Large Concrete Precast Box Girders along the New Italian High Speed Railway Lines

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Summary

The paper discuss the principal technical issues related to the design, precasting and launching of a large concrete box girder that has been extensively used on the new high speed railway lines recently built in Italy. Using two of these box girders, precast and launched separately, each weighting over 400t, simply supported 35m span decks are built in less then a week time. Over 4km of viaducts have been built using this technology between Turin and Milan. A similar box girder had been previously used on the Rome-Naples line although with a smaller span and different pretensioning arrangement. Deflected tendons were used there that are no longer allowed by the client. The new beams, longer and heavier had to make use of strand sheathing instead to reduce stress concentration at the beam ends. The pro and cons of the two solutions are discussed and the principal guide lines for calculating and designing these types of beams are reviewed. The prefabrication and launching procedures for these elements are finally illustrated with specific reference to the construction of the four major viaducts along the Turin-Milan railway line.

Keywords: Pre-tensioning; pre-casting; high speed railway lines; bursting; spreading; spalling.

1. Introduction

The new Italian High Speed Railway Network ("Sistema Alta Velocità"), also dubbed "Alta Capacità (AC)" for High Capacity, is being built to meet the increased demand in passenger mobility between the main Italian cities, namely; Naples, Roma, Florence, Bologna, Milan, Turin, Venice, ecc.. These cities lay only few hundred kilometres from each other, an ideal distance to link with a fast railway connection thus reducing the motorway and air traffic. The new AC line between Turin and Milan will be 124.5 km long. The Turin-Novara segment (86.5km) is almost finished, connecting Turin to the Malpensa (Milan) International Airport. The Novara-Milan segment is currently under construction with completion due in 2009 (see Fig. 1).

The new line is being built within the so called Turin-Milan technological corridor, a land strip full of utilities and infrastructures, including the homonymous motorway, currently being widened to 4 lanes each carriageway. Since the line is running in a flat area, the Padana (Po river) plain, 80% (100km circa) of the line runs on ground, 15% (20km circa) on viaduct and a remaining 5% in artificial tunnels, the latter used mostly for environmental impact mitigation purposes and when crossing other infrastructures at high skew.

The contract is managed by the General Contractor FIAT S.p.A. with the work carried out by the CAV.To.Mi. Consortium, the latter including the two contractor Impregilo and Condotte and MaireEngineering (formerly known as Fiatengineering, the design subsidiary of FIAT). Works are finished on the Turin-Novara segment and are 30% completed on the Novara-Milan stretch (December 2005).

Prefabrication has been extensively used along the line: viaducts, artificial tunnels but also culverts and retaining walls have been partially or totally built this way. The larger share is taken though by the precast concrete decks used for the viaducts. These decks mostly belong to one of the following three types: the single box girder, fully precast with span of 20m and 25m and up to 500 ton weight, the twin box girder, fully precast as well, with span of 31.5m and 34.5m and the four small box girder, with typical span of 25m, where only the trough girders are precast and the top concrete slab cast in situ. All these types have already been used on other AC lines, the single box girder on the Rome-Florence line during the '80 and the other two types on the most recent Rome-Naples line.

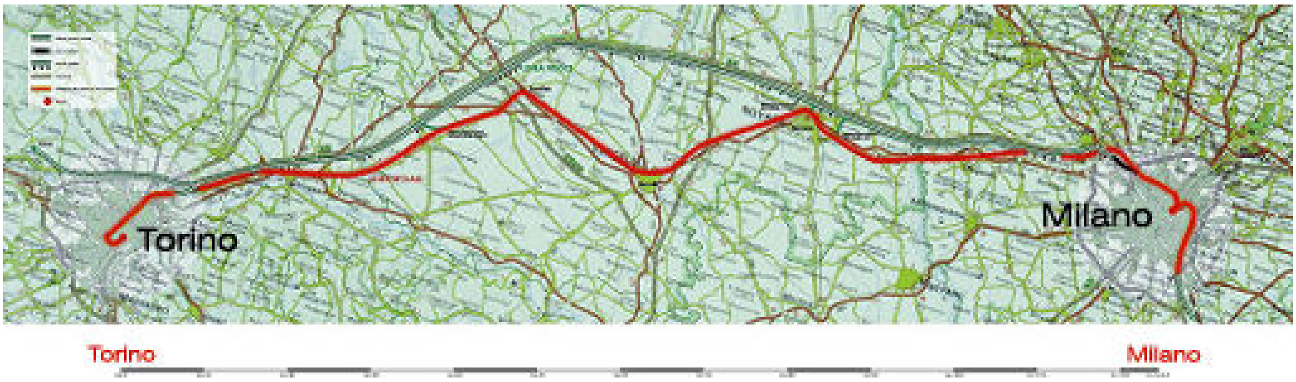

Fig. 1 *The new Turin – Milan AC Line*

The technical and practical aspects of the twin box girder (*bicassone*) shall be illustrated in the following. Use of this type of girder as been very successful and with further optimization it will be most likely used again in the forthcoming projects. On the Turin-Milan lines, it has been used for 5 viaducts, namely:

- Malone River crossing, at pk 11+615, total length 345m;
- Orco e Rio Palazzolo River crossing, at pk 12+671, total length 732m;
- Chivasso Fly over, at km 14+035, total length 966m;
- Dora Baltea River crossing, at pk 23+882, total length 1346m;
- Ticino River crossing, at pk 97+190, total length 1173m.

2. The "Bicassone" box girder

The bicassone of the Turin-Milan line, with his 34.5m span, is the longest prefabricated girder used on the Italian Railway line so far. A smaller (31m) version was recently used on the Rome-Naples line and possibly a longer version of 37.5m, is being taken into consideration for the prosecution of the Corridor 5 (Lisbon-Kiev) from Milan to Venice via Verona.

The constant improvement in the performance of materials and construction tools has generally triggered an increase in the span length of these beams. For instance, the four small box girder deck type previously described has been stretched to 27m on the Turin-Milan line and 30m on the Florence-Bologna. For pretensioned concrete beams, the limit to increasing their span is give by the stress concentration at the beam ends, as discussed in details in the following paragraphs

The main geometric characteristics of the *bicassone* are the following: pier spacing (gross span) 34.5m, net span 32.1m, spacing between the tracks 5m, total deck width 13.6m. Each deck is made of 2 precast pretensioned concrete box girders. The connection between the two girders is provided by 5 diaphragms, which are sealed with 5cm mortar and postensioned, and a 45cm wide longitudinal strip between the top slabs which is cast in situ bonding the protruding and additional reinforcement therein.

The height of the box girders is 3.12m at midspan increasing at 3.57m near the supports where the bottom slab and the webs are thickened from 35cm to 80cm and the top slab from 28cm to 43cm. The thicker end sections still make it possible for the internal steel formwork to be extracted trough the end diaphragms.

These are 80cm thick while the intermediates are 35cm. The postensioning is made of two cables 6T15 at the top and two cables 4T15 at the bottom for the end diaphragms and two cables 7T15 and one 4T15 for the intermediate ones.

The girder longitudinal prestressing is made with 144 pretensioned 0.6” strands (just above 23kg per sqm of deck).

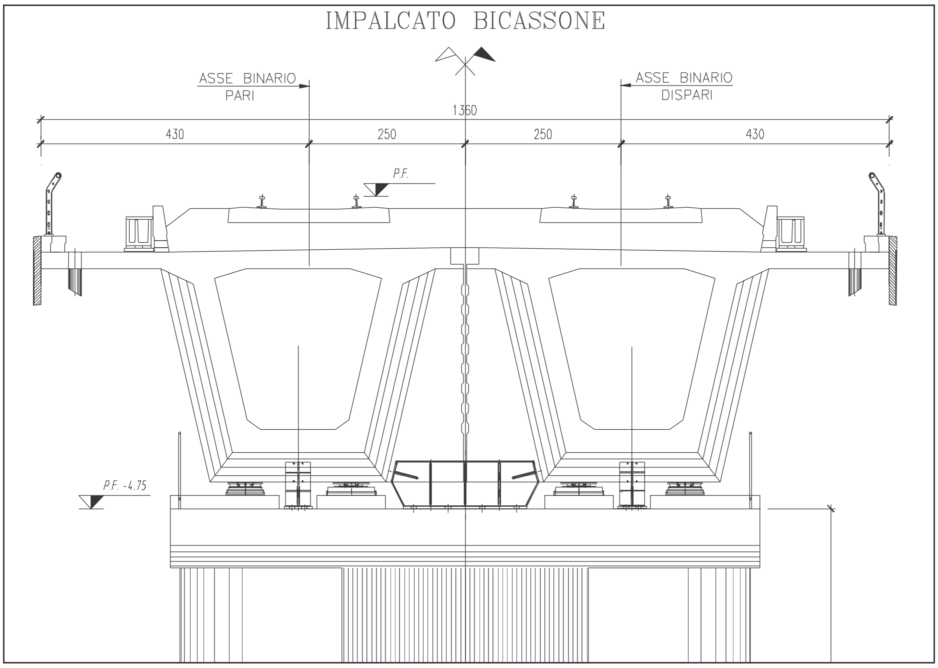

Fig. 2 *The bicassone geometry*

3. The strand sheathing

The limit to increasing the performance of these girders is often found in concrete cracking at the beam ends caused by the prestressing forces. A number of beams, in recent years, have shown moderate to severe cracking both in railway and roadway applications. This problem is endemic to pretensioned beams because of two basic mechanisms:

- Stress transfer of the single strand tends to cause bursting (expansion) of the surrounding concrete.
- The strands run generally parallel and closely spaced in the bottom slab and so they arrive at the beam ends. This configuration causes tensile stresses due to spreading of the prestressing forces and due to spalling of the end beam sections (see Fig. 3).

The bicassone was set to suffer from similar problems. The bicassone used along the Rome-Naples line had only 124 strands, 40 of them deflected upward 10m before the anchorages. Since for the Turin-Milan line it was decided to use only straight strands and the girder was 10% longer than the Naples one, 168 strands were to be used, 120 placed in the bottom slab and the other 48 in the webs just below the top slab. This means that with the same geometry the new girder would have had 120 strands anchored in the bottom slab instead of the 84 of the Rome-Naples one.

A number of numerical investigations were therefore performed to assess the stress increase at the anchorages due to this different prestressing arrangement. The lack of any inconvenience on the Rome-Naples beams would not guarantee, in fact, a similar outcome when increasing by 50% the bottom prestressing strands. It should be noticed that the maximum crack width tolerated by the Italian Railway Norm [1] de facto requires tensile concrete stresses to remain below the tensile resistance. This is because as soon as cracks develop, they are hardly restrained by the reinforcement since stress gradients are extremely high and anchorage length of the reinforcement, insufficient. Only confinement against bursting is very effective as in this case gradients are null along circular close hoops. Overstuffing the anchorages with reinforcement is neither an option as the excess of reinforcement my help initiating cracks.

The situation shares many similarities with the shear behaviour of reinforced concrete members where stresses are better kept below the tensile resistance or otherwise significant cracking develops before the reinforcement comes in with a comparable contribution [2]. From a fracture mechanics point of view, the problem is the insufficient ductility (fracture energy) of concrete that does not increase proportionally with the compressive strength and therefore the increase in the bending resistance of the beams is not matched by the available concrete toughness at the beam ends.

Fig. 3 *Typical cracking of a prestressed trough beam*

Finally it was decided to sheath 48 strands and eliminate half (24) of the top ones. Strand sheathing postpones the prestressing force application up to the end of the sheathed length. Sheathing is made with plain PVC tubes. The inert strands are generally left into the beam. In our case, 48 strands were sheathed to the same length (5.1m) following a technology approved by the Italian Railway Agency where one or more boxes are inserted in the bottom slab (see Fig. 4) where sheathing of the strands terminates. Once the beam has been cast, the sheathed strands are cut at the boxes, which remain empty during casting of the beam, and pulled out from the anchorages. The boxes and the empty PVC tubes are then injected with mortar from the beam end. The sheathed strands are therefore “active” only from these boxes onwards. The inert strands are removed reducing the risk of corrosion since they would not be encased and passivated by the surrounding concrete.

Fig. 4 *The sheathed strands and the cutting boxes*

From the Finite Element analysis of the two configurations (with and without sheating) a significant decrease of the principal tensile stresses (the blue end of the spectrum) at the beam ends can be easily appreciated. The results obtained using the well established formulae available in literature [3][4][5] are in a reasonable agreement.

The maximum tensile stresses found for the sterilized configuration (1.5÷2 MPa) are below the "average" tensile resistance of concrete. Those sceptical of the numerical modelling results (writer included) can nonetheless appreciate that none of the prefabricated girders built thereof showed cracking at the anchorages. The table below compare the maximum tensile stresses calculated with the 3D finite element analysis to the ones obtained with the above said empirical formulae.

$\sigma_{bursting}$	Not Sheathed	Sheathed	$\sigma_{spalling}$	Not Sheathed	Sheathed
3D Model	1.4÷1.5 MPa	0.6 MPa	3D Model	3÷3.5 MPa	1.5÷2 MPa
Leonhardt	1.45 MPa	0.85 MPa	Model Code 90	2.94 MPa	1.68 MPa

Table 1 *Comparison of stress prediction by FE and literature*

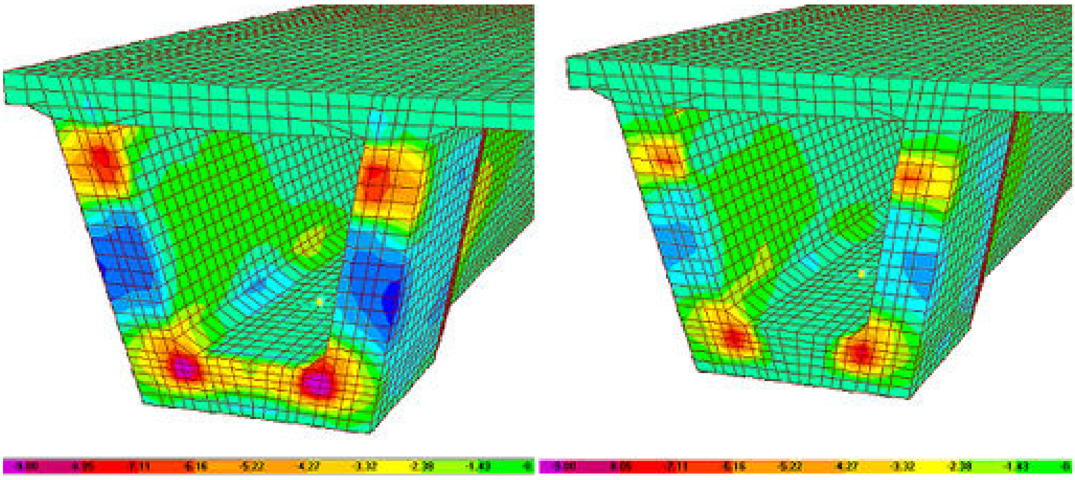

Fig.5 *Principal stress at anchorages (Dark blue=3.3MPa)*

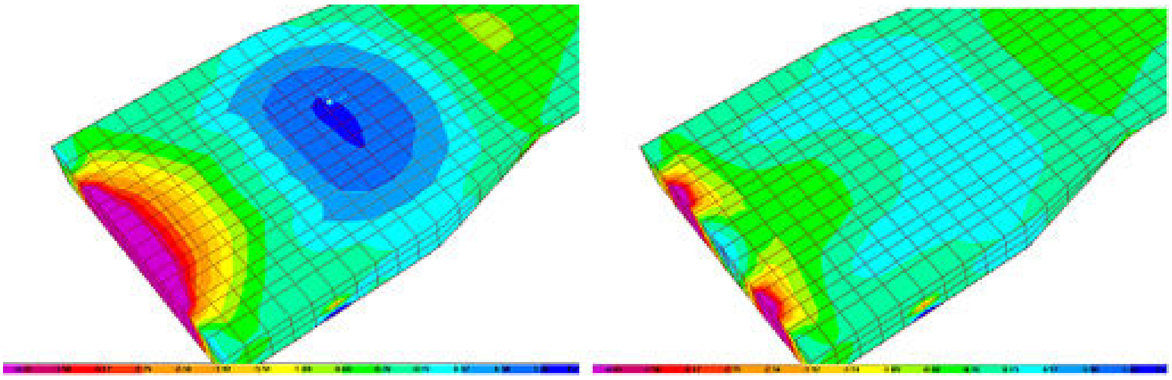

Fig. 6 *Principal stress in the bottom flange (Dark blue=1.4MPa)*

4. Geometrical tolerance and torsional stiffness of the box girder

The torsional stiffness of the box girder and the unavoidable out of plane tolerance of the bearings are such that the girders, once lowered on the 4 bearings, tend to rock and lift one of the two inner supports (leaving only three loaded). This uneven distribution is made evident by the eccentricity of the beam centre of gravity (0.265m) with respect to the support axis, due to deck top slab outer cantilever.

In order to adjust the reactions on site, gauging with steel plates beneath the bearings was required once the girders were lowered in place. Measured average stiffness came out to be 200kN/mm. Back calculating the equivalent torsional stiffness of a De Saint Venant beam yield KTOR = 5.8 105 kNm rad-1 instead of KTOR = It * G / L = 2.9 106 kNm rad-1 which is the value found using the Bredt section torsional inertia It, and assuming all other mechanisms totally rigid. A closer value is found with the 3D model (KTOR = 1.2 106 kNm rad-1). Since this model still yields twice the on-site measured stiffness, the missing compliance must be found in the bearings apparatus and under structures.

These results are extremely interesting from a designer point of view because even though the real torsional stiffness is significantly lower then what would be generally assumed from the beam geometry alone, still the reaction on the 2 plus 2 supports of each beam, is likely to be uneven with one in four bearings being unloaded and the adjacent one overloaded with half the beam weight (the other half carried by the other two opposite bearings). This uneven distribution is further exacerbated by torsion. When only one track is loaded, by far the most common situation under traffic, the load is partially transferred to the adjacent box. This transfer is balanced out by torsion in the two adjacent box girders and the associated push and pull effect on each couple of bearings.

Fig. 7 *Prefabrication yard at Chivasso*

5. Prefabrication

The girders were manufactured in plants adjacent to the line. For the Turin-Milan line three locations were required; the same equipment was firstly installed in Chivasso (for the first 3 viaducts) and subsequently moved to Saluggia (for the Dora Bridge) and finally to Romentino (for the Ticino Bridge). The plants are made of three different areas:

- An assembly line for setting up the steel reinforcement cages and the prestressing strands. This is generally placed under a longitudinal shelter
- Strand tensioning and concrete casting and curing yard
- Storage area

Material	Quantities
Concrete Volume (C45/55)	181.6 m^3
Reinforcement (F_{yk} >440MPa)	21560 Kg
Weight ratio (reinforcement/concrete)	118.7 Kg/m^3
Pretensioned strands (f_{ptk}>=1900 MPa)	5338 Kg
Post-tensioned strand (transverse, f_{ptk}>=1900 MPa)	900 Kg

Table 2 *Material and specifications (one box girder)*

Production follows the so called "assembly line" method. The reinforcement gages are assembled using a template and subsequently lifted into the steel formworks. The operation is carried out separately for the lower part (bottom slab and webs) and for the top slab. Subsequently the two parts are joined together into the formworks and minor components are added such as the para ballast reinforcement. Once the strands have been tensioned, concrete is poured and cured. Material quantities and specifications used for a single box-girder are summarised in Table 2.

Fig 8 *The truck crane*

6. Launching

The beams can be lifted from the formworks once concrete has reached a C30/37 resistance. This was generally achieved within 24 ours.

Depending on the height of the line, certain yards required two travelling crane to lift the girders onto the embankment. Once on the line, the girders were moved into their final destination with a giant crane truck with rubber wheels. This equipment weights 210t and is capable of carrying over 460t (see Fig.8 and 9). The equipment is completed by an under bridge for the crane truck to run over it and place the box girder in its final position (as shown beside). The sequence is the following:

- Loading of the crane truck
- Transportation of the girder to the front end
- Launching of the girder using the under bridge
- Forward shift of the under bridge
- Lowering of the girder into position
- Repositioning of crane truck and under bridge

Fig 9 *Launching with the under bridge*

7. Conclusion

The *bicassone* is certainly among the most efficient prefabricated structures used on the new high speed railway line in Italy. Efficiency has been achieved both in terms of material quantities (concrete and pretensioning steel) and speed of fabrication and erection. At certain stages, when access along the line was required for other operations to be carried out, the consortium was capable of producing and launching 100m of viaduct per week (i.e. roughly one beam per day).

Strand sheathing is certainly a viable solution for reducing the stress concentration at the beam ends. Tensile and bond stresses are in fact the bottle neck of these type of structures where otherwise the increasing compressive strength of concrete is opening up the way to unlimited progress in structural performances.

Strand deflection, which has recently lost appeal, at least for very large elements as the ones under consideration, could be reintroduced as it increase the shear performance of the beams and avoid strand localization at beam ends. To this extent, a simple and effective strand deflection procedure need to be defined similarly to the strand sheathing technique described in the paper for straight prestressing.

The authors are currently studying the possibility to extend the range of application of the bicassone girder up to 40m span.

Fig 10 *The finished viaduct (Chivasso)*

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