IABSE
International Association for Bridge and Structural Engineering

IABSE Symposium 2010, Venice, Italy

34th International Symposium on Bridge and Structural Engineering,
Venice, Italy, September 22–24, 2010

Large Structures and Infrastructures for Environmentally Constrained and Urbanised Areas

Organzied by
The Italian Group of IABSE

Co-organisers
University IUAV of Venice
Politecnico di Milano

with
Politecnico di Torino
University Federico II
University La Sapienza
University of Trento

IABSE
ETH Hönggerberg
8093 Zürich, Switzerland
Tel: +41-44-633-2647/Fax: +41-44-633-1241
secretariat@iabse.org/www.iabse.org

Book of Abstracts ISBN 978-3-85748-122-2, pp. 778-779.
CD-Rom Proceedings, Paper A-634, 8 pages.

Structural modelling of the piers of the Paderno d'Adda Bridge (1889, Italy)

Rosalba FERRARI
Doctoral Student
Università di Bergamo
Facoltà di Ingegneria
Dalmine (BG), Italy
rosalba.ferrari@unibg.it

Rosalba Ferrari holds a degree (Master Level) in Building Engineering (2009). She is currently Doctoral Student at UniBG.

Mattia FACHERIS
Graduate Student
Università di Bergamo
Facoltà di Ingegneria
Dalmine (BG), Italy
mattia.facheris@studenti.unibg.it

Mattia Facheris holds a degree (Bachelor Level) in Building Engineering (2009). He is currently Graduate Student at UniBG.

Egidio RIZZI
Professor
Università di Bergamo
Facoltà di Ingegneria
Dalmine (BG), Italy
egidio.rizzi@unibg.it

Egidio Rizzi is full professor of Mechanics of Materials and Structures. He joined UniBG in 2001, after serving at PoliBA (98-01) and PoliMI (95-98).

Summary

This note focuses on a specific aspect of the structural modelling of the Paderno d'Adda Bridge, a marvellous Italian historic wrought iron bridge with riveted connections that was completed in 1889 and opened to both railway and road traffics [1-2]. Within the current attempt of building a full 3D FEM model of the structure [3-7], the metallic piers of the bridge are considered [5-6], specifically the *pier on the arch*. The morphology of the piers has been reconstructed from the inspection of the original design drawings and implemented into a FEM model. Then, a structural analysis has been performed in the elastic range, by considering loading distributions that were conceived at design stage and also conditions that are nearer to present-state railway standards.

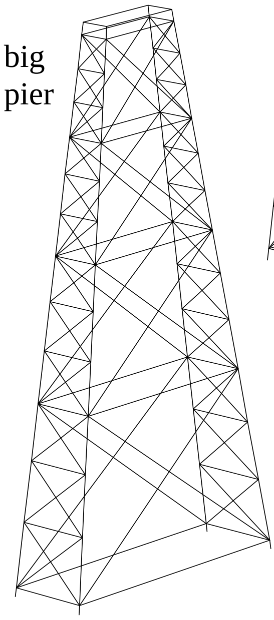
Keywords: 19th-century historic bridge, railway arch iron bridge, FEM model, structural analysis.

1. Introduction

The Paderno d'Adda Bridge, sometimes called San Michele Bridge, is an impressive iron viaduct located in Lombardia, northern Italy, near Milano, North-East from it (Fig. 1). It allows the elevated crossing of the river Adda between Paderno d'Adda (Lecco province) and Calusco d'Adda (Bergamo province), to a height of about 85 m from water [1-2]. It was completed in 1889 by the "*Società Nazionale delle Officine di Savigliano*" *(SNOS)* and designed through the practical application of graphical-analytical methods such as the "*Theory of the ellipse of elasticity*" [3-4]. The bridge is composed of: a 266 m long upper continuous box beam on 9 supports, 4 of them resting on the underneath arch; 5 vertical piers that provide 5 of the 9 bearings of the beam; a marvellous doubly-built-in parabolic arch with inclined faces of about 150 m of span and 37.5 m of rise.

Fig. 1: View from downstream of the Paderno d'Adda Bridge, Lombardia, Italy (1889).

Despite its age, the bridge is still in service, for both railway and automotive traffics. However, its state of conservation gives today some concerns, since maintenance seems to have been scarce, especially in the last twenty years or so. In light of this, it appears worthwhile to attempt the formulation of a complete structural model of the bridge [3-7], useful to assess its structural performance for different loading scenarios, under static and dynamic environments and according to both design-state conception and present-state conditions. Towards this modelling, as a first step, the design morphology of the different parts of the structure have been determined by the inspection of the original technical drawings made by the SNOS (Fig. 2b), which are guarded at the Archivio Storico Nazionale di Torino, in view of assembling a complete FEM model of the bridge that would be loyal, as much as possible, to design conception.



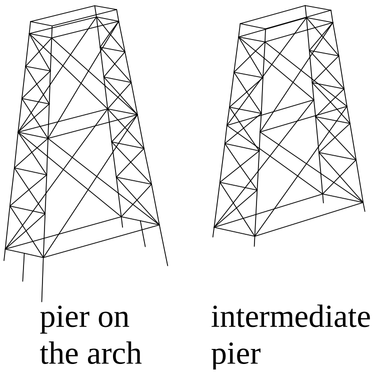
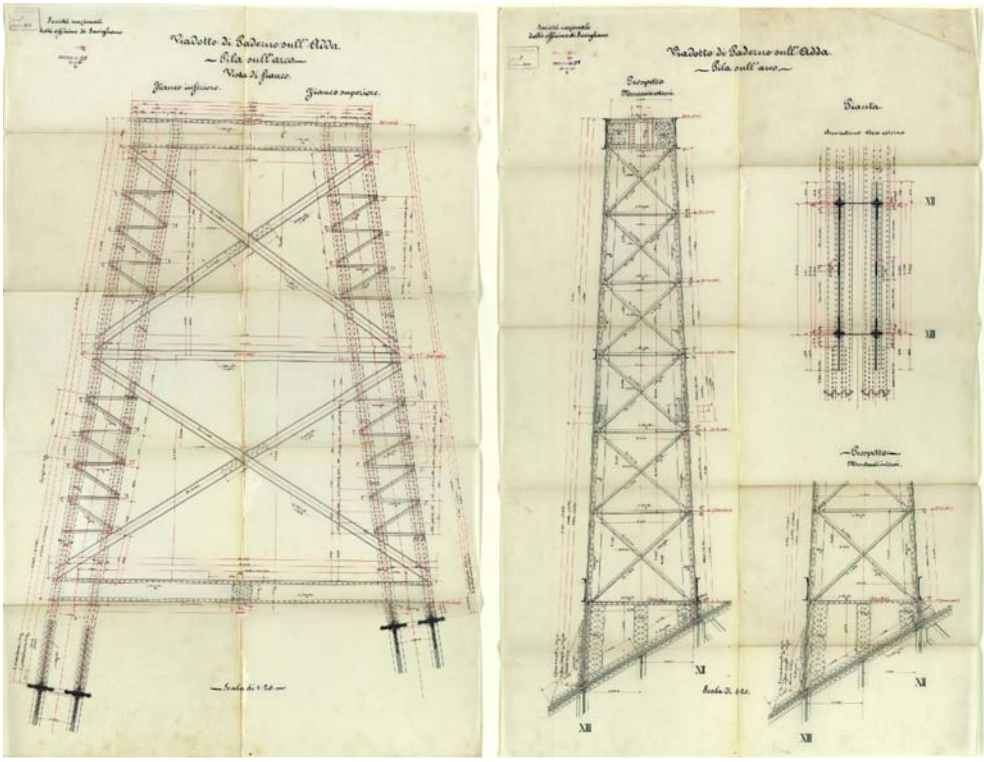


Fig. 2: (a) FEM model; (b) Original drawings.

In this paper, focus is made on the modelling of the piers, which are recognized to appear in three basic typologies [5-6]. The geometric characteristics are detected systematically and implemented into a true 3D (ABAQUS) FEM truss model with beam elements mutually built-in at the nodes (Fig. 2a). Explicit detail is given specifically for the *pier on the arch*. Numerical simulations are carried-out for different loadings, reproducing conditions that were assumed at design stage, plus cases with superposition of effects, including a train braking action, that the members, with original



dimensioning, should experience today, according to present standards. The other piers have been then extruded and finally mounted on a full 3D FEM model of the bridge [7]. The FEM model could be further elaborated by additional info that may arise from direct inspections, towards the assessment of the present conditions of the bridge.

References

[1] SOCIETÀ NAZIONALE DELLE OFFICINE DI SAVIGLIANO, *Viadotto di Paderno sull'Adda (Ferrovia Ponte S. Pietro-Seregno)*, Torino, Tip. e Lit. Camilla e Bertolero, 1889.

[2] NASCÈ V., ZORGNO A.M., BERTOLINI C., CARBONE V.I., PISTONE G., ROCCATI R., "Il ponte di Paderno: storia e struttura", *Restauro*, Anno XIII, n. 73–74, 1984.

[3] FERRARI R., *Sulla concezione strutturale ottocentesca del ponte in ferro di Paderno d'Adda*, Laurea Thesis in Building Engineering, 228 pages, December 2006.

[4] FERRARI R., RIZZI E., On the theory of the ellipse of elasticity as a natural discretisation method in the design of Paderno d'Adda Bridge (Italy), in *Proc. of 6th Int. Conf. on Structural Analysis of Historic Construction (SAHC08)*, Bath, UK, 2-4 July 2008, Vol. 1, pp. 583–591, 2008.

[5] FACHERIS M., *Analisi morfologica e modellazione per elementi finiti della pila sull'arco del ponte di Paderno d'Adda*, Laurea Thesis in Building Engineering, 125 pages, September 2009.

[6] FERRARI R., *Analisi strutturale degli elementi portanti del ponte di Paderno d'Adda*, Master Thesis in Building Engineering, 108 pages, September 2009.

[7] FERRARI R., FACHERIS M., RIZZI E., Structural Analysis of the Paderno d'Adda Bridge (Italy, 1889), *Proc. of 7th Int. Conf. on Structural Analysis of Historical Constructions (SAHC10)*, Shanghai (China), 6-8 October 2010, to appear, 2010.

Structural modelling of the piers of the Paderno d'Adda Bridge (1889, Italy)

Rosalba FERRARI
Doctoral Student
Università di Bergamo
Facoltà di Ingegneria
Dalmine (BG), Italy
rosalba.ferrari@unibg.it

Rosalba Ferrari holds a degree (Master Level) in Building Engineering (2009). She is currently Doctoral Student at UniBG.

Mattia FACHERIS
Graduate Student
Università di Bergamo
Facoltà di Ingegneria
Dalmine (BG), Italy
mattia.facheris@studenti.unibg.it

Mattia Facheris holds a degree (Bachelor Level) in Building Engineering (2009). He is currently Graduate Student at UniBG.

Egidio RIZZI
Professor
Università di Bergamo
Facoltà di Ingegneria
Dalmine (BG), Italy
egidio.rizzi@unibg.it

Egidio Rizzi is full professor of Mechanics of Materials and Structures. He joined UniBG in 2001, after serving at PoliBA (98-01) and PoliMI (95-98).

Summary

This note focuses on a specific aspect of the structural modelling of the Paderno d'Adda Bridge, a marvellous Italian historic wrought iron bridge with riveted connections that was completed in 1889 and opened to both railway and road traffics [1-2]. Within the current attempt of building a full 3D FEM model of the structure [3-7], the metallic piers of the bridge are considered [5-6], specifically the *pier on the arch*. The morphology of the piers has been reconstructed from the inspection of the original design drawings and implemented into a FEM model. Then, a structural analysis has been performed in the elastic range, by considering loading distributions that were conceived at design stage and also conditions that are nearer to present-state railway standards.

Keywords: 19th-century historic bridge, railway arch iron bridge, FEM model, structural analysis.

1. Introduction

The Paderno d'Adda Bridge, sometimes called San Michele Bridge, is an impressive iron viaduct located in Lombardia, northern Italy, near Milano, North-East from it (Fig. 1). It allows the elevated crossing of the river Adda between Paderno d'Adda (Lecco province) and Calusco d'Adda (Bergamo province), to a height of about 85 m from water [1-2]. It was completed in 1889 by the *"Società Nazionale delle Officine di Savigliano" (SNOS)* and designed through the practical application of graphical-analytical methods such as the *"Theory of the ellipse of elasticity"* [3-4]. The bridge is composed of (Fig. 2): a 266 m long upper continuous box beam on 9 supports, 4 of them resting on the underneath arch; 5 vertical piers that provide 5 of the 9 bearings of the beam; a marvellous doubly-built-in parabolic arch with inclined faces of about 150 m of span and 37.5 m of rise.

Fig. 1: View from downstream of the Paderno d'Adda Bridge, Lombardia, Italy (1889).

Despite its age, the bridge is still in service, for both railway and automotive traffics. However, its state of conservation gives today some concerns, since maintenance seems to have been scarce, especially in the last twenty years or so. In light of this, it appears worthwhile to attempt the formulation of a complete structural model of the bridge [3-7], useful to assess its structural performance for different loading scenarios, under static and dynamic environments and according to both design-state conception and present-state conditions. Towards this modelling, as a first step, the design morphology of the different parts of the structure has been determined by the inspection of the original technical drawings made by the SNOS, which are guarded at the Archivio Storico Nazionale di Torino, in view of assembling a complete FEM model of the bridge that would be loyal, as much as possible, to the design conception.

In this paper, focus is made on the modelling of the piers of the bridge, which are recognized to appear in three basic typologies [5-6]. The geometric characteristics are detected systematically and implemented into a true 3D FEM truss model, with beam elements mutually built-in at the nodes. The model has been assembled within the commercial code ABAQUS. Explicit detail is given specifically for the *pier on the arch* (Fig. 3), with account of the mutual connections beam/pier and pier/arch. Numerical simulations are carried-out for different loading configurations of the pier, reproducing conditions that were assumed at design stage, plus cases with superposition of effects, including a train braking action, that the structural elements, with original dimensioning, should experience today, according to present standards of safety. Later on, possible reconstructions of present-state geometries (with variation due e.g. to corrosion and damage) could be further taken into account to evaluate possible scenarios of conservation interventions on the bridge.

2. Morphology of the piers and FEM schematisation

Of the nine bearings of the upper box beam, five are constituted by truss metallic piers with appreciable vertical body, see Fig. 2 (the two *bearings on the arch* II-III, in magenta in Fig. 2, that are symmetrically located by the crown, lay directly on the arch extrados). Four of these piers are placed symmetrically, in couples, with respect to the keystone: one couple of piers (in blue in Fig. 2), of height near 14 m, rests on the haunches of the arch at bearings I and IV (*piers on the arch*); the other (in red in Fig. 2), of height 31.5 m (*big piers*), bears directly on built-in stone supports on the river banks, which host as well the arch shoulders. The other single pier (in green in Fig. 2), of height 11.1 m (*intermediate pier*) is located on the Calusco bank and constitutes an additional support, since the upper beam is not placed symmetrically to the crown of the arch (bearing III on the Calusco side is at half length of the upper continuous beam). The morphological analysis of the piers and consequent FEM modelling has therefore focused on *three pier typologies*.

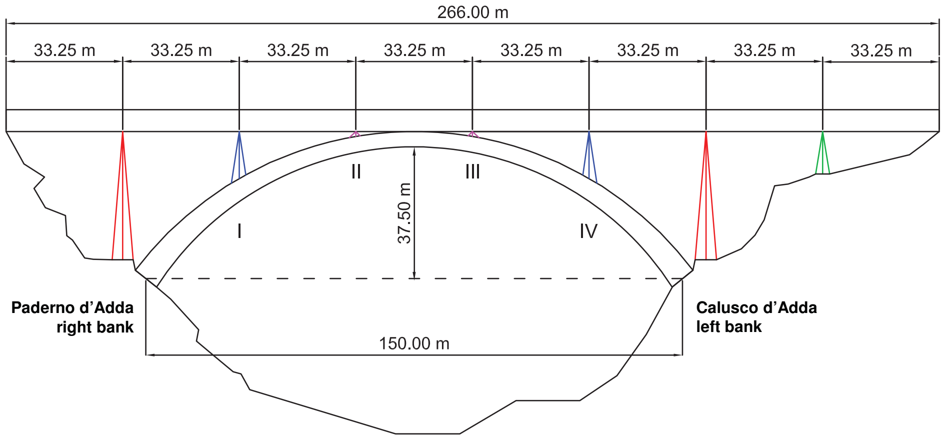


Fig. 2: Sketch from downstream of the structure of the Paderno d'Adda Bridge, with indication of the five piers (and of inner bearings II-III on the arch).

Fig. 3: View from downstream of the pier on the arch (Calusco side).

The piers appear to have been derived from a unique generating pyramid, always sectioned first at the same height at the top and then at different heights at the bottom, depending on the relative distance between the upper truss beam and the piers/ground or piers/arch connections. The upper rectangular closing frame on top, which hosts as well the bearing devices, appears to be the same for all the piers, with longitudinal (in a front view of the longitudinal plane of the bridge) 1.6 m and transverse (in planes orthogonal to the longitudinal plane of the bridge) 6.3 m widths. Of the four faces of the box profile of the piers, the front ones lay in the same α-inclined planes of the arch profile, with $sin\alpha = 0.15$, i.e. $\alpha \cong 8.63$ (thus, in a sense, the piers protrude from the arch towards the top); the lateral ones lay in β-inclined planes of a smaller inclination angle β of around $\beta \cong 2.8°$. The piers are made by a pair of front box trusses, each formed by four T-section columns linked longitudinally by short horizontal bars and St. Andrew's crosses and transversally by even shorter horizontal and inclined bars. The two box trusses are further connected transversally by a main transverse windbracing system with slender horizontal bars and St. Andrew's crosses (see the representative scheme of the pier on the arch in Fig. 4a, as compared to the real view in Fig. 3).

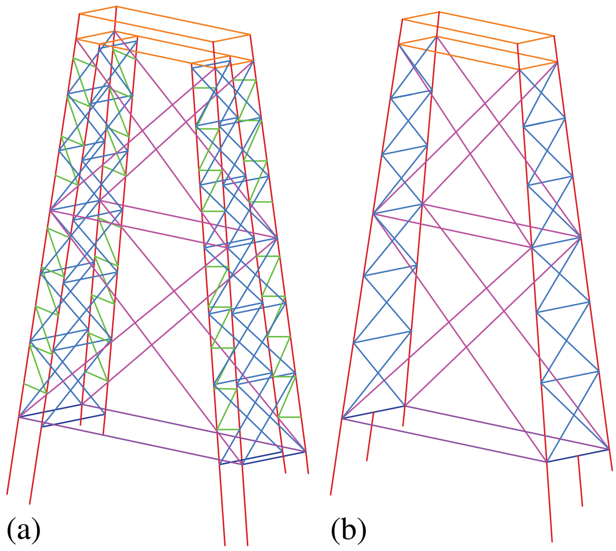


Fig. 4: Pier on the arch: (a) true morphology, (b) FEM model.

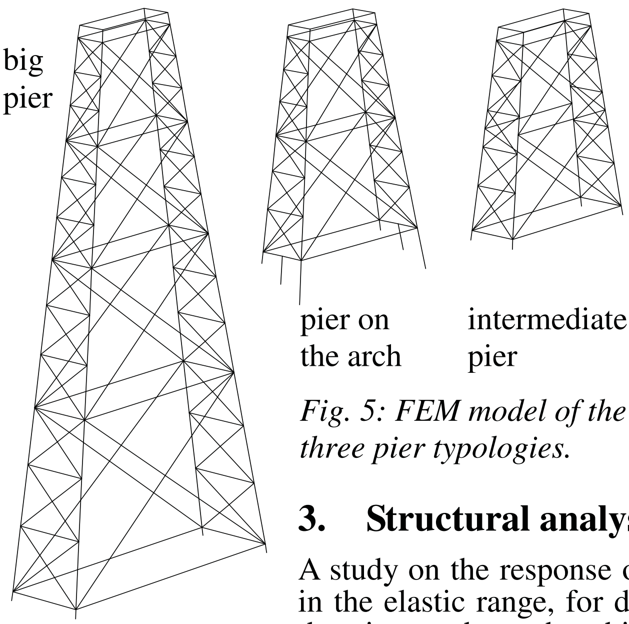


Fig. 5: FEM model of the three pier typologies.

In making the FEM model (Figs. 4b, 5), some simplifications have been considered. Each box truss has been described by a single planar truss frame laying in the α-inclined plane of the front faces, with transverse mutual connections between the two box trusses that resemble the true transverse windbracing system of the piers. The model has been outlined by assigning bars with constant cross sections, endowed with equivalent geometrical characteristics (area, principal moments and torsional inertia). Concerning the connections beam/piers, which are stiffened by plates, the corner mounting elements have been prolonged on top until the upper height of these reinforcing plates and connected there by means of horizontal bars. Similarly, for the pier on the arch, the stiffened plate connection pier/arch has been made by prolonging the corner elements of the pier to the height of the arch extrados. An additional stiffening element has been also inserted in an intermediate location between the two corner columns and between the bottom impost plane of the lower windbracing system and the arch extrados. As mentioned by Nascè et al. in [2], the local sections of all these elements, that are devised to simulate the stiffening plates, are assumed with higher geometrical characteristics, specifically one thousand times the value that should be directly assigned to them. The main figures (elements, nodes) of the FEM model of the three pier typologies (Fig. 5) are as follows: big pier (224, 317), pier on the arch (120, 181), intermediate pier (110, 160).

3. Structural analysis of the pier on the arch

A study on the response of the FEM model of the piers has been attempted in the elastic range, for different static loading configurations. Specifically, the pier on the arch, which has been assembled first and for which a few data and results can be accessed from [1], has been analysed separately with some detail [5], with absolute built-in constraints at the bottom nodes. The piers are then made part of a complete model of the bridge and analysed therein [6-7]. To the wrought iron material, the following nominal characteristics have been assigned, see Refs. [1-2]: $E = 17{\cdot}10^6$ t/m^2 for the Young's modulus, $G = 6.54{\cdot}10^6$ t/m^2 for the shear modulus (derived approximately from a Poisson's ratio of around $\nu = 0.3$); the admissible stresses in the structural members are indicated in $\sigma_a = 6.0$ kg/mm^2, with reduction to $\sigma_a = 4.2$ kg/mm^2 for the slender bars of the transverse windbracing systems.

The loading conditions considered in [1] for the pier on the arch are as follows: self-weight of the upper beam; accidental vertical load on the beam, self-weight of the pier; horizontal wind load on the beam and the pier. Similar conditions have been reproduced into the FEM model of the pier on the arch. Also, additional loadings and combinations have been considered, as summarised below:

- VL1: point vertical loads applied on top of the pier and on the nodes of the corner elements, with built-in constraints imposed at the horizontal impost of the bottom windbracing system;
- VL2: same as above but, as in all following ones, with built-it constraints at the true bases of the pier laying on the arch's extrados;
- WA: transverse horizontal wind action on the beam and the pier;

- BA: train braking action;
- SE1: superposition of effects of vertical loads and wind action;
- SE2: superposition of effects of vertical loads, wind action and train braking action.

The following output response parameters have been considered: displacement values of the pier nodes at the top closing; axial forces and normal stresses in the various bar typologies, with indication of maximum and minimum values; plots of magnified deformed configurations (amplification factor: 600 for VL1, VL2, WA and SE1 configurations; 200 for BA and SE2 conditions), with representation of displacement or axial force colour scales. The results of the various loading cases are analysed in detail in the following.

3.1 Vertical Loads 1 (VL1)

This loading condition on the pier on the arch (pier I on the Paderno side), documented by the SNOS in [1], considers: the self-weight of the upper beam, 211.8 t; the accidental load on the beam for the "1st load distribution", leading to maximum action at bearing I, 340.6 t, for a total of 552.4 t; the self-weight of the pier, estimated in 29.5 t. Consistently, the applied vertical loads to the FEM model have been implemented as: vertical loads at the top of the pier (on the four vertexes of the superior closing) 138.1 t, to represent the total of 552.4 t coming from above; vertical distributed load on the corner nodes (excluding the previous, on 6 nodes per each of the 4 corner elements) 1.23 t, to represent the pier weight of 29.5 t. Images of input and output are displayed in Figs. 6a,b.

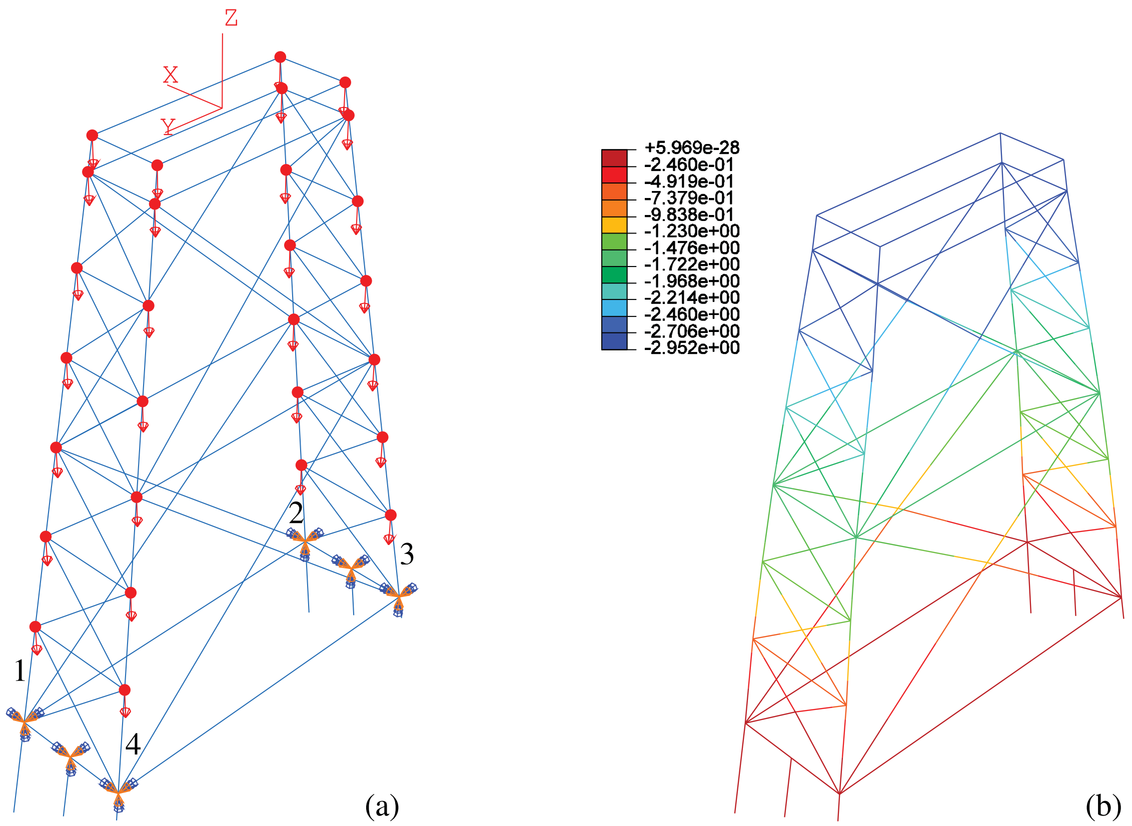


Fig. 6: (a) VL1 condition and (b) magnified deformed configuration (vertical displacement scale in mm).

This condition has been considered for a first comparison of order-of-magnitude agreement with the pier contraction reported by the SNOS in [1] and to assess the symmetry of the assembled model, with reasonable positive outcomes for both issues. The resulting vertical displacements are in the order of $u_Z = -2.95$ mm (see the reference system on top of Fig. 6a), as compared to $u_Z = -2.7$ mm given in [1]. Thus, the FEM model of the pier appears slightly more compliant than what conceived at design stage. Indeed, there might be an effect of the stiffening plates that have been much simplified here, together with of the simplifications done in modelling the geometries of the bars. The axial forces in bottom corner bars 1-4 (Fig. 6a) amount to $N_{1\text{-}4} = 141333$ kg.

3.2 Vertical Loads 2 (VL2)

This loading condition considers the same loads as in the previous but assumes, as in all that follow, built-in constraints at the true extremities of the corner members on the arch's extrados. Fig. 7 reports the magnified deformed configuration, with representation in colour scale of the axial forces in the bars (Table 1).

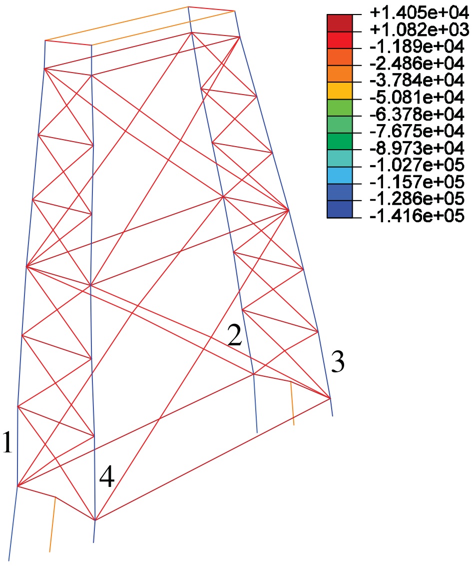


Fig. 7: VL2 condition. Magnified deformed configuration (axial force scale in kg).

Table 1: VL2 condition. Axial forces and stresses in bars 1-4 and maximum/minimum values in the various bar types (+ tension, – compression).

Bar Type	Axial Force [kg]	Area [mm^2]	Stress [kg/mm^2]
Corner bar 1	– 141615	34224	– 4.14
Corner bar 2	– 141615		– 4.14
Corner bar 3	– 141505		– 4.13
Corner bar 4	– 141505		– 4.13
Corner columns	– 128471	34224	– 3.75
	– 141615		– 4.14
Longitudinal bracing	+ 5577	3000	+ 1.86
	– 5014		– 1.67
Transverse bracing	+ 3897	3247	+ 1.20
	– 5391		– 1.66

The symmetry of the model response with respect to the longitudinal plane (X, Z) is confirmed. The stresses in the various bars are all below the scheduled admissible values. The displacements of the top rectangular closing are obtained as follows: vertical displacements $u_Z = -3.42$ mm (on side 1-2) and $u_Z = -3.19$ mm (on side 3-4); horizontal longitudinal displacements towards shoulders $u_X = 1.79$ mm.

3.3 Wind Action (WA)

This loading considers the transverse (Y direction) horizontal wind action on the beam and the pier.

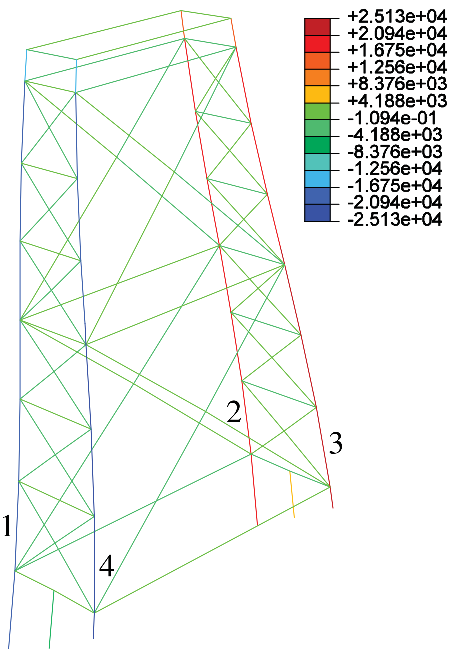


Fig. 8: WA condition. Same as Fig. 7.

Table 2: WA condition. Same as Table 1.

Bar Type	Axial Force [kg]	Area [mm^2]	Stress [kg/mm^2]
Corner bar 1	– 20837	34224	– 0.61
Corner bar 2	+ 20837		+ 0.61
Corner bar 3	+ 24381		+ 0.71
Corner bar 4	– 24381		– 0.71
Corner columns	+ 25127	34224	+ 0.73
	– 25128		– 0.73
Longitudinal bracing	+ 898	3000	+ 0.30
	– 898		– 0.30
Transverse bracing	+ 3680	3247	+ 1.13
	– 3680		– 1.13

From [1], the respective wind actions are quantified as $W_b = 22.4$ t, $W_p = 4.8$ t and applied at the quotes of the centres of gravity of the beam and the pier.

These actions are statically-equivalent to a horizontal force of $W = W_b + W_p = 27.2$ t acting at the quote of the bearing device (253.5625 m on the sea level) and to an overturning moment $M_W = 105.967$ t·m, which can be taken into account by a couple of vertical forces with arm equal to the 5 m width of the upper beam and magnitude $F_W = 21.193$ t. These loads are then applied to the FEM model by four transverse horizontal forces of $W/4 = 6.8$ t at the corners of the top rectangular closing of the pier (in direction Y) and two couples of opposite vertical forces of $F_W/2 = \pm 10.597$ t (in direction Z, positive on the corners on side 2-3 and negative on the corners on side 1-4). Results are reported as before in Fig. 8 and Table 2. The displacements of the top closing are obtained as: vertical displacements of sides 2-3 and 1-4 respectively $u_Z = \pm 0.17$ mm; horizontal transverse displacements $u_Y = 2.14$ mm.

3.4 Train Braking Action (BA)

An additional loading configuration is considered, with account of a possible longitudinal train braking action directly transferred to the pier. The bearing devices, originally conceived as cylindrical rollers, appear to be quite rusted today. Thus, it looks worthwhile to inspect the possible transfer of braking on the piers. The train braking action has been devised as follows, according to the standards of the Italian State Railways (*Istruzione I/SC/PS–OM/2298 del 02/06/1995*). For a "normal traffic" train (*Treno di carico LM71*), the characteristic value of braking is taken as 2.0 t/m, which leads, on a span of 33.25 m, to a longitudinal horizontal force that is estimated in 66.5 t. As above, such force is applied to the FEM model by 4 concentrated loads of 16.63 t, in the longitudinal (towards shoulder) X direction, at the 4 corners of the top closing.

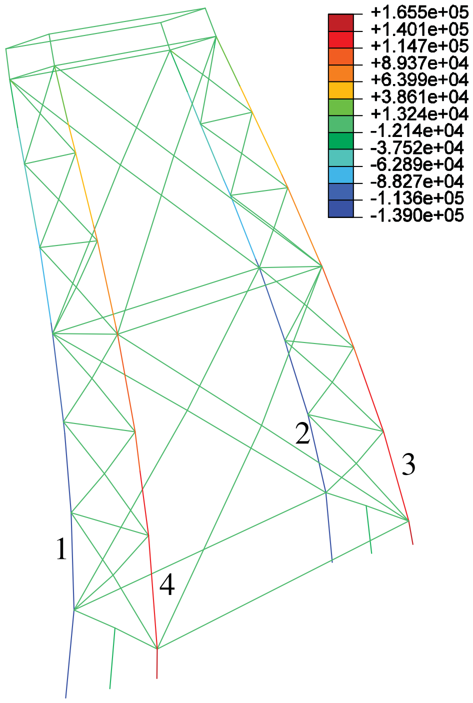


Fig. 9: BA condition. Same as Fig. 7.

Table 3: BA condition. Same as Table 1.

Bar Type	Axial Force [kg]	Area [mm^2]	Stress [kg/mm^2]
Corner bar 1	– 138489	34224	– 4.05
Corner bar 2	– 138493		– 4.05
Corner bar 3	+ 138284		+ 4.04
Corner bar 4	+ 138280		+ 4.04
Corner columns	+ 165498	34224	+ 4.84
	– 139018		– 4.06
Longitudinal bracing	+ 19685	3000	+ 6.56
	– 19690		– 6.56
Transverse bracing	+ 4187	3247	+ 1.29
	– 4010		– 1.24

Results are illustrated as above in Fig. 9 and Table 3. A slight unsymmetry of the model can be read in the differences between the axial forces in bottom corner bars 1-2 and 3-4. The displacements of the top closing have been recorded as: $u_X = 22.9$ mm; $u_Z = -1.6$ mm on side 1-2, $u_Z = 1.1$ mm on side 3-4.

This loading condition appears to be rather tough for the pier, especially for the bars of the longitudinal bracings, that already display stresses beyond the scheduled admissible stress of 6.0 kg/mm^2.

3.5 Superposition of Effects 1 (SE1)

This condition considers the superposition of effects of vertical loads (VL2) and transverse wind action (WA). It has been run on the FEM model, with later check that the obtained response corresponds to the algebraic superposition of effects of the previous FEM outcomes. Results are reported in the usual form in following Fig. 10 and Table 4.

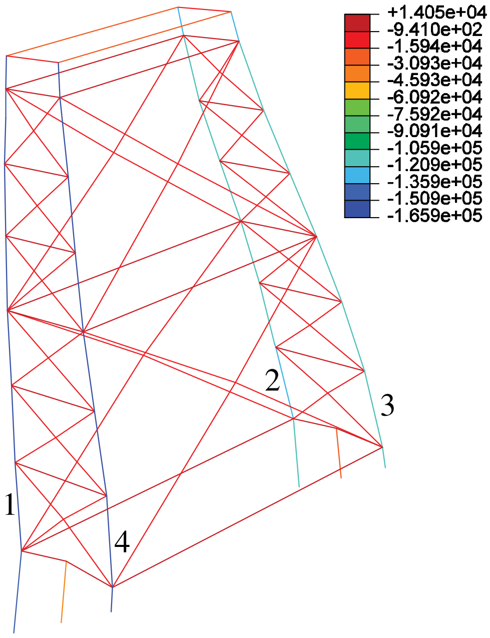


Fig. 10: SE1 condition. Same as Fig. 7.

Table 4: SE1 condition. Same as Table 1.

Bar Type	Axial Force [kg]	Area [mm^2]	Stress [kg/mm^2]
Corner bar 1	– 162003	34224	– 4.73
Corner bar 2	– 121227		– 3.54
Corner bar 3	– 117125		– 3.42
Corner bar 4	– 165885		– 4.85
Corner columns	– 106215	34224	– 3.10
	– 165885		– 4.85
Longitudinal bracing	+ 6473	3000	+ 2.16
	– 5838		– 1.95
Transverse bracing	+ 3897	3247	+ 1.20
	– 8950		– 2.76

Recorded top displacements are: $u_X = 1.79$ mm and $u_Y = 2.14$ mm, on average; $u_Z = -3.59$, -3.25, -3.02, -3.36 mm, in top corners 1 to 4. The stresses remain all below the admissible stresses.

3.6 Superposition of Effects 2 (SE2)

This condition considers the explicit superposition of previous VL2, WA and BA loadings. Results are illustrated as above in Fig. 11 and Table 5. The top displacements are in the order of $u_X = 23.72$ mm, $u_Y = 2.14$ mm and $u_Z = -5.07$, -4.74, -1.95, -2.29 mm, in top corners 1 to 4. It is apparent that, admitting the braking action might reach the pier, the compressive stresses in the bars become important and may exceed the admissible stresses in the bars of the longitudinal members.

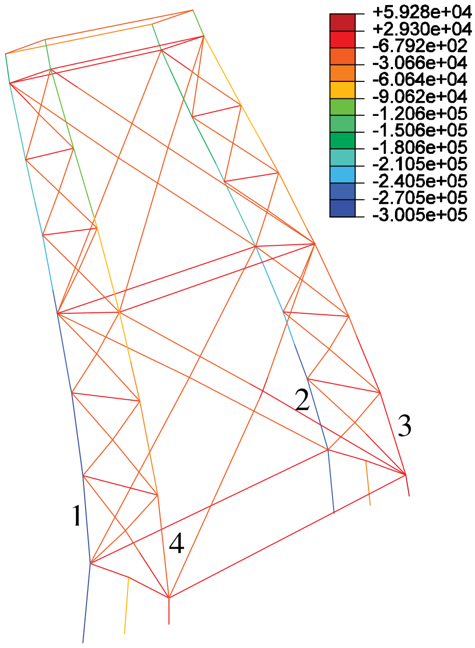


Fig. 11: SE2 condition. Same as Fig. 7.

Table 5: SE2 condition. Same as Table 1.

Bar Type	Axial Force [kg]	Area [mm^2]	Stress [kg/mm^2]
Corner bar 1	– 300491	34224	– 8.78
Corner bar 2	– 259720		– 7.59
Corner bar 3	+ 21160		+ 0.62
Corner bar 4	– 27605		– 0.81
Corner columns	+ 59283	34224	+ 1.73
	– 300491		– 8.78
Longitudinal bracing	+ 17160	3000	+ 5.72
	– 23034		– 7.68
Transverse bracing	+ 3132	3247	+ 0.96
	– 11961		– 3.68

Further algebraic superpositions of effects could be considered for the different combinations of sign of WA and BA actions. This originates following Table 6, which reports all results, including those that should correspond to simulations SE1 and SE2 run on the FEM model. They show that the maximum compressive stress in the bottom corner bars may be accounted at around 9 kg/mm^2, in excess of 1/2 to the target value of 6 kg/mm^2.

Table 6: Loading actions and algebraic combinations. Normal stresses in bottom corner bars 1-4.

Bottom Corner Bar	Stress [kg/mm^2]							
	Actions			Combinations				
	VL2	WA	BA	SE1: VL2 +WA	SE2: VL2 +WA+BA	VL2 –WA+BA	VL2 –WA–BA	VL2 +WA–BA
1	– 4.14	– 0.61	– 4.05	– 4.75	– 8.80	– 7.58	+ 0.52	– 0.70
2	– 4.14	+ 0.61	– 4.05	– 3.53	– 7.58	– 8.80	– 0.70	+ 0.52
3	– 4.13	+ 0.71	+ 4.04	– 3.42	+ 0.62	– 0.80	– 8.88	– 7.46
4	– 4.13	– 0.71	+ 4.04	– 4.84	– 0.80	+ 0.62	– 7.46	– 8.88

4. Conclusions

The present paper has provided a brief description of the FEM modelling of the piers of the Paderno d'Adda Bridge (1889). Further details on specific aspects are available in [5-6]. Starting from the pier on the arch, which has been also analysed for different loading conditions, as reported here, the other piers have been then extruded and finally mounted on a full 3D FEM model of the bridge, which is now under first completion [7]. The model that has been put in place should turn-out useful for a systematic investigation on both static and dynamic responses of the bridge, in the original design-state conditions. Further, the model could be elaborated by additional information that may arise from direct inspections on the bridge, towards the assessment of present-state conditions, following the remodelling interventions that have been made in the life span of the bridge and the state of damage, corrosion and fatigue that has developed in such time range.

Acknowledgements. This work has been carried-out at the University of Bergamo, Faculty of Engineering (Dalmine). The financial support by *"Fondi di Ricerca d'Ateneo ex 60%"* at the University of Bergamo is gratefully acknowledged.

References

[1] SOCIETÀ NAZIONALE DELLE OFFICINE DI SAVIGLIANO, *Viadotto di Paderno sull'Adda (Ferrovia Ponte S. Pietro-Seregno)*, Torino, Tip. e Lit. Camilla e Bertolero, 1889.

[2] NASCÈ V., ZORGNO A.M., BERTOLINI C., CARBONE V.I., PISTONE G., ROCCATI R., "Il ponte di Paderno: storia e struttura. Conservazione dell'architettura in ferro", *Restauro*, Anno XIII, n. 73–74, 1984.

[3] FERRARI R., *Sulla concezione strutturale ottocentesca del ponte in ferro di Paderno d'Adda*, Laurea Thesis in Building Engineering, Advisor E. Rizzi, Università di Bergamo, Facoltà di Ingegneria, I-24044 Dalmine (BG), Italy, 228 pages, December 2006.

[4] FERRARI R., RIZZI E., On the theory of the ellipse of elasticity as a natural discretisation method in the design of Paderno d'Adda Bridge (Italy), in *Proc. of 6th Int. Conf. on Structural Analysis of Historic Construction (SAHC08)*, Bath, UK, 2-4 July 2008, Vol. 1, pp. 583–591, 2008.

[5] FACHERIS M., *Analisi morfologica e modellazione per elementi finiti della pila sull'arco del ponte di Paderno d'Adda*, Laurea Thesis in Building Engineering, Advisor E. Rizzi, Co-Advisor R. Ferrari, Università di Bergamo, Facoltà di Ingegneria, I-24044 Dalmine (BG), Italy, 125 pages, September 2009.

[6] FERRARI R., *Analisi strutturale degli elementi portanti del ponte di Paderno d'Adda*, Master Thesis in Building Engineering, Advisor E. Rizzi, Università di Bergamo, Facoltà di Ingegneria, I-24044 Dalmine (BG), Italy, 108 pages, September 2009.

[7] FERRARI R., FACHERIS M., RIZZI E., Structural Analysis of the Paderno d'Adda Bridge (Italy, 1889), *Proc. of 7th Int. Conf. on Structural Analysis of Historical Constructions (SAHC10)*, Shanghai (China), 6-8 October 2010, to appear, 2010.