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Comparison on different design approaches applied to a New Tunnel Lining System reinforced by Tubular Arch

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ABSTRACT

Keywords: Tubular Arch, tunnel first lining design approach, tunnel support system

Peoples' and operators' safety in construction are tightly linked to the engineering choices, as much as to the necessity of reducing time and costs of realization. The timely address and the enhancement of the interaction between the rock masses and the support it is of paramount importance, and such to achieve a better control and to limit the ground deformations during the excavation particularly when continuous and immediate support is required.

Recent innovation was introduced in the design approach and construction of the tunnel lining, substantiated according to the AFTES recommendation and Eurocode3, and focused on the first support. A modern design approach implements lighter solution optimizing a composite section with sprayed concrete, fibres and tubular steel arches, in lieu of traditional open profile, with enhanced performance given by the effective cooperation between concrete and reinforcement.

Implementation of tubular steel arches in the tunnel support provides the engineers and the contractors with a wider range of options, and gives birth to a viable, safer and cost-effective support system able to negotiate with the most challenging ground conditions.

In this paper the authors describe the recent developments on regard of this whole new tunnel support system, presenting the recent further development and related case histories.

1. Foremost

Recent innovation was introduced in the design approach and construction of the tunnel lining, substantiated according to the Eurocode3, and focused on the first support. A rational design approach implements lighter solution was proposed and tested optimizing a composite section with sprayed concrete, fibres and tubular steel arches, in lieu of traditional open profile, with enhanced performance given by the effective cooperation between concrete and reinforcement.

Open steel profiles (IPE, HE, IPN) typically used as first lining support, show significant performance variation in their static structural properties – particularly, along directions different than the normal and central position and such due to their shapes and geometries – which can lead to major structural problem, as instance buckling (Fig.1.a). With reference to particular local geological conditions a closed circular profile will bring a better performance conditions compare to an open profile. Implementing a circular steel profile, with equivalent area to open steel profile, enables a better stress redistribution due a higher resistant cross section, and to the ability to take control of axial and eccentric loads, acting along any direction (Bringiotti, 2003).

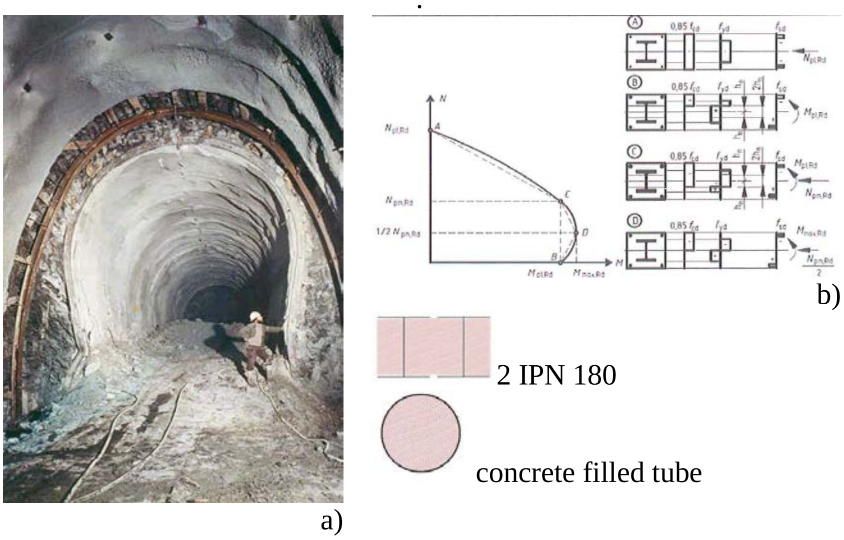
2. *Numerical analysis*

In a typical tunnel design in which support consists of steel sets embedded in spayed concrete, the designer needs to know the contribution of each of these support elements and to be able to adjust the number and dimensions of each to accommodate the loads imposed on the lining. In current tunnel design, these loads are obtained from numerical analyses in which “beam elements” are attached to the tunnel boundary and the axial thrust, bending moments and shear forces induced in these elements are computed directly.

Numerical analyses have been made prior to the experimental activity, targeting to consistently compare open and tubular steel sets through the evaluation of their respective cross section area, moments of inertia and resistance modulus. Particularly, 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). This approach is in compliance with the requirements of Eurocode 3 and NTC 2008 (Italian Standard Reference).

Some assumptions have been introduced in the calculation:

- Progressive damage (crushing) of the section was not considered. This assumption neglects the change of position of the neutral axis, caused by progressive damage of the concrete filling which is the main cause of instability of open profiles ribs, e.g. it works in favour to the open profile
- Tube ductility capability - due to its geometry - was not considered. The circular profile uses gradually its own ductility capability, till full exploitation. This is basically the worst condition for the tubular rib, e.g. deliberately neglects pipe geometrical advantage
- Twisting moments were not considered for open profile, e.g. the resulting load forces were considered acting always on the shear centre axis (condition of planarity)



b)

a)

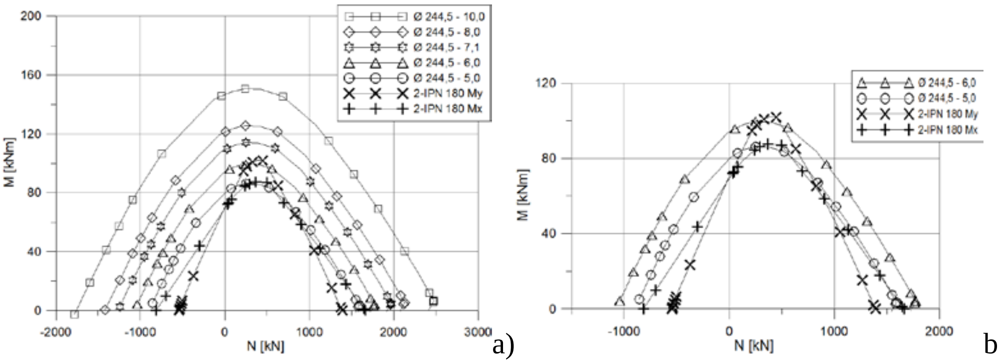
Figure 1 – a) Example of open profile buckling; b) Calculation of the N-M domains for the two steel section types considered collaborating with the concrete filling (Eurocode 3, 2004).

The above assumptions aimed to test and to compare the tubular steel arches - and open steel profiles - under the more unfavourable conditions, e.g. neglecting the geometrical advantages given by the circular section, and without considering that when subjected to a twisting moment – e.g. torsion - the assumption of planarity is no longer applicable for beam whereas such is still valid for hollow circular sections with constant thickness, e.g. a tubular pipe.

As a matter of fact, presence of non-axial loads – not planar – is amongst the primary causes of a steel arch instability causing horizontal load components, and therefore twisting. The results of such is that high bending moments are generated, and thus bigger open profiles are usually implemented to cope with these higher bending moments.

Figure 2.a reports all the beam resistance domains generated according to Eurocode 3 during the initial numerical analysis, including both beams – for typical European steel set, e.g. double IPN 180 - and equivalent tubular steel arches with different thickness. Particularly, resistance domains resulted significantly higher for the circular section with increased resistance in compression and bending as a consequence. A significant beam asymmetric behaviour along x-axis and y-axis was reported too.

Further on, attention was focused on solutions the closer to the beam performance (Figure 2.b below, refers). Full report on test results will be given (Chapter 3 below, refers).



a) b)

Figure 2 - Resistance Domain Comparison: a) all profiles analysed; b) profiles selected for experimental activity (convention: positive compression strength)

2.1. *Non planar loads. Detriment to the beam performance*

Traditionally, analyses on deformation and stress redistribution into the rock masses are based on evaluation of stress and strain along a cross section of the tunnel. However, the third dimension assumes a critical role as the excavation approaches and the stressed rock is dislodged. Figure 3 gives example on how the radial convergence and ground stresses redistribute close to the tunnel face, on bi-dimensional model.

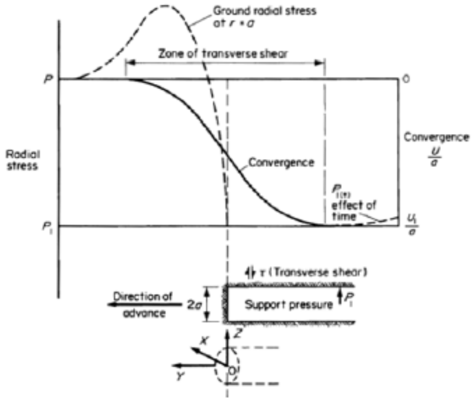


Figure 3 - Radial convergence and ground stresses in the vicinity of a tunnel face

Some assumptions are given, especially homogeneous and elastic behaviour for the rock masses (e.g. N=1) and uniform support along the excavated surface (plain strain). However, in real case scenario as soon and as far the excavation proceeds the major principal stress rotates – e.g. twists – along both tangential and longitudinal axis. Moreover, local conditions may generate additional uneven load condition – such as irregular excavation profile and specific geological features – which result further detrimental and effecting the performance of the beam arches

Figure 4 gives indication of the stress - shear – generated at a point close to the tunnel face due to the rotation of the stress axis and the resulting load, which is acting away from shear centre axis (condition of planarity).

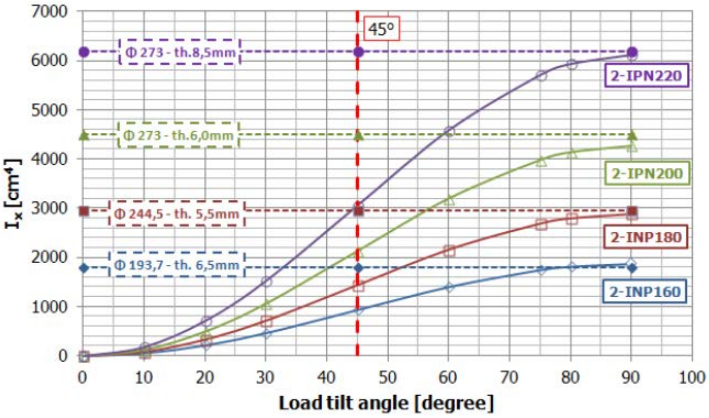


Figure 4 – Rotation of the stress and resulting performance of a beam arch (Zenti et al, 2015)

Particularly, the rotation of the stress direction generates twisting, and buckling of the beam arch. As a result of the rotation of the stress axis, the resulting bending capacity of the beam is approximately half of the maximum capacity deliverable. Moreover, beam arches performance differs and depends on the direction of the load applied whereas tubular – e.g. circular – arch is not affected by this difference due to its symmetric shape.

3. *Testing*

Tests to substantiate the numerical analyses were carried out at laboratory, and at site on actual tunnel sections. Tests at site aimed to assess and to compare the structural response of the different types of steel arches, namely beam and tubular arches, when installed.

3.1. Laboratory Test. Bending

Test set up, and samples conditions are reported in Figure 5. A total of 12nos samples – 4nos for each type of steel arch - were tested at 24 hours and at 48 hours after spraying. Particularly, crucial key factors for the assessment of the rest result are listed below:

- The samples were prepared at site. In fact, aim of the test was to test actual specimens of sprayed concrete, including over-spaying or shortening of thickness
- Bending test were done with a 4-point flexure bending test (Figure 5.a below, refers).
- Due the different shape of the steel arch, spraying – and filling - of the steel arch were easily achieved for pipe arch. Whilst, a not negligible over spraying occurred for the beam arch (Figure 5.c below, refer)

- Beam samples were not doctored to fit the ideal rectangular section, rather the trapezoidal section was considered to adjust the numerical model (Figure 5.d below, refers)

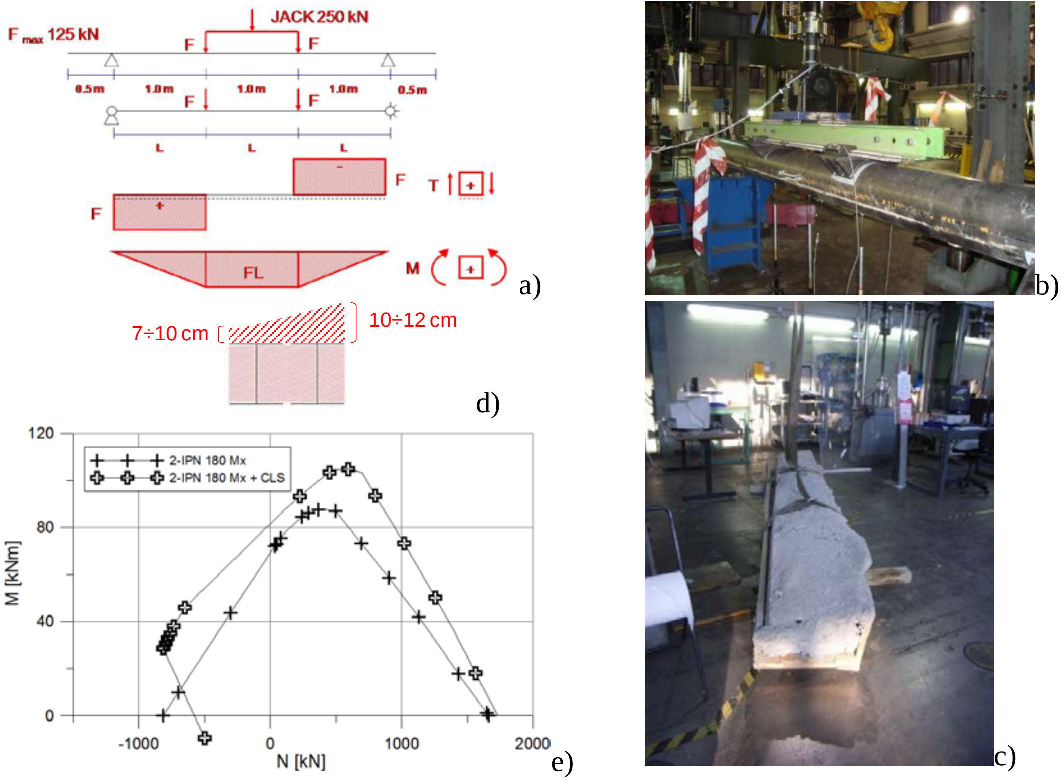


Figure 5 - Test set up: a) Static scheme; b) Tubular rib; c) Standard Rib; d) Static scheme; e) Resistance domain

Moreover:

- Test set up was chosen as it represents the ideal load condition for beam, e.g. the load is applied along the main beam axis. Furthermore, small eccentricity in the load applied generates twisting moments (non-planar condition) as happens on site
- Higher bending moment was calculated as result of the additional sprayed concrete thickness ($M_x = 87.7$ kNm, $M_{x+cls} = 104.9$ kNm)

Laboratory test results are summarised Figure 6 and, in spite of been tested under beam-ideal condition, equivalent steel-cross-section tubular arches have proved themselves with a more uniform structural performance. Moreover, it is of paramount importance to point out that whilst beam arches are characterised by elastic-plastic behaviour, tubular steel arches show elastic-hardening behaviour.

The latest is of paramount importance, as tubular steel arch and sprayed concrete behave as an actual mixed-composite section and benefits of the higher strengthening concrete characteristic given by the curing under confined condition (Mander, Priestley, Park, 1988).

3.2. Site tests – Load and strain. Monitoring results

Full scale site tests were arranged during the implementation of tubular steel arches in two different tunnel projects, namely Varano tunnel and Borzoli-Erzelli service tunnel (Italy), with tunnel excavation radius of 5m and 6m, respectively, rock mass ranging between fair to poor rock mass and stable core-face conditions (Lunardi, 2008).

Specific monitoring set ups were designed for each projects in order to assess the performance and behaviour of tubular arches to be monitored and compared to the original beam arches implemented. The tubular arches and beam arched behaviours were investigated under homogenous and consistent rock mass conditions, e.g. systematic rock mass assessments were done along the monitored tunnel stretch (survey spacing 10m approximately).

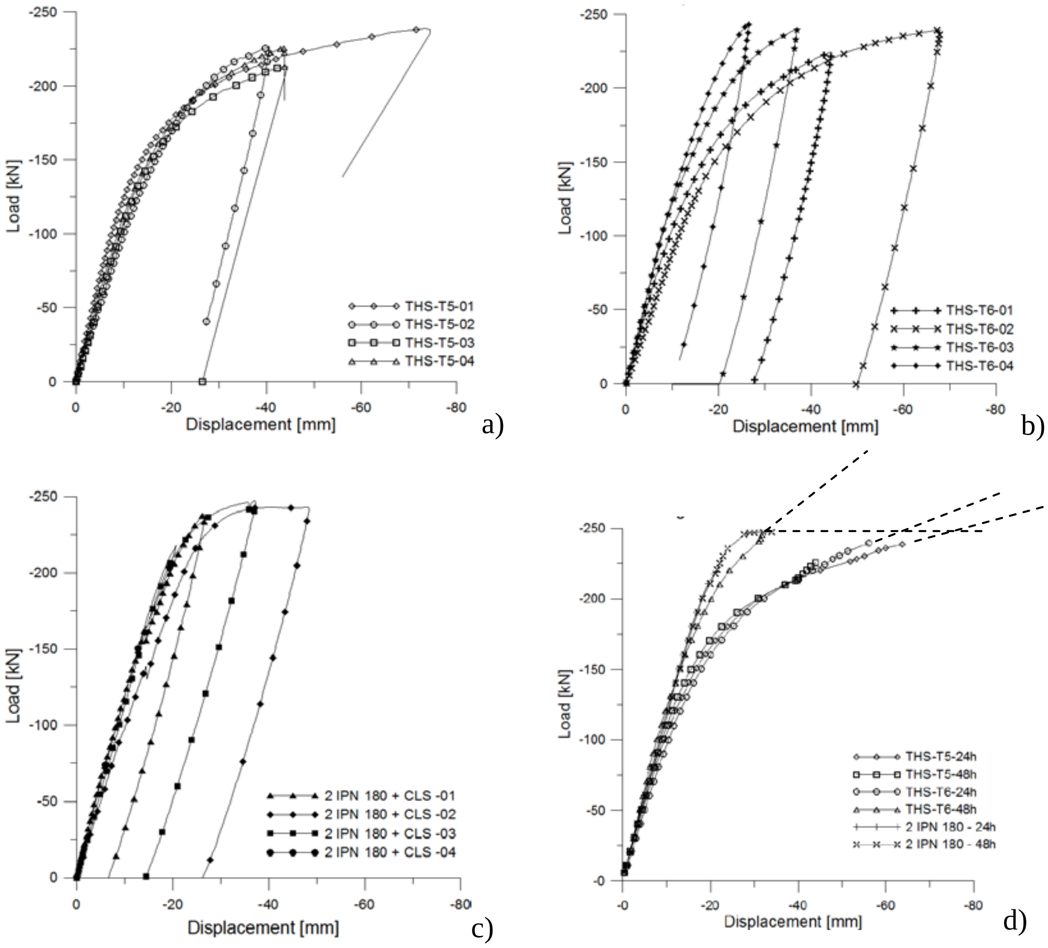


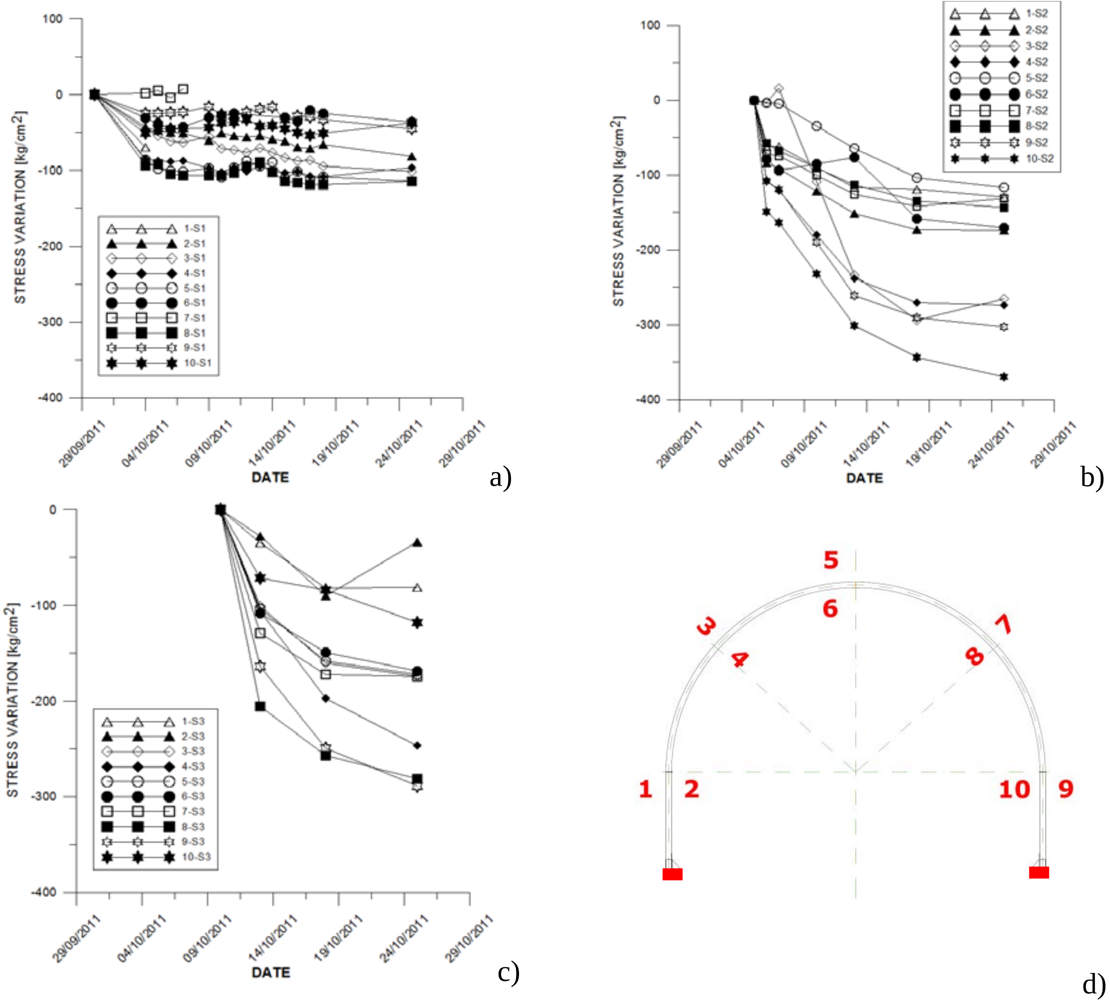
Figure 6 – Note: 01 and 02 test results at 24 hours, 03 and 04 test results at 48 hours; a) TSH-T5; b)TSH-T6; c) 2 IPN 180 + CLS ; d) Average results; (Zenti et al, 2012).

The monitoring plans implemented, at specific locations, strain gauges, load cells and 3D-optical readings. Effects given by different steel arch spacing was investigated too.

Particularly, from the monitoring records (Figure 7):

- 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
- Stress distribution in tubular arches is consistently uniform and significantly lower than the corresponding beam arches solution (Figure 7.a and 7.b, refer)

- Despite the significant step increase (+17%) in Section C, stress level present in the tubular arches (spacing 1800mm) remains below the corresponding stress level measured within standard beam arches (spacing 1500mm)



a) b) c) d)

Figure 7 – Varano tunnel.Monitoring records: a) Section tubular steel arch (1.5m spacing); b) Section beam steel arch (1.5m spacing); c) Section tubular steel arch (1.8m spacing); d) Instrumentation scheme (strain gauges 1-10, and topographic targets; and load plates). Note: sprayed concrete class – 28/30; sprayed concrete thickness – 200mm; steel grade S275 (both tubular and beam arches) (Lunardi P. et al, 2013)

Moreover (Figure 8 below, refers):

- In spite of uniform rock mass conditions, load distributions were recorded differing significantly in beam support, and in tubular support
- In spite of such, stress distribution in tubular arches was consistently uniform and significantly lower than the corresponding beam arches solution
- As result of such, tubular steel arches effectively transferred the load to the foot whereas beam steel arches did not
- Optical targets recorded negligible variation in terms of convergence and deformations

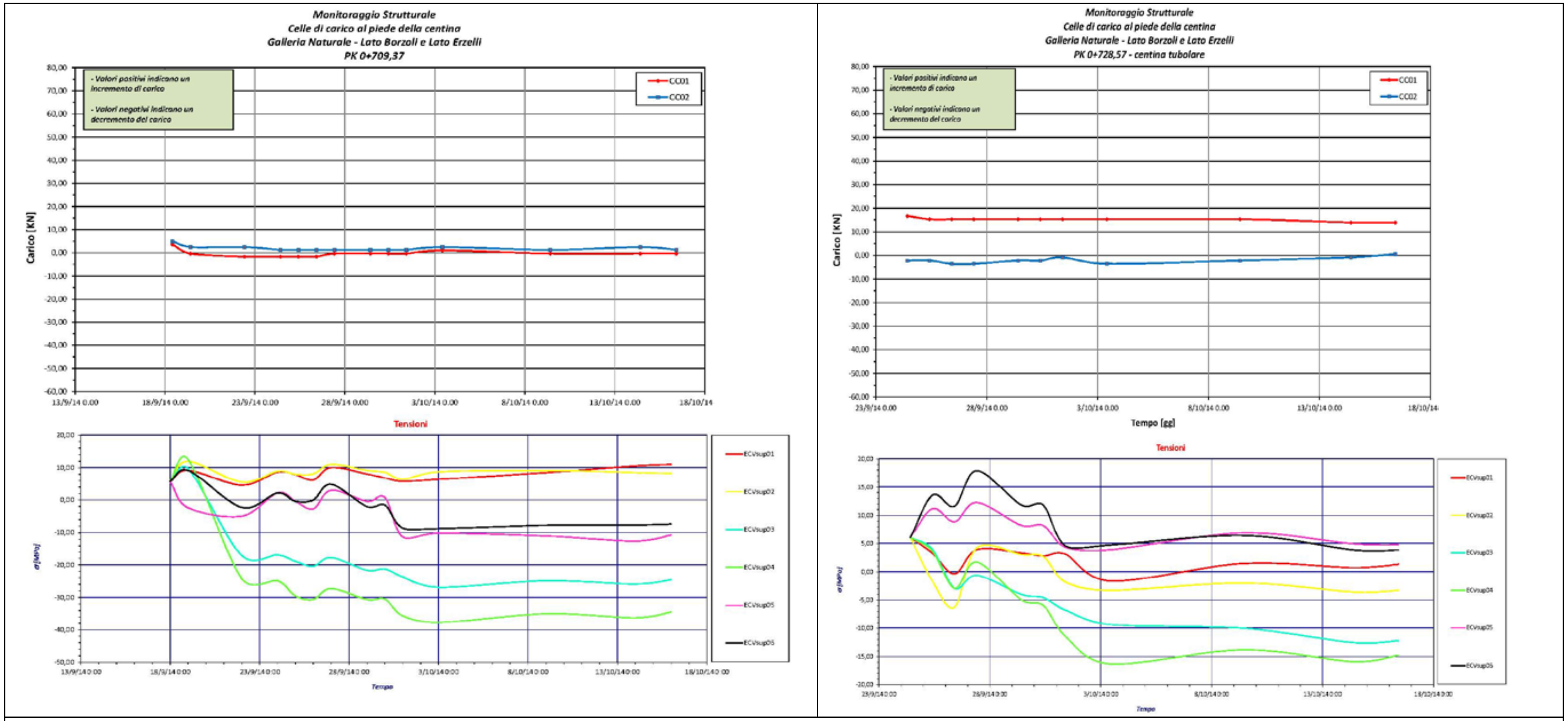


Figure 8 – Borzoli-Erzelli service tunnel. Monitoring records: a) Section beam steel arch load cells (above), and strain gauges variation (below); b) Section tubular steel arch load cells (above), and strain gauges variation (below). Note: sprayed concrete class – 28/30; sprayed concrete thickness – 200mm; steel grade S275 (both tubular and beam arches); spacing 1.2m (Zenti et al, 2014)

4. *Case study. Design analysis on equivalent tubular steel arches according to Japanese Standard recommendation*

4.1. Japanese standard specifications

Japan Society of Civil Engineers provides reference for steel supports (JCI - Standard Specifications for Tunnelling – 2006: Mountain Tunnels. 2007), and Table C 3.21 (Clause 56 "Cross Section and Steel Support Material", refers) lists the parameter of steel products used in steel supports. Particularly, H-beam (minimum SS400 steel grade, equivalent to European S275) are indicated amongst the most common supports, namely:

- 150x150x7x10
- 175x175x7.5x11
- 200x200x8x12

Based on recommendations given (Chapter 2 above, refers), equivalent sections for these three H-beam steel sets used as tunnel supports were calculated and related to the performance of equivalent tubular steel arches. Design substantiations were based on the following assumptions (Table 1 below, refers):

Table 1 – Tunnel supports. Design parameters for material

Item	Unit	Value	Reference
Steel support spacing	mm	1000	Ground Class D1-D2, Clause 42 - Design Concepts of Tunnels Support
Sprayed concrete thickness	mm	200-250	Ground Class D1-D2, Clause 42 - Design Concepts of Tunnels Support
Sprayed concrete class	N/mm^2	18	Medium section tunnel, Clause 45 – Mechanical Characteristics of Shotcrete

Note: Sprayed concrete flexural toughness is advised for fibre reinforced sprayed concrete (Clause 48 – Reinforced concrete)

4.2. Design method. Calculation of equivalent section

Tunnel support is constituted by a series of 'beam elements' which interact with the surrounding rock mass to limit the convergence of the tunnel (Figure 9 below, refers). The steel sets are assumed to be symmetrically placed in the sprayed concrete lining so that the neutral axes of both the steel sets and the sprayed concrete lining are coincident. For the purposes of these analyses an elastic shell behaviour was assumed, thus within the service state limit, a complete load transfer from the rock mass to the tunnel liming, and no rock mass improvement – e.g. rock bolts - was considered.

In order to calculate the moments and axial thrusts induced in the steel sets and the sprayed concrete shell and to compare these with the capacity of the steel sets and sprayed concrete, the following steps are required:

- An "equivalent" rectangular section with a width of b, a thickness t_{eq} and a modulus of E_{eq}, is determined
- The capacity of the steel sets and the sprayed concrete lining are determined
- A numerical model of the tunnel is constructed and beam elements representing the equivalent rectangular section are applied to the tunnel perimeter
- The bending moments and axial thrusts are redistributed back onto the steel sets and sprayed concrete lining

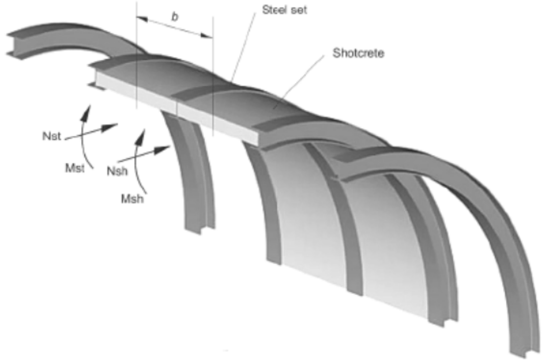


Figure 9 - A section of width b in a composite lining consisting of steel sets, spaced at a distance s, embedded in sprayed concrete. Moments M_{st} and axial thrusts N_{st} are induced in the steel sets and moments M_{sh} and thrusts N_{sh} are induced in the sprayed concrete shell

Design method applied follow recommendations, particularly:

- The tunnel stability is supposed to be achieved due to the cooperation between the ground strength and the support strength (Chapter 4.3 AFTES 1993, refers)
- Thickness and modulus of the reinforced section – sprayed concrete and steel arch – are designed according to Chapter 4.4.4.1 of AFTES Recommendations (Design of sprayed concrete for underground support, 2001). Thickness of the sprayed concrete was assumed constant
- The resulting loads accordingly to the above procedures were redistributed equally to both sprayed concrete, and steel arches. Moreover, each of the above shall be double checked again separately applying the relevant standard. For steel arches Chapter 4.4.4.2 was applied (AFTES Recommendations: Design of sprayed concrete for underground support, refers)
- Moment-thrust (MN) and shear-thrust (QN) were verified according to Eurocode 3, EN 1993-1-1: 2005

Moreover, a reduced steel cross section was considered (Chapter 6.2.6, and Chapter 6.2.10 of Eurocode 3, refer), and it was assumed that flexural moment and shear were taken fully by the steel arch whereas the thrust to be equally redistributed on the reinforced section (EN 1993-1-1: 2005, refers). Table 2 below lists the materials characteristic considered:

Table 2 – Material characteristics

Item	f_{ck} (MPa)	R_{ck} (MPa)	f_{yk} (MPa)	f_{tk} (MPa)	σ_{adm} (MPa)
Sprayed concrete	18	24			8.25
Steel S275[1]			275	430	190
Steel S355			355	510	240

Note: 1) Equivalent to SS400 (JIS)

The following Figure 10 reports on the best fit comparisons based on the worst case scenario, and without correlation to an actual tunnel load - thus, further optimisations can be done adopting alternative sprayed concrete strength, or pipe wall thickness. In spite of the above, a significant reduction in term of weight of steel can be recorded (Table 3 below, refers).

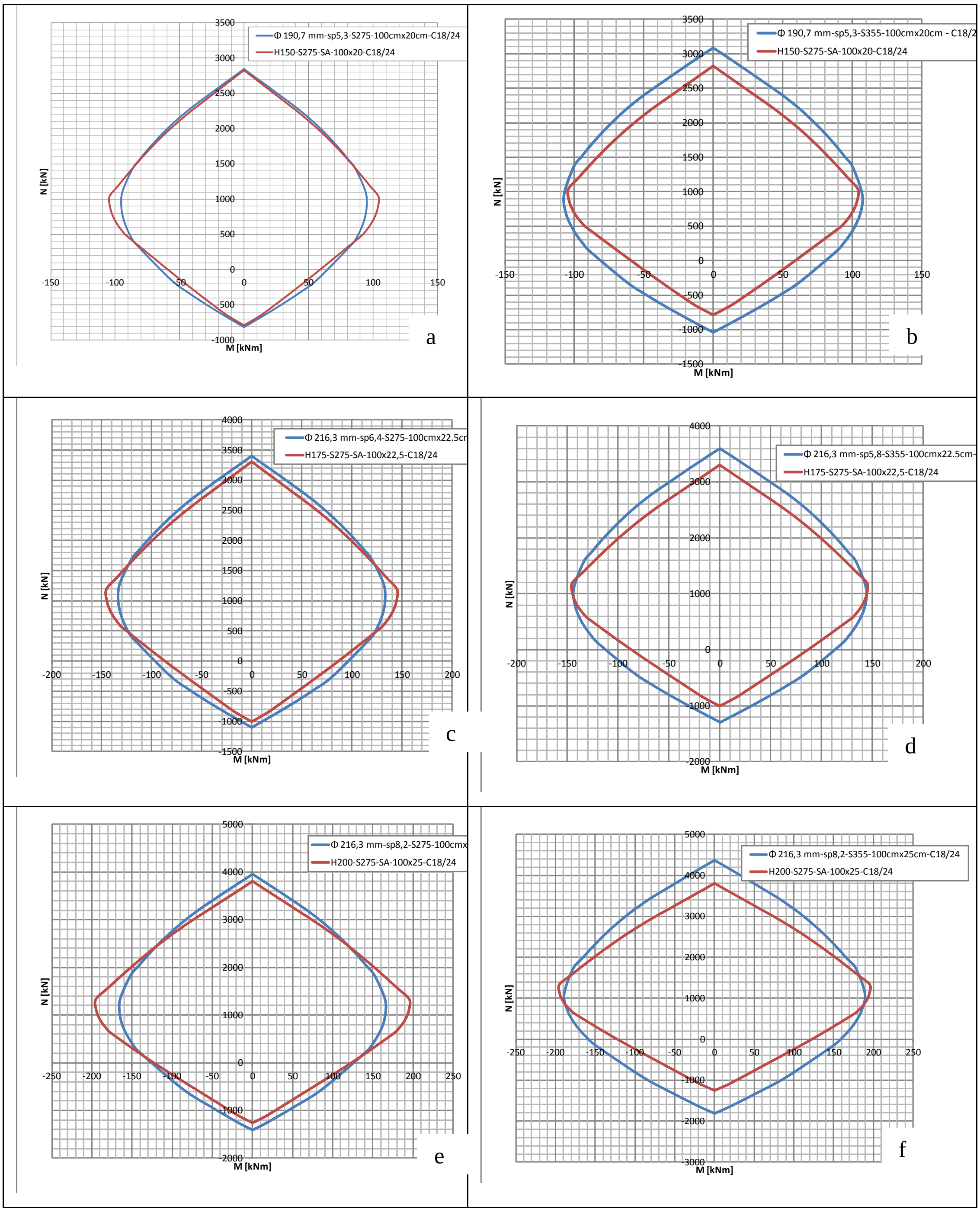


Figure 10 – Shell, considered as reinforced section, support capacity comparison. Left column: tubular steel arches S275 steel grade; Right column: tubular steel arches S355 steel grade

Table 3 – Steel set weight comparison (kg/m)

Item	a	b	c	d	e	f
H-beam arch (kg/m)[1]	31.1	31.1	40.4	40.4	49.9	49.9
Tubular steel arch (kg/m)[2]	24.2	24.2	33.15	30.1	42.1	42.1
Variation (%)	-22	-22	-18	-25.5	-15	-15

Note: 1 – JIS G3192:2008; 2 – JIS G 3452 SGP

5. *Conclusions*

Laboratory and site tests were done to assess the performance of a new type of steel arch, e.g. tubular hollow steel arches, and the compatibility of such with the standard operational construction stages and machineries particularly concerning installation of the arches, and stress-strain response.

In spite of the fact that the worst case conditions were considered, the numerical and experimental investigation confirms that the tubular steel arches have overall better performance. Particularly, in all sections tested the deformation records were observed always within the elastic range and the tension values - stress control stations – for tubular arches recorded significant lower values compared with the corresponded standard beam arches. The major reason to affect beam arches performance was referred to the non-uniform behaviour of the beam when loaded along different axis, or under symmetric non-axial load. On such regard, tubular steel arches where proved to offer a better stress redistribution, e.g. better response toward asymmetric loads – torsion - such as uneven excavation profile, or singular geological conditions, which list amongst the major causes of beam arch instability. Furthermore, it was confirmed that steel arch and concrete filling behaves as actual composite section in accordance to the latest international standards recommendation. In fact, the concrete filling is actively contributing to enhance the structural capacity of the section.

Eventually, a case study developed on the Japanese Standard Specifications for Tunnelling 2006 – Mountain Tunnels and based on the typical characteristic of the materials used for the first lining – e.g. temporary lining – proved that significant reduction in terms of equivalent steel weight could be recorded implementing tubular steel arches and, yet, to deliver consistency into the overall support capacity of the first lining.

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