

# The Prarolo railway arch bridge in Italy: structural assessment and analysis through traditional mechanical methods

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**ABSTRACT:** The Prarolo arch bridge was built between 1850 and 1853 on the railway line Genoa-Turin (Italy), based on the General Road Society design. The bridge has a straight plan and curved tracks ( $R = 400$  m); it was built in mixed masonry (stone blocks and bricks), having a 40 m single span and two truncated-cone abutments (height = 22 m, base diameter = 20 m), inside which the vault is extended. The bridge design and construction are based on the French models of “Ecole des Ponts et Chaussées”, elaborated by the Piedmont civil engineers in the 19th century. The main objectives of this research are the bridge structural assessment as a unique construction (on the basis of geometrical and constructive issues, technology and material properties, etc.), also aiming to verify whether the current damage pattern may be ascribed to service loads. In the paper, the previously cited knowledge path is described: traditional mechanical methods for design and verification (e.g. static thrust line through graphical methods, Equilibrium Limit Analysis) are applied and extended to the 3D-representation of the thrust line related to centrifugal actions. Therefore, even if in a simplified way (not considering the dynamic effect), the modification of the dead-load thrust line, due to the centrifugal effects of the traffic flow, is studied. The limit speed value for the train is evaluated using this approach, adopting where possible the calculation suggestions of the railway technical rules (Guidelines no. 1/SC/PS-OM/2298, 1995).

## 1 INTRODUCTION

The Italian railway network, and its main lines, was built mainly between 1860 and 1910. A large number of masonry arch bridges is still in service, steel and r.c. structures being found on the few lines built after World War I or as a replacement of the bridges destroyed during World War II. Nowadays, all the lines rely on masonry bridges also for challenging situations, such as the crossing of important rivers and of large and deep valleys. Even now, in case a masonry bridge goes out of order, for any reason, the railway system could suffer serious problems even if the bridge is of ordinary importance.

Heavy commercial-traffic flow imposes the re-classification of several existing lines and, consequently, the refurbishment of masonry constructions, if needed. On the other hand, even arch masonry bridges of secondary lines might need some structural assessment, especially related to lack-of-maintenance topics.

The study of the Prarolo arch bridge may be ascribed to this last framework. Even if the railway has become a secondary one, the transport capacity required by the system, mainly in terms of an increased maximum allowed weight/axle, but also in terms of train speed and serviceability of the infrastructure, has increased recently. The main objectives of this research are the bridge structural assessment as a unique construction (on the basis of geometrical and constructive issues, technology and material properties, etc.), also aiming to verify if the current damage pattern may be attributed to service loads. Moreover, this bridge was basic for the

masonry vault studies developed in the 19th century, leading to the construction of famous examples by architects and engineers who inherited the cultural know-how, both theoretical and practical, of building issues.

## 2 THE PRAROLO ARCH BRIDGE: ENVIRONMENT AND GENERAL DESCRIPTION

The initial idea about the construction of the railway lines in the Savoy kingdom (Northern Italy and the island of Sardinia) was developed in 1826: some businessmen asked for the railway, in order to connect the city of Genoa (and its Mediterranean trading port) to the Po river area in Piedmont (Northern Italy). In September 1848, the first stretch of track between Moncalieri and Turin was inaugurated. The whole course between Turin and Genoa was opened on 20<sup>th</sup> February, 1854. It included several works of art: ten tunnels (overall length = 7381 m), twenty bridges and viaducts having spans between 5.3 and 16.5 m, twenty-two single span bridges (between 7.5 and 40 m), fifty-one flyovers and more than five hundred small bridges. Moreover, the Sampierdarena viaduct was about 670 m long (Ballatore, 1996).

The Prarolo arch bridge was built between 1850 and 1853 on the railway line Genoa-Turin, based on the General Road Society design.

Among the bridge peculiarities, the consistent mass of the constructive elements stands out; nevertheless, their shapeliness and perfect integration in the natural environment are evident. This harmonic impression of the bridge and the surrounding landscape, characterized by conglomerate rocks and sandstone banks, probably derives from the use of these local materials in the building of the main elements.

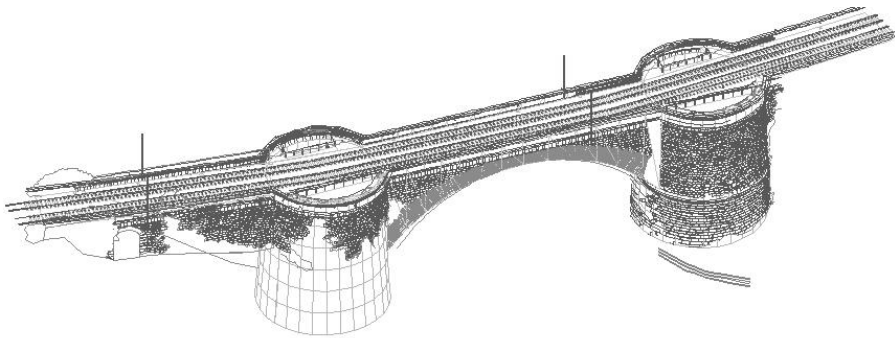


Fig. 1: Scheme of the Prarolo arch bridge (Northern Italy).

### 2.1 Historical background

During the Restoration, when Piedmont was annexed to France, the building technique underwent a typological alteration that accounted for the development of the French technical-scientific culture (Ecole des Ponts et Chaussées), to which the Enlightenment was the background. This transformation led to the abolition or, at least, the decrease of the strictly non-structural elements, being addressed as overabundant.

In the '20s and '30s of the 19<sup>th</sup> century, in Piedmont buildings of freestone became very popular, but on the other hand a new constructive technique using brickwork developed and was wholly established. The latter left a typological mark through the whole 19th century, becoming the reference for the constructive heritage in the Scrivia Valley, where the Prarolo bridge is built.

This technique allowed the building of several works of art in a quicker and cheaper way; nevertheless, in the middle of the 19<sup>th</sup> century, these bridges seemed to be innovative and traditional at the same time.

## 2.2 Geometry and material technology

In relation to a wider study of the Prarolo bridge (Balbi *et al.*, 2001), the building phase and the interventions needed after the inauguration of the bridge were investigated. The findings of the specifications and the private communications between the building firm, the General Road Society and the Minister allows us to understand the practice issues and variations related to the construction phase.

In particular, the design drawings with the construction section clarify the building technique used in the parts for which survey and inspection are not feasible, such as the inner part of the abutments and the vault extrados. When possible, the information obtained from the drawings was validated through the documentation written when building was in progress.

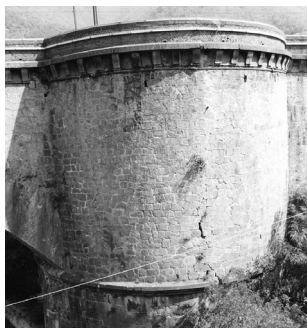
The bridge design and construction are based on the French models of “Ecole des Ponts et Chaussées”, elaborated by the Piedmont civil engineers in the 19<sup>th</sup> century. In those years, the bridge was extremely innovative for the Italian situation for several reasons: the arch profile (“of equal resistance”) that follows the line of thrust; the massive structure, in which part is resisting and the non-stressed portions are hollow; the “en croissette” (with tiers) armilla that reproduces the internal-structure exactly; the brick vault having a multi-centre arch as directrix in correspondence with the longitudinal axis and a lowered-arch directrix in correspondence with the armilla sections.

From the specifications, it can be deduced that, in order to avoid the trouble related to the curved plan for the bridge (being part of a curved stretch), the work of art was built with a straight plan, with an increase of 0.5 m in the transversal dimension. In this way, the tracks can show the prescribed curved path, but the bridge plan can be straight.

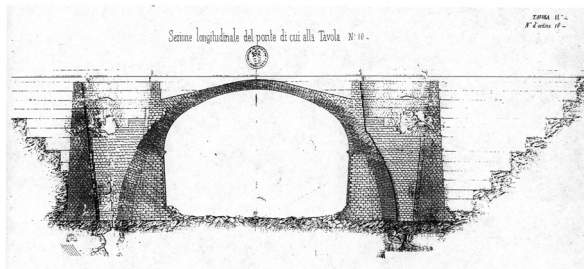
The Prarolo bridge is a single span structure, in which the vault (40 m span, 10 m rise) has a multi-centre arch profile; the vault building was envisaged of freestone, but finally made up of bricks. Its contour shows increasing thickness from the crown to the springing points and it is joined to the circular abutments through particular embrasures. Similar to the French “cornes de vache”, these joining surfaces follow the circular contour of the abutments with convex profiles.

The truncated-cone abutments (two circular towers), originally introduced in the freestone bridge building, was widely applied in England on brickwork and stone masonry bridges; this typology became popular in Piedmont during the ‘40s of the 19<sup>th</sup> century. It was applied to build wing walls and abutments of four bridges in the Scrivia Valley: two of these are partly hollow inside the tower. Moreover, in the Prarolo bridge, this shape is related to the obliqueness in respect to the river flow, being more effective from the hydrodynamic point of view.

*...Inside the abutments or towers, two buttresses, parallel to the bridge axis and 7.5 m far from one another, from midpoint to midpoint, will be built; they will be 1.5 m thick on top, with 0.2 m decrease each 2 m in height, like the perimeter walls...These two buttresses are not so useful to link the walls, as to be counterforts in relation with the vault thrust ...[the vault] will be extended inside the buttress up to the rock ...*



(a)



(b)

Fig. 2: (a) Circular abutment; (b) Longitudinal section from the archive.

As previously described, the towers (height = 22 m, base diameter = 20 m) are made up of walls with decreasing thickness from top to bottom; the vault is prolonged inside these towers, where counterfort elements, being an extension of the theoretical “line of thrust”, bear the arch thrust.

The hollow part is partly filled with brick masonry, up to the arch haunches, in order to structurally connect the constructive elements, but without adding excessive mass.

The Prarolo bridge may be considered as an industrial-archaeology construction, but it seems to anticipate modern methodologies in terms of design, technology and building management. Nevertheless, as regards building materials, the bridge is still conceived as a work of art of the 19<sup>th</sup> century: in fact, at that time, transport costs were very high and builders preferred to use local material, simply available, even if the design should have been changed.

The “*Specifications for the building of the railways between the Campasso river [...] and the first turn of the Genoa royal road, beyond Isola del Cantone*” allows us to understand the practice issues and to find descriptions of the building materials for various constitutive elements of the bridge. Rubble stone and pebbles were used for the foundations, except the external leaf of the steps that is made up of freestone, in order to behave better against the hydraulic action. For the abutments, counterforts and other walls, the arch skewbacks and the spandrels, rubble stone and pebbles were used, except the base (roughly squared stone). Moreover, suggestions about the building technique were described in the specifications.

The main difference between the structure designed and the one built can be found in the vault material: originally planned in stone masonry (the part inside the towers included), it was realized using bricks.

From the requirements of the National Railway Authority, it seems that the mechanical characteristics of the materials were used to classify and verify their quality rather than to assume a limit load for masonry, which is quite a modern concept. Nevertheless, in a 1905 technical manual, printed fifty years later the construction of the bridge, reference was found to the allowable compressive stress of masonry as a function of the brick unit strength (table 1). The value in case very hard bricks is assumed as a reference in the following analyses (§ *Structural assessment*).

Table 1: Mechanical parameters of brick and masonry (Baggi, 1926).

CLAY BRICKS	Compressive strength - BRICK	Allowable stress - MASONRY
Normal bricks	15 – 20 MPa	0.6 – 0.8 MPa
Selected bricks	20 – 25 MPa	0.8 - 1 MPa
Very hard bricks	30 – 35 MPa	1.2 – 1.4 MPa
Solid spongy bricks	10 – 15 MPa	0.4 – 0.6 MPa
Hollow spongy bricks	5 – 8 MPa	0.2 – 0.3 MPa
<i>Floating</i> bricks (of pumice-stone)	1.5 – 2.5 MPa	0.08 – 0.1 MPa
Hollow bricks	10 – 15 MPa	0.4 MPa

### 2.3 Damage and degradation pattern

After the bridge testing in 1854, information is quite scarce. On February 13, 1859, the passing of a train caused some cracks *in the bridge abutments, dislocation of the masonry, settlements of the tracks.*

*... two significant cracks, starting from the road surface and ending at the vault springing point. A small settlement of the brickwork took place... because of that, the tracks moved down and had to be repaired.*

The retrofitting interventions of the bridge abutments were described afterwards in the correspondence between the building firm and the General Road Society:

*... steel rings were placed around the towers that are this bridge's abutments... [they] were successfully concluded two days ago, the rings being perfectly adherent to the outside walls and so strong that no more trouble seems to be possible...*

Neither in the National nor in the Railway Society archives, was useful information about the subsequent transformation of the bridge (presumably regarding the equipment, substitution of some small masonry portions in the parapets) found.

Only the tower base and southern part of the subway can be directly accessed, because of the lack of scaffolding. A detailed description of the damage and degradation pattern may be found in Balbi *et al.* (2001). On the Prarolo bridge, the main surface alteration and degradation

concerns can be reasonably ascribable (directly or not) to various environmental factors, such as: climatic inclemency, heavy rainfall, wind and air-pollution. In brief, the degradation phenomena (concretions, efflorescence and deposits) were found on the vault intrados; they are currently ongoing because the water pipe-system inside the masonry elements is not working and the lack of maintenance of the extrados waterproofing cover (made up of bitumen) probably caused some failures in it. Moreover, in wider parts, mortar disgregation in the masonry joints (vault, tower basements) and brick-surface erosion (armilla) may be found.

### 3 STRUCTURAL ASSESSMENT

Through the typical methodologies of monumental heritage preservation, some research leading to structural knowledge was developed, aiming to assess the safety level of the building due to the actual traffic loads (sometimes increased as the railway codes envisage), in particular for centrifugal actions.

In the next sections, the previously cited knowledge path is described on the basis of a 3D model of the bridge: this was evaluated from the survey observation and the building documentation for the inner parts. Traditional mechanical methods for design and verification (e.g. static thrust line through graphical methods, Equilibrium Limit Analysis) are applied and extended to the 3D-representation of the thrust line related to centrifugal actions. Therefore, even if in a simplified way (not considering the dynamic effect), the modification of the dead-load thrust line, due to the centrifugal effects of the traffic flow, is studied. The limit speed value for the train is evaluated using this approach, adopting where possible the calculation suggestions of the railway technical rules (Guidelines no. 1/SC/PS-OM/2298, 1995).

#### 3.1 Dead loads

As previously described, the vault contour has increasing thickness from the crown to the springing points. The vault profile (various lowered-arches in correspondence to the longitudinal axis) is joined to the circular abutments through particular embrasures. These surfaces follow the circular contour of the abutments with convex profiles. These features have to be accounted for in the dead load evaluation.

Besides the brick vault weight (mass density =  $1800 \text{ kg/m}^3$ ) that is prolonged inside the towers up to the height of the foundations (base section) as in Fig. 2-b, the calculation takes into account the dead load of the elements above the vault itself. These elements are:

- the skewbacks: built of brick masonry (mass density =  $1800 \text{ kg/m}^3$ );
- the backfill: made up of loose soil or gravel (mass density =  $1600 \text{ kg/m}^3$ );
- the railroad ballast (mass density =  $2200 \text{ kg/m}^3$ );
- the spandrel walls: made up of light-stone masonry (mass density =  $1800 \text{ kg/m}^3$ );
- the cornice and the parapets.

Thanks to the preliminary study of the constitutive elements in the bridge structure and to a detailed geometric solid model, the loads borne by the vault were adequately evaluated. From now on, the safety-check procedure considers equivalent loads in case of the analysis of the 2D bridge model.

In the Prarolo bridge, in order to check the vault stability in case of dead load, the traditional method proposed by Méry (known as the “*minimum thrust line*” method), adopting the Equilibrium Limit Analysis notions in a graphical procedure, is applied to two longitudinal sections: the one corresponding to the midpoint, where the arch thickness is maximum, and the one close to the spandrel walls, where the arch thickness is minimum. As a consequence of the method hypotheses (masonry is a no-tension material; stresses are so low that masonry has effectively an unlimited compressive strength; sliding failure between blocks does not occur), if the line of thrust is within the middle third of the arch in each transversal section, the thrust value does not produce any tensile stress. This compression-only condition is assumed to satisfy the safety check in case of the prescribed loads.

Due to the symmetry of geometry and loads, the dead load analysis involved the half vault: the structure was divided into eight blocks, for which the weight connected to the actual

geometry and the mass centroid were calculated. The total dead load of the analysed part is about 58,000 kN.

Besides the free span, the vault is made up of another two blocks (numbered 7 and 8), prolonged inside the circular tower. Other masonry parts are present in the springing point area, but they do not load the vault because their weight is directly borne by the tower masonry walls. The overall load, due to the free span part, is about 35,000 kN and the overall centroid is determined by the graphical evaluation through the funicular polygon of the applied forces (Fig. 3).

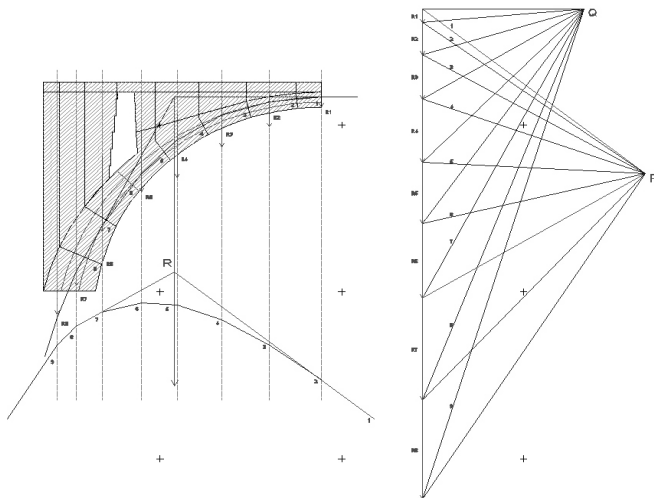


Fig. 3: Graphical check of the transversal section at the midpoint of the bridge (under Méry hypotheses).

As the line of thrust is within the middle third of the arch, both in the longitudinal section corresponding to the midpoint and in the one close to the spandrel walls, it can be assumed that the whole stress state in the arch is compression only.

### 3.2 Traffic flow: maximum allowed weight/axle

The Italian railway technical rules (Guidelines no. 1/SC/PS-OM/2298, 1995) take into account two categories of commercial lines from the point of view of maximum allowable axle load: D4-type lines, with a 225 kN/axle load, covering approximately 2/3 of the whole system, and almost all the remaining lines are of C3-type, with allowed axle load of 200 kN/axle. The structural check of the Prarolo bridge in case of traffic flow refers to D4-type carriages and LM 71 locomotives. This condition is associated with a normal traffic flow. The weight of an LM 71 locomotive (4 axles at 1.6 m) is 250 kN/axle and the carriage load may be distributed on the two sides (80 kN/m). Generally, the D4-type loads may be longitudinally distributed (equivalent load equal to 156.25 kN/m on 6.4 m).

The presence of one locomotive alone on both the tracks was also considered: if the resulting force P (2000 kN) is asymmetrically applied on the railroad (10 m from the crown), the worst loading condition is achieved. This is not surprising in case of long single-span bridges, for which the distributed load of the carriages at the haunches increases the stability, raising the vertical component of the thrust. On the safe side, the effect of the stress spatial distribution due to the fill was not accounted for.

From the thus originated line of thrusts, it can be obtained that no tension stress developed in any arch section that is subjected to compression state. In Fig. 4-a, the graphical analysis results are sketched: even if not represented, the detailed geometry and loads were assumed in the procedure.

In the previously analysed longitudinal profiles, the compressive stress (evaluated through Navier formulation in the crown section, springing points and each intermediate sections) is compared to an admissible value for the masonry material of the arch (corresponding to *Very*

hard bricks in table 5). The compressive stress is high (near the safety value) in various sections of the arch; nevertheless, it can be reasonably hypothesized that part of the masonry elements not assumed as a “resisting structure” (e.g. the skewbacks) play a not negligible structural role. Under this convincing assumption, the bridge seems to be well proportioned in case of loads due to normal traffic flow.

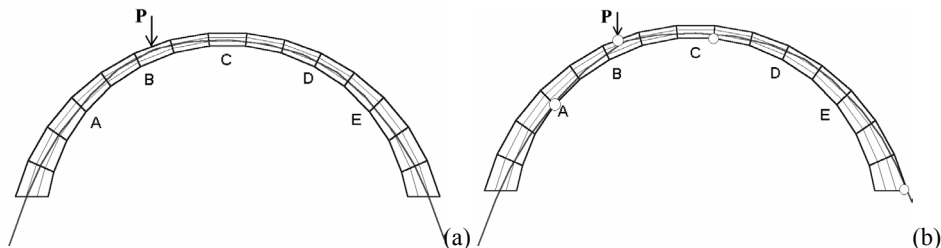


Fig. 4: Detail of the lines of thrust in the vault transversal section: (a) point load  $P = 2000$  kN; (b)  $P = 8000$  kN (possible kinematism).

Through *limit design* concepts, Heyman stated in the safety theorem: “if a line of thrust can be found which is in equilibrium with the external loads and which lies wholly within the masonry, then the structure is safe” and in the uniqueness theorem: “if a line of thrust can be found which represents an equilibrium state for the structure under the action of the given external loads, which lies wholly within the masonry, and which allows the formation of sufficient hinges to transform the structure into a mechanism, then the structure is on the point of collapse” (Heyman, 1966).

So, aiming to identify a possible collapse condition for this kind of load, the resulting force  $P$  was increased until a kinematism could be recognized (Fig.4-b): the changes in the lines of thrust led to a four-hinge mechanism (in the point of tangency of the arch and the thrust line). The  $P$  value in this condition is about 8000 kN, but obviously this is not a reasonable value, because masonry crushing due to compressive stress may develop previously; nevertheless, this analysis may be useful in order to have an idea about a possible kinematic configuration of the arch.

### 3.3 Traffic flow: centrifugal action

A further safety check in case of centrifugal actions was pointed out; traditional mechanical methods for design and verification (e.g. Equilibrium Limit Analysis) are applied and extended to the 3D-representation of the thrust line related to centrifugal actions. Therefore, even if in a simplified way (not considering the dynamic effect), the modification of the dead-load thrust line, due to the centrifugal effects of the traffic flow, is studied.

The centrifugal action is evaluated adopting where possible the suggestions of the Italian railway technical rules (Guidelines no. 1/SC/PS-OM/2298, 19959. They prescribe the evaluation of the distributed load due to a D4-type carriages on curved tracks ( $R = 400$  m) on the whole bridge. Two trains in opposite directions were accounted for and the horizontal resulting force was applied at 1.8 m height above the railroad, considering the radial direction: the load condition is symmetric and the analyses are carried out on a half bridge.

The evaluation of the reaction forces which equilibrate the applied load (and the related points of application) was analytically obtained through two consequent steps: the first is finalized to the determination of the overall reaction forces (and point of application) at the springing points. In this phase, an iterative procedure (varying the point of application of the horizontal load) is carried out, in order to ensure that the point of application of the reaction forces lies within the middle third, both in the transversal and longitudinal sections of the bridge. In this situation, it is assumed, in a simplified way, that no tension stress develops on the block interface. Assuming the previously computed quantities, the subsequent step involves the evaluation of the reaction forces (and point of application) which equilibrate the applied load for each block, imposing that the line of thrust lies within the middle third, as described.

Being, as in Fig. 5:

- S = thrust in the crown section (along X axis due to symmetry), applied to point P<sub>s</sub> (coordinates y<sub>s</sub>, z<sub>s</sub> in the transversal plane);
- H = horizontal force due to the centrifugal action, applied to point P<sub>h</sub> (coordinates x<sub>h</sub>, z<sub>h</sub> in the longitudinal plane);
- W = dead load, applied to point P<sub>w</sub> (coordinates x<sub>w</sub>, y<sub>w</sub> in the horizontal plane);
- F = reaction force at the springing points (components F<sub>x</sub>, F<sub>y</sub>, F<sub>z</sub>), applied to point P<sub>f</sub> (coordinates x<sub>f</sub>, y<sub>f</sub>, z<sub>f</sub>).

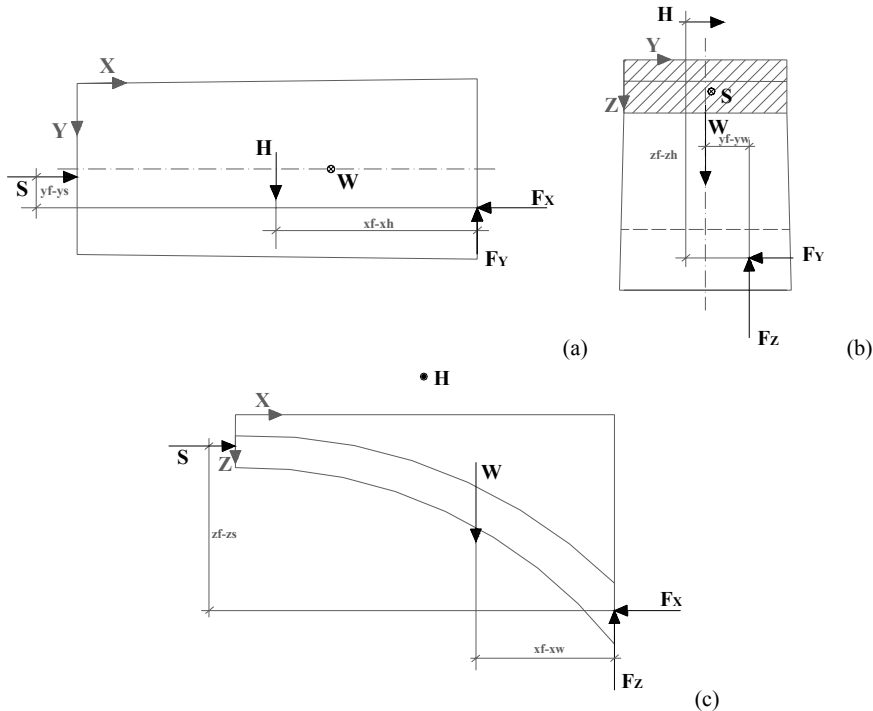


Fig. 5: Applied forces and reactions: (a) plan view; (b) transversal section in crown; (c) longitudinal view.

Using the railway technical rule formulation, the resulting horizontal force H due to the centrifugal action was computed, in relation to the V speed of the train, as in eq. (1):

$$H = 2 \cdot x_h \cdot \frac{V^2}{127 \cdot R} (f \cdot q_{vd}) \quad (1)$$

where:

q<sub>vd</sub> = design value of the vertical distributed load (D4 type carriages) = 80 kN/m;

V = train speed in km/h;

R = curvature radius of the tracks = 400 m;

x<sub>h</sub> = coordinate of the point of application of H;

f = reduction factor, function of the V speed and the length of the loaded track.

Imposing the translational and rotational equilibrium and assuming a trial z<sub>f</sub> value, the values of F<sub>x</sub>, F<sub>y</sub>, F<sub>z</sub>, x<sub>f</sub>, y<sub>f</sub> are evaluated, as in eqs (2)-(6). The trial z<sub>f</sub> value has to ensure (if possible) that F is applied according to the middle-third rule in the springing-point section.



$$F_z = W \quad (2)$$

$$F_x = S = W \cdot \frac{(x_f - x_w)}{z_f - z_s} \quad (3)$$

$$F_y = H = W \cdot \frac{(y_f - y_w)}{(z_f - z_h)} \quad (4)$$

$$x_f = x_w + \frac{S(z_f - z_s)}{W} \quad (5)$$

$$y_f = \frac{y_w \cdot (x_f - x_h) \cdot (z_f - z_s) - y_s \cdot (x_f - x_w) \cdot (z_f - z_h)}{(x_f - x_h) \cdot (z_f - z_s) - (x_f - x_w) \cdot (z_f - z_h)} \quad (6)$$

The second step deals with the evaluation of the  $F_i$  force (and related point of application) equilibrating the applied loads on the  $i$ -th block interface, from the crown to the springing points.

While in the overall equilibrium condition only translational reaction forces are accounted for, moments about the  $X$  axis are computed at the block interface: they may represent in a very simplified way interlocking effects in the masonry material. This is equivalent to assigning eccentricity  $e_{yw,i}$  to the dead load resulting force  $W_i$  on the  $i$ -th block interface, that is considered to be applied to point  $P'_{w,i}$  (coordinates  $x_{w,i}$ ,  $y_{w,i}$  in the horizontal plane), as in eqs. (7) and (8).

$$e_{yw,i} = \frac{H_i \cdot (z_{f,i} - z_{h,i}) - W_i \cdot (y_{f,i} - y_{w,i})}{W_i} \quad (7)$$

$$y_{w,i}' = y_{w,i} + e_{yw,i} \quad (8)$$

where the subscript  $i$  refers to the quantity value in eqs. (2)-(6) in correspondence with the  $i$ -th block interface.

Through the equilibrium equations, imposing the value of  $S_i$ ,  $H_i$  and  $x_{f,i}$ , the quantity  $y_{f,i}$  e  $z_{f,i}$  are evaluated, iterating until the balancing force  $F_i$  is applied according to the middle-third rule in the section.

In case of the prescribed centrifugal loads, the safety of vault of the Prarolo bridge is ensured, as the reaction force lies within the middle third, both in the transversal and longitudinal sections of the bridge.

In figure 6, the plan view of the bridge is shown: two possible line of thrust in case of centrifugal action are also displayed, accounting for the eccentricity  $e_{yw,i}$  of the dead load resulting force  $W_i$  on the  $i$ -th block interface or not. It can be noted that the hypothesis of interlocking effects (represented by moments about  $X$  axis transferred at the block interface) implies "overstrength" in the arch behaviour; in fact, the line of thrust not accounting for the eccentricity  $e_{yw,i}$  is nearer than the other to the limit condition based on the middle third rule.

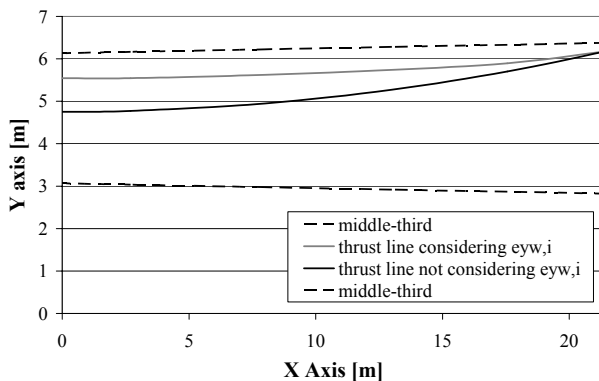


Fig. 6: Thrust line for dead load and centrifugal action (plan view).

Nevertheless, both the conditions are safe in the longitudinal, transversal section and plan; so, the stability of the vault of the Prarolo bridge is considered to be ensured.

Assessing the train speed related to the limit condition (tension at least acting on one block interface), the approximate value  $V = 289$  km/h (much higher than the prescribed one) was obtained.

#### 4 EVIDENCE ABOUT CRACK AND DEFORMATIVE PATTERN

Even if the simplified analysis suggests that the vault should not have suffered from damage due to the traffic flow, the cracks in the circular abutments testify that some trouble has occurred. However, the special geometry and the inner hollow parts of these elements do not permit simplified studies.

As previously described, two significant sub-vertical cracks, starting from the road surface and ending at the vault springing point were surveyed: this damage pattern may be reasonably ascribed to the passing of a train (as reported in the documents) and the technology used in the retrofitting intervention confirmed the feasibility of this hypothesis. Moreover, the steel hooping position seems to be too high and this may reduce its effectiveness.

Instead, the partial detachment of the armilla stones of the vault may be put down to a poor connection to the structural brick vault; in fact, the different thermal dilatation characterising the two materials could have induced the disengagement.

#### 5 FINAL REMARKS

The Prarolo masonry arch bridge has been assessed through a multi-disciplinary approach, in order to tackle the issues related to monument preservation, emphasizing the importance of synthesis and comparison of data from different sources, in order to obtain a more detailed and more realistic overview of the problem.

Combining the elements from the *in situ* findings and from historical studies, some hypotheses on the structural behaviour and causes of the current damage pattern were determined.

The simplified analyses through traditional mechanical methods for design and verification suggest that the vault should not have suffered from damage due to dead load or traffic flow, but a more detailed safety check on the circular abutments (where ancient cracks were identified) may be very useful in order to understand the quality of the structural behaviour.

Nevertheless, the main preservation issue is related to the degradation phenomena (concretions, efflorescence and deposits) found on the vault intrados, mainly due to various environmental factors (climatic inclemency, heavy rainfall) and lack of maintenance of the extrados waterproofing cover.

Moreover, in the ambit of a wider study developed by the Faculty of Architecture (University of Genoa, Italy), the described studies were functional to putting forward the restoration design for the bridge.

#### ACKNOWLEDGEMENTS

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