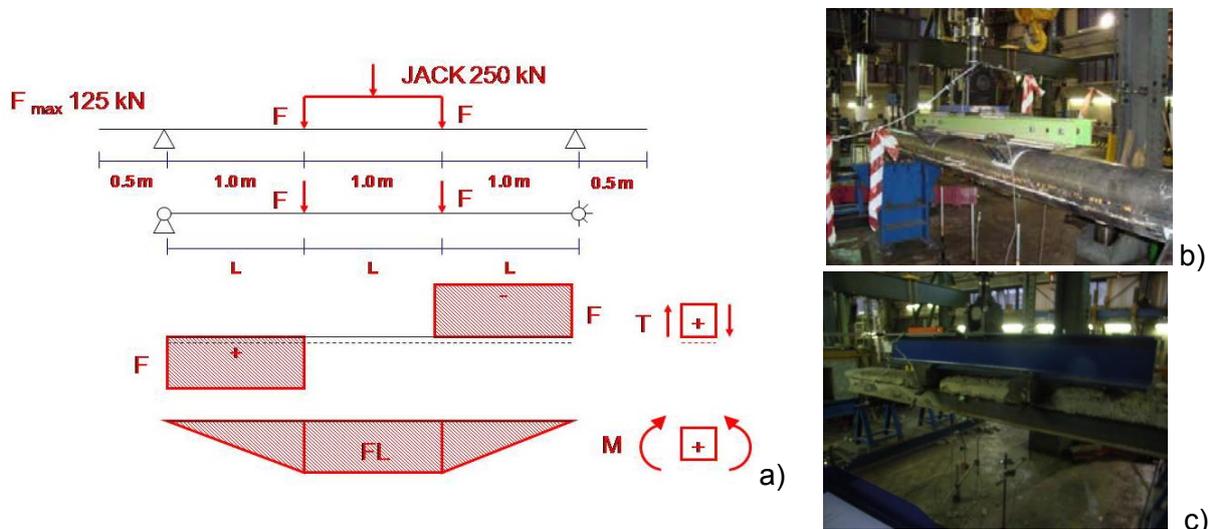
Figure 4 - Test set up: a) Static scheme; b) Tubular rib; c) Standard Rib.

Figure 5 summarize the test results. Looking at the results, it shows the *Standard Rib* characterized by an elastic plastic behaviour, while *Tubular Ribs* show an elastic hardening behaviour. In the recent years, for example in seismic design, it has established the trend, acknowledged by many standards, to allow structures to overcome the elastic phase, allowing large structural deformations in plastic phase. It is possible to follow this design trend using *Tubular Ribs* but not using *Standard Rib*.

At the end of laboratory investigation it is possible to make some considerations; It is worth recalling, in the case of standard rib have been detected a not negligible shotcrete covering layer. This contribution is quantifiable in at least 15% rise of the maximum bending moment that the section is able to undertake. This provision did not come out from

experimental results. The experimental analysis showed that in ideal conditions using the *Standard Rib*, the *Tubular Rib* has comparable performance.

By replacing the open profile with the tubular hollow section, with the same steel cross section area, the last one has improved structural statics properties, ensuring the ability to take control of axial and eccentric loads along any direction.
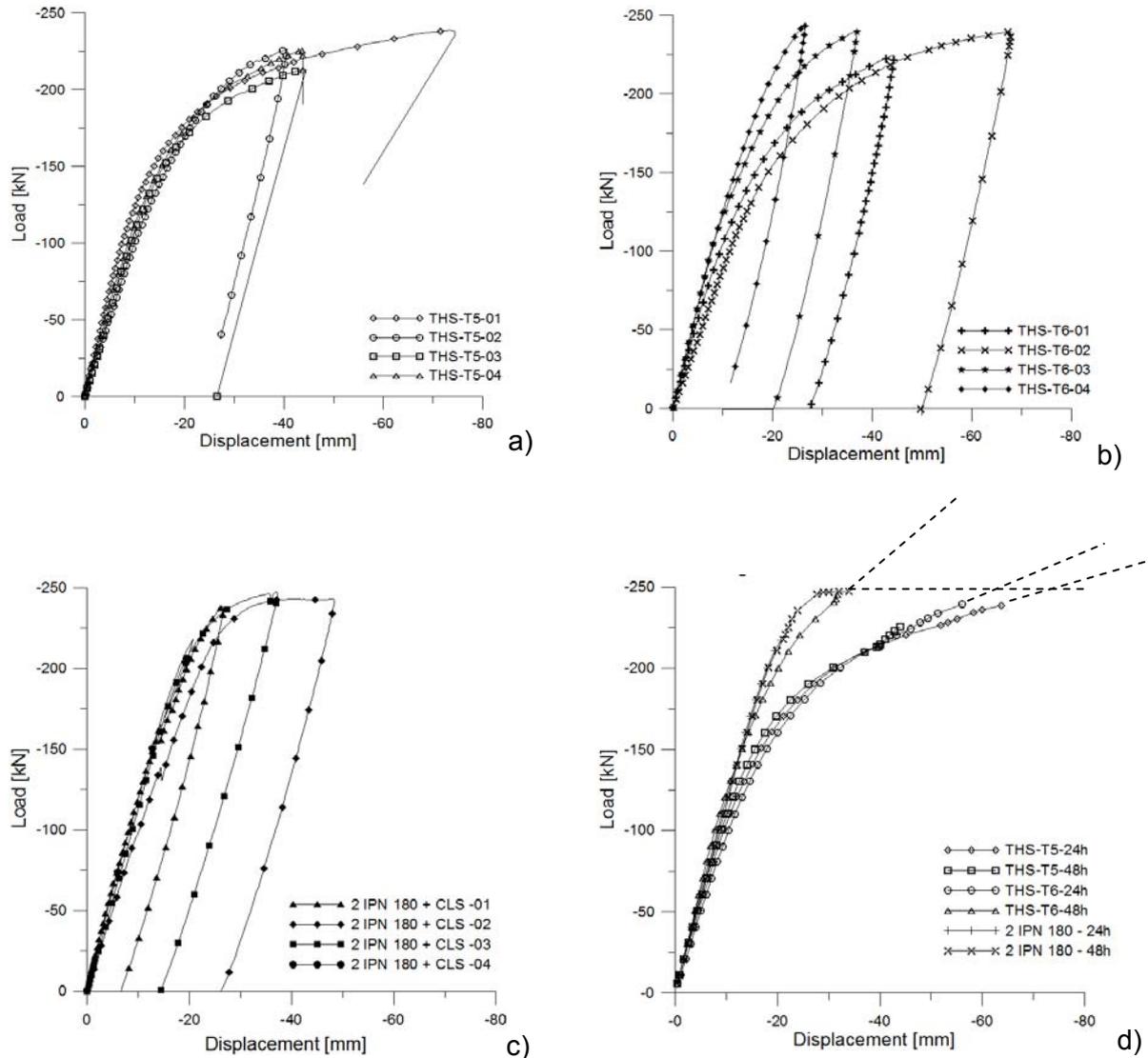
Figure 5 - Test results: 01,02 are referred to 24 hours tests, 03, 04 are referred to 48 hours tests a) TSH-T5; b)TSH-T6; c) 2 IPN 180 + CLS ; d) Average results.

3.2 Full scale testing of steel arch tunnel supports

The field test described below have been performed to verify the compatibility of the tubular rib with the underground work operational needs of and to confirm the results of laboratory tests conducted on static efficiency of tubular ribs. By monitoring, it was possible compare *Tubular rib* stress strain response against the ribs formed by open profile defined as Standard Rib. The field test was carried out in the Varano Tunnel, in a stretch at the North entrance from Foligno, within a rock mass belonging to the Maiolica Formation of good mechanical characteristics (Barton et al., 1974). Within this type of mass a *category A* behaviour "stable core-face" (diagnosis phase, Lunardi, 2008) have been expected.

The excavation tunnel section designed for this stretch correspond to a section section type Ac. This section is characterized by a shotcrete reinforced by a standard rib made of a

single HEB 140 installed every 1.50m (1 HEB 140). The selected Tubular Rib for the full scale test was Tubular Hollow Section characterized by a 193.7mm diameter and 5mm thickness in S275 Steel Class (TSH-193.7-T5). The Tubular Rib resistance domain is comparable to the one of Standard Rib (1 HEB 140), see Figure 6.a).

The field test performed allowed to verify a good compatibility of the tubular rib with the underground operational needs. The tubular rib is very stable and easy to handle during transport and installation. The buckling risk during installation, as a consequence of its high rigidity, has been eliminated. This ensures to work with a higher safety level.

a) b)
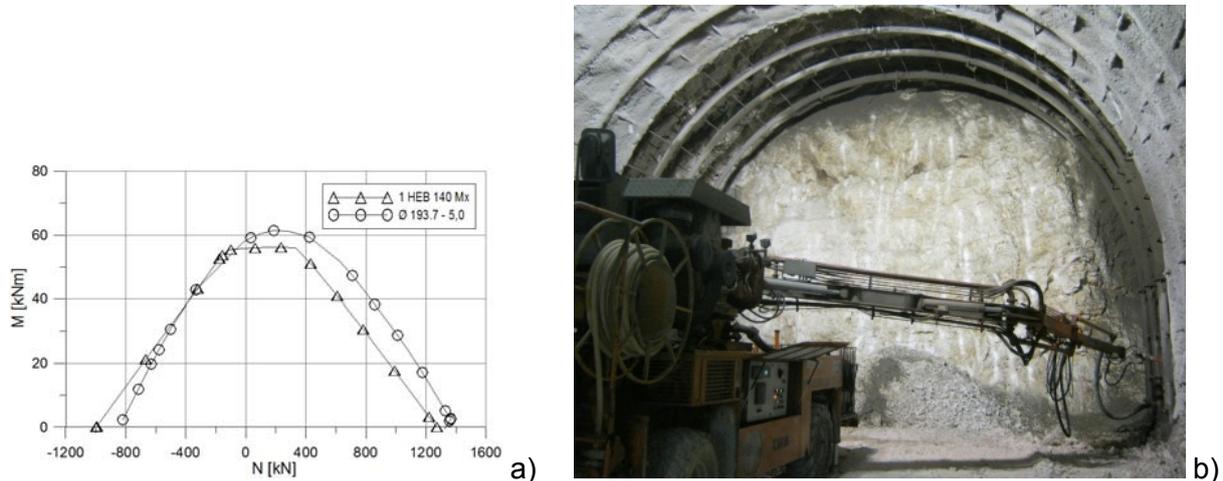
Figure 6 – Full Scale Test: a) Resistance Domain Comparison (convention: positive compression strength); b) Tubular Rib Installation.

The filling phase is very fast and functional to ensure complete filling of the profile. The remaining operational phases necessary for tunnel construction remain unchanged.
In order to test the Tubular Ribs and compare them in terms of stress-strain response (monitoring phase, Lunardi 2008), with the HEB 140ribs, 3 sections were tested, which features are listed below:
- Section 1: Length 28.5m approximately. Section type AC - tubular ribs with an external diameter of 193.7, thickness of 5mm, installed each 1.50m.
- Section 2: Length 28.5m approximately. Section type AC - standard rib made of a single HEB 140 each 1.50m
- Section 3: Length 28.8m approximately. Section type AC - tubular ribs with an external diameter of 193.7, thickness of 5mm, installed each 1.80m.
This last section has been tested after the evidence of good stress-strain response highlighted by monitoring in section 1 and 2.

To verify the work in progress, within approximately 86m tunnel length, the following monitoring activities have been conducted:
- No. 8 structural geological surveys of the face (a survey every 10-15m) in order to determinate the geological and geomechanical condition.
- Installation of No. 8 topographic measurement stations to evaluate the deformation response of the first lining (one station every 10-15m).
- Construction of No. 3 stations for the rib stress control (one for each section of the field test). Each station characterized, by 2 load cells placed at the foot of the rib and No. 5 pairs of strain gauges placed at intrados and extrados of the rib corresponding to side wall, heading and top heading, see Figure 7.d).
The mass presents homogeneous characteristics; this has been demonstrated by geological surveys carried out to the face. The deformation response recorded in each test section was always within the elastic range, with displacement and convergence values below 0.5 cm, in rapid stabilization.

Evaluating the results of stress control stations it is clear that stresses that affect tubular ribs are lower than the ones corresponding to standard ribs. This is particularly evident comparing the measured tensile stress on the tubular ribs in Section 1 (pk 22 +983.75) with the same stress at the standard ribs inside Section 2 (23 pk +013.76), see Figure 7.a) and b). In Section 3, (1.8m installation step) the stress level present in the tubular rib remains below the corresponding stress level measured in the standard ribs with a 1.5m installation step, despite the significant step increase.
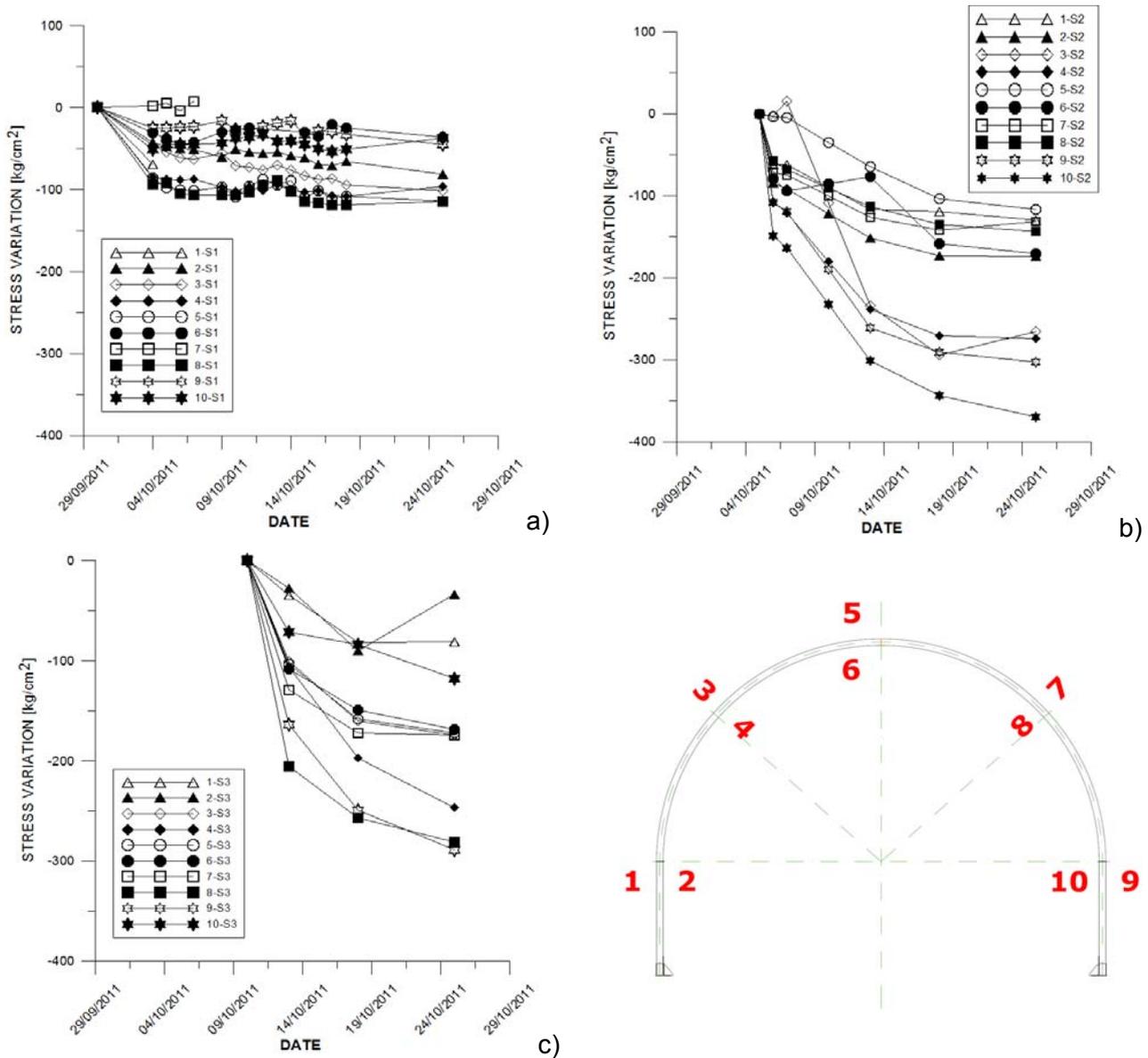
Figure 7 – Results of stress control stations: a) Section 1; b) Section 2; c) Section 3; d) Instrumentation positioning.

4. CONCLUSIONS

The numerical and experimental investigation confirms that the Tubular Hollow cross Section shows better performance conditions compare with and Open Steel profile Standard Rib Laboratory tests results confirmed the composite section performance of the tubular rib as usually modeled in the design phase, this assumption was not confirmed for the Standard open profile Rib.Field tests were carried out to evaluate the compatibility of the new type of

ribs with underground work concerning installation and stress-strain response. From operational point of view the tubular rib behaves very stable and easy to handle during transport and installation. This ensures a high safety level to the workers. The high rigidity of the proposed profile eliminates the risk of possible buckling during the installation. In all sections tested, the deformation response recorded always maintained within the elastic range. The tensions measured at stress control stations in the tubular ribs show significant lower values compared with the corresponded standard open profile ribs.

The tubular hollow cross section offers a better stress redistribution, this ensure the ability to take control of axial and eccentric loads along any direction.

Referring to a particular local load conditions, hollow profile circular section has better performace conditions. A good example of this problem is the not homogeneous contact conditions between the profile and the soil which may occur during the excavation of a tunnel. It is not always found a plane strain condition.

It is acceptable to assume a double "T" worst working conditions in presence of eccentric loads. These problems can be solved using a symmetrical axial cross, like a tubular rib

The tubular hollow section has improved structural statics properties, ensuring the ability to take control of axial and eccentric loads along any direction.

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