Diagnostics, dynamic monitoring and earthquake resistant design: the structural rehabilitation project of the Ciadel iron Bridge

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1 Introduction

The seismic risk affecting bridges is very definitely a more topical issue than ever: much of the infrastructure network was built in the 1960s-70s, which inevitably makes a large part of these structures inadequate in terms of today's anti-seismic regulations. Deserving of separate focus in this respect are the steel bridges erected in the early-20th century, such as the one referred to in this article. In these cases, in addition to technical aspects, we must take into account the limitations related to the artistic constraints associated with works of art. The Ciadel iron bridge over the Gesso river was declared of cultural interest pursuant to articles 10 and 12 of Legislative Decree 42/2004 by means of Decree no. 164/2016 dated 6 June 2016, *"The bridge, as indicated on the plaque on the pylon, was built in 1895 by the Società Nazionale delle Officine di Savigliano, one of the major Italian companies which, between the 1880s and the 1930s, designed, produced and built large metal structures, mainly for the Italian State Railways…"*

No further information exists regarding the Ciadel Bridge, apart from the odd rumour according to which it was partially destroyed by retreating Germans in the last days of the Second World War and subsequently repaired and rebuilt in the early 1950s; no documented historical evidence of this exists however.

Fig.1 – archive image – Ciadel Bridge

In view of what has been said, some in-depth knowledge of these infrastructural works becomes fundamental, in order to adequately manage maintenance operations and obtain useful information, not only for the designer who will have to carry out structural evaluations, but also and above all for the public administrations who will have to perform and plan census and seismic safety checks and inspections.

The procedure for dealing with these problems, put forward in this article, therefore consists of 3 distinct and complementary phases: *knowledge* of the bridge itself, *numerical modelling* using finite elements, and the *evaluation* and *mitigation* of seismic risk by means of structural rehabilitation work.

In order to provide a practical example, this paper proposes a methodological approach as regards the seismic safety assessment and upgrading project of the Ciadel iron bridge over the Gesso river in the municipality of Borgo San Dalmazzo (CN), starting from the dynamic characterisation of the artefact and then calibrating the F.E.M. numerical model at the basis of the structural analyses used to plan the seismic upgrading jobs.

2 Regulatory framework

Recent regulatory developments tend, at last, to make use of dynamic monitoring by suggesting or requiring that the structure be equipped with a permanent monitoring system. Technical Construction Standards 2018 already explicitly state that upon completion of the civil works "*the person appointed to carry out the tests may also arrange for specific dynamic tests to determine the dynamic behaviour of the structure".* Application Circular no. 7/2019 also adds that *"...dynamic load tests may also be substituted for static tests, by virtue of the special nature of the structure and the boundary conditions in which the test may be performed*".

The "*Guidelines for risk classification and management, safety assessment and monitoring of existing bridges*" (attached to the opinion of the Public Works National Council no. 88/2019) emphasises the need to carry out seismic vulnerability assessments on existing structures in order to adapt them to the new safety standards introduced by the current Technical Construction Standards. The text also sets out guidelines on the implementation of bridge surveillance and monitoring systems, focusing in particular on the need to carry out dynamic response surveys. Finally, the subject of instrumental monitoring (Structural Health Monitoring - SHM) is explored in depth, indicating the procedures for the installation, in cases where the class of attention requires it, of "intelligent" systems and sensors capable of identifying conditions of structural damage and activating warning systems when certain threshold values are exceeded.

For the actual performance of the tests described in this article, useful reference was also made to ISO/FDIS 4866 – "Mechanical vibration and shock, Vibration of fixed structures, Guidelines for the measurement of vibrations and evaluation of their effects on structures" and UNI 9916-2004 - Criteria for measuring and evaluating the effects of vibrations on buildings.

3 Description of structure and structural rehabilitation project

The fundamental aspect on which the main design solutions were based is that of the durability of the structure which, having been built in 1895, has already reached an age well beyond the normal life span of similar structures designed according to current standards.
The other fundamental criteria taken into account in determining the work to be carried out on the bridge, in addition to the central theme of durability, are the following:

- *Weight of traffic transiting on bridge*: a load capacity limitation of 20 tonnes is currently imposed. The safety requirements of the structure in relation to this load capacity have been determined on the basis of the indications contained in the 2020 Bridges Guidelines for existing infrastructures;
- *Structural behaviour from a static viewpoint*: the behaviour of the structure with respect to static gravitational forces, the evolution of the state of tension in the elements and the relative work ratio were investigated with reference to the results of the tests carried out relating to the mechanical and physical-chemical characterisation of the material;
- *Structural behaviour from a dynamic viewpoint*: the behaviour of the structure to actions of a dynamic type was investigated. Such investigations, crucial for understanding the response of the bridge to seismic excitation, were supported by the results of the dynamic analyses performed in the field;
- *Checking the behaviour of the infrastructure from a hydraulic viewpoint* with regard to the design flood discharge and the determination of possible hydraulic critical conditions in the stretch of riverbed affected by the works;
- *Preservation and protection of the aesthetic and landscape characteristics of the bridge*, especially given the existence of the decree certifying its cultural interest, and to ensure the most harmonious integration of the planned works in the natural river environment.

From the analysis of the various aspects mentioned above, the design process was developed. This first identified various intervention options, each of which was then critically compared, examining their strengths and weaknesses in relation to satisfying the various requirements.
Analyses from a structural perspective, both in the static and dynamic spheres, have therefore made it possible to determine the extent of the reinforcements to be carried out on the metal structure of the bridge both on a global and local scale. The most impactful jobs on a global scale concern the insertion of diagonals in the lateral fields of

the two trusses constituting the main load-bearing structure of the bridge. These serve the dual need to improve the seismic behaviour of the structure and to lower the state of tension in the steel elements, especially at the end fields. Local structural interventions, on the other hand, substantially consist of reinforcement, repair and restoration jobs on the deteriorated elements, the dimensional characteristics of which (thickness, section, etc.) have been compromised by the state of degradation in progress.

Other interventions of a structural nature consist in the replacement of the structural bearings, the reconstruction of the supports and the construction, at the top of the abutment body, of a series of micropiles connected by a reinforced concrete girder. The purpose of these works is to improve the constraint conditions of the structure and ensure more correct transmission of the stresses (especially in a horizontal direction) in the foundation by unloading the existing abutment structures as much as possible.

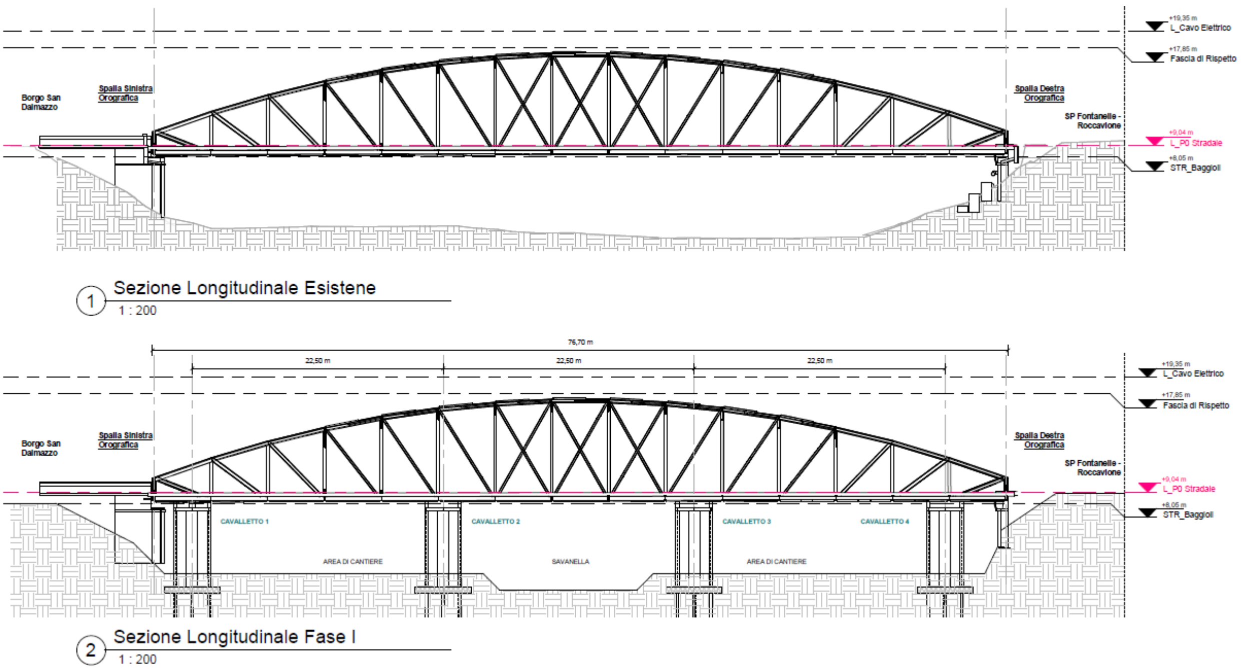


Fig. 3.1 – longitudinal bridge sections

From a landscape perspective, the most important jobs to be done concern the installation of global scale reinforcements consisting in the addition of diagonals in the lateral fields of the trusses and the painting of the structure. As far as the first job is concerned, reinforcement elements as close as possible to the original girders (press formed, coupled sections, cross stiffening brackets, etc.) will be made, compatibly with the adaptability of today's workshop production techniques to those of the time when the bridge was built. With regard to the colour of the structure, three options were examined (Corten effect, green, white colour) and, following a careful analysis from a historical perspective aimed at determining the most probable original colour of the artefact, white was chosen.

4 Mechanical characterisation of materials

Before proceeding with the dynamic characterisation of the bridge, a series of investigations was carried out on the sections making up the structure in question. The characteristics of the materials were determined using destructive and non-destructive methods as required by NTC 2018. In order to investigate the state of preservation of the bridge and the possible presence and extent of the described degradation phenomena, a plan of investigation was conceived aimed at evaluating the chemical-physical characteristics of the material constituting the structure on which to base future structural evaluations at the various design levels. The samples taken were then processed in the workshop to obtain a test piece according to UNI EN ISO 377.

In the laboratory, a tensile and resilience test was performed according to UNI EN ISO 6892-1 and ISO 148- 1 respectively. This consisted in subjecting the test piece with a predefined geometric shape to a continuous tensile stress and recording the load variation as a function of the progressive elongation. The result of the test is schematised in the load-elongation diagram where, in the first straight section of the diagram (elastic section), the load values corresponding to the elastic deformation are shown. In this stretch, by releasing the load, the deformation is cancelled. This reference test proved useful in determining the actual yield and rupture values, which were useful for incorporation into the calculation model and also locally assessing the interventions.

DATI DICHIARATI			RISULTATI DELLE PROVE			
				Prova di trazione		
Identif. provino	Data prelievo	Tipologia profilo	Sezione effettiva [mm^2]	Snervamento f_y [N/mm^2]	Rottura f_t [N/mm^2]	Allungamento [%]
01	20.04.2021	--	164,0	339*	446**	35,6
02	20.04.2021	--	202,0	277*	423	38,1
03	20.04.2021	--	195,0	303*	364	38,6
04	20.04.2021	--	140,0	328*	427	42,8
05	20.04.2021	--	187,1	333*	426	49,1
06	20.04.2021	--	186,0	310*	396	38,7

Prove effettuate con macchina di prova METRO.COM ENGINEERING matr. n. 9260 di classe 1 secondo UNI EN ISO 7500/1
* $f_{(0,2)}$ tensione di scostamento dalla proporzionalità allo 0,2%
** rilevata frattura in corrispondenza del piano di simmetria orizzontale del provino nella direzione di laminazione **(delaminazione)**
Preparazione e sagomatura dei provini eseguita dal Laboratorio

Tab. 4.1 results of the mechanical characterisation tests of the materials (iron test pieces)

In addition to these tests, hardness investigations were carried out with a portable durometer, which, using the rebound hardness method by means of a rebound instrument (probe), is capable of measuring hardness on various types of material and converting values into the main measurement scales (Rockwell B, Rockwell C, Brinell, Vickers). Tests were also carried out to verify the integrity of the nailing by means of ultrasonic testing and finally chemical analyses to verify the composition of the metal alloy in the laboratory.

5 Dynamic investigations

This paragraph shows the results obtained through the dynamic investigation campaign carried out. In particular, in order to extract the dynamic parameters of the structure (*natural frequencies, damping and modal forms*), identification tests were performed using the technique called Operational Modal Analysis (OMA), which allows the dynamic behaviour of the structure to be described simply by recording the very low levels of vibration to which the structure is subjected using environmental excitation as input.

OMA is a very interesting technique and offers a number of advantages: the test is completely non-invasive and inexpensive; no external equipment is required to force vibrate the structure, and above all, the test does not interfere with the use of the structure, which can remain in operation during monitoring.

In order to then assess the amplitude of the dynamic response of the deck at the various natural frequencies, the structure was dynamically excited by means of an innovative linear vibrodyne, which allowed the steel deck to be put into structural resonance by introducing a known input into the structure. This type of analysis, known as Experimental modal analysis (EMA), made it possible to evaluate the structural response of the bridge under the action of known and controlled forces, as well as to confirm the determination of the natural frequencies obtained using OMA techniques.

5.1 Operational Modal Analysis - OMA: test planning

The data were obtained by means of continuous recording of environmental accelerations derived from the natural excitation of the structure caused by external phenomena, such as wind, microseisms and noise from human activity (e.g. vehicular traffic). The tests were carried out with the aid of the following instruments:

- Seismic accelerometers (Integrated Electronic Piezoelectric - IEPE) KS48C voltage sensitivity 1V/g and measuring range ±6g;
- 8-channel Dynamic Data Acquisition System, DaTa 500 (DRC srl), 24-bit Digital Signal Processor (DSP), with analogue anti-aliasing filter and high-frequency acquisition range (0.2Hz to 200kHz).

Figure 5.1 measurement chain

The accelerometers were installed at the most significant points of the deck and data acquisitions were made to measure the structural response to environmental vibrations.

Fig. 5.2 – view of monitored bridge and layout of sensors – IngeoLab srl

Once the accelerometer data had been acquired, the time histories were processed by the dynamic identification algorithm. In this case, the Stochastic Subspace Identification (SSI) algorithm was used, which operates in the time domain.

5.2 Experimental modal analysis - EMA: mode activation by means of forced oscillation

In order to validate the results obtained (in terms of frequencies) using the OMA technique and to emphasise the response of the structure, a linear vibrodyne was used capable of applying an artificial external force to the deck.

A vibrodyne is a device capable of delivering sinusoidal dynamic forces to a structure once it has been firmly secured to it. Commercially available vibrodynes perform this task by means of eccentric masses that, placed in rotation, generate a force along their resultant. The pulsation of the force is changed by varying the rotational speed of the masses.

Operationally, what is known as a "frequency sweep" is carried out by stressing the structure at gradually increasing frequencies and at the same time acquiring the response of the structure itself by means of accelerometers positioned at significant points of the structure. When the vibrodyne passes through a frequency coinciding with a natural frequency of the structure, we obtain an amplification of the amplitudes measured at that frequency (resonance phenomenon).

However, the operating principle of vibrodynes with rotating masses produces the drawback of having forces with low modulus at low frequencies (typical of civil structures) and high modulus at high frequencies (typically outside the range of interest for civil structures). The masses involved also make these types of equipment difficult to move.

These limitations are overcome by the vibrodyne used in this case study, the VIBRA 9001-LiTeM which features linear rather than rotational operation.

Fig. 5.3 VIBRA 9001 linear vibrodyne, controller and software – Litem - life testing machine

A slide on which a mass of up to 40 kg can be applied is moved on a linear guide with a maximum acceleration of 1 g (adjustable). The electronic controller that manages its operation is able to modify (reduce) the stroke of the slide as the (known) frequency of the pulsating force increases. The management software performs the frequency sweep, thus keeping the force value constant as its frequency varies between about 0.7 and 30 Hz.

In the case in question, the linear vibrodyne was anchored to the bridge deck by mechanical solidarization with the structural part. The acquisitions were then made by orienting the vibrodyne along the Y direction of the deck. In the X direction, the vibrodyne was firmly secured to the structure at about 2 m from the centre line. The idea was to avoid placing the vibrodyne at a structural node.

From the analysis of the acquisitions performed and in particular from the processing of the time histories by means of their Fourier transform, it was found that an excellent correlation existed between the frequencies obtained by OMA identification and the frequencies corresponding to the maximum amplitude of the signals obtained during the EMA test (with vibrodyne).

It was ascertained how the possibility of having a constant force of an appropriate magnitude even at low frequencies is an advantage in conducting the frequency sweep. What is more, the vibrodyne also proved effective in identifying modes higher than the third, where identification software is less reliable. Figure 4.4 shows the modal shapes obtained.

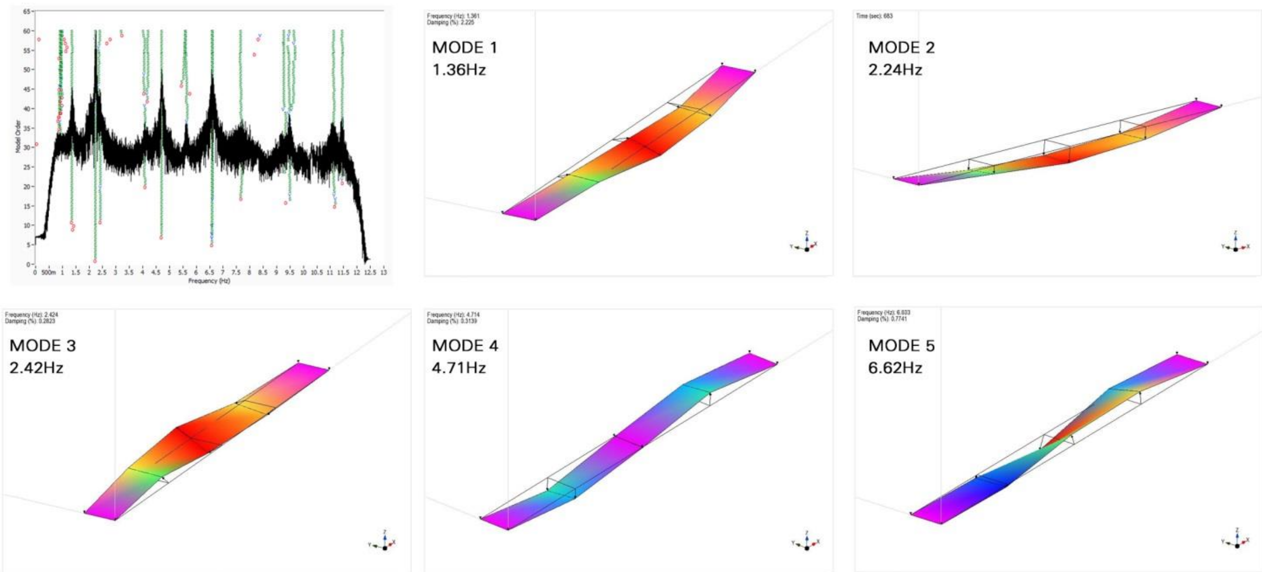


Fig. 5.4. dynamic identification of iron bridge, stabilisation diagram and modal shapes

In conclusion Tab.5.1 shows the first 5 identified vibration modes

Mode No.	Frequency (Hz)	Damping (%)	Mode type found
1	1.36	2.30	Flexural Y
2	2.24	0.12	1st Flexural Z
3	2.42	0.28	1st Torsional
4	4.71	0.31	2nd Flexural Z
5	6.62	0.42	2nd Torsional

Tab. 5.1 – Frequencies and modal shapes identified by means of dynamic investigation

6 Modelling and calibration of FEM model

For the identification of the static and dynamic behaviour of the road bridge, a theoretical-experimental approach was followed that involved the preparation of a FEM model and its calibration with an iterative process on the basis of the experimental dynamic responses, as previously described. The final model, validated on the dynamic investigations carried out, became the tool for the evaluation of the static and dynamic response of the structure in the linear elastic field.

Before going ahead with the structural analysis, it is advisable to proceed with the calibration of the model, comparing the responses in terms of frequency and vibration modes of the structure with the dynamic results obtained from the dynamic tests performed by the company Ingeolab srl. The model calibration process involved the manual modification of a number of parameters (masses, stiffnesses, mechanical properties of materials and boundary conditions) in order to minimize the differences between the finite element model and the experimentally obtained parameters.

	Modal values					
Mode No.	***Pulsation (Rad/s)***	***Period (s)***	***FEM model frequency (Hz)***	***Energy (J)***	***Dynamic investigation frequency (Hz)***	Δ
1	9.64	0.65	1.53	46.46	1.36	11%
2	14.52	0.43	2.31	105.35	2.24	3%
3	17.36	0.36	2.76	150.72	2.42	12%
4	33.71	0.19	5.37	568.29	4.71	
5	55.14	0.11	8.78	1520.22	6.62	
Total				**2391.05**		

Tab. 6.1 – Modal parameters obtained by means of FEM model and comparison with experimental data

These results show a difference of around 10% for the first 3 modes of vibration; these results are considered acceptable in order to continue carrying out the structural calculation and the modelling of the further calculation steps.

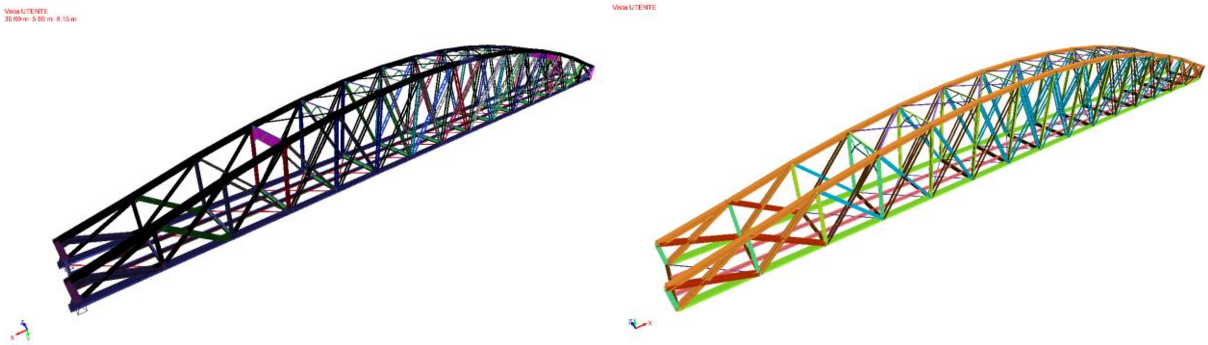


Fig. 6.1 3D view of FEM model used and calibrated

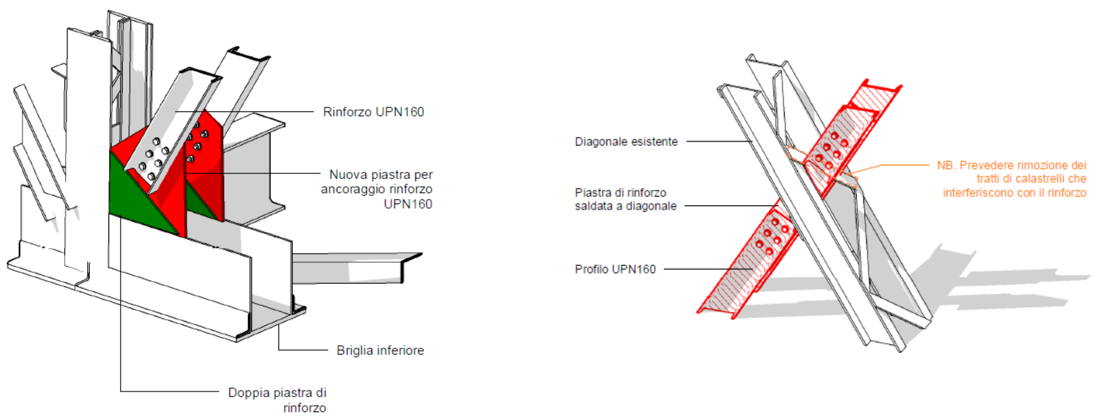
The calculation model was developed and schematized by means of two parallel models - a model consisting of linear elements, such as to easily evaluate the sextet of stresses, and a two-dimensional model in order to carry out local checks for the concentration of stresses within the deck in question.

6.1 Structural work for seismic upgrading

The work done on the bridge structure, from a global viewpoint, consists in the insertion of diagonal braces to complete the diagonal cross bracing in the fields of the two main trusses.

In order to maintain the utmost similarity with the existing structure, these braces are made up of UPN 160 profiles in the central fields and UPN 300 in the end fields, coupled to each other and connected by means of cross stiffening brackets consisting of 6 mm thick plates bolted externally to the UPN platforms themselves. The new braces are connected to the existing structure at the junction between the upper/lower chords and the upright. In both cases a central plate and two side padding plates welded to the elements of the existing structure are fitted. The coupled UPN braces are connected to these plates by means of M16 bolts and are disconnected at the intersection of the existing diagonal braces in the centre of the span by means of loose plates which are also secured to the UPNs by means of M16 bolts.

Fig. 6.2 details of the structural works carried out on the steel parts



Localised jobs mainly concern the stiffening of the connection between the uprights and the lower chord by inserting an angular profile with rib welded to both the chord and the upright.

The localised job in correspondence to the bearings consists in the insertion of a 30 mm thick plate under the chord featuring a central hole suitable for accommodating the centring device of the structural bearing itself.

6.2 Details of bridge deck removal and installation operations

A final interesting aspect of the project concerns the bridge deck removal and installation operations, for which a series of technical and engineering solutions described below were necessary. These operations consist in moving the structure from its current location to a specially prepared construction site area on the left bank of the river, where the subsequent work will take place, by sliding the bridge horizontally using special guides on rollers positioned on the provisional supports.

The first step consists in the construction of the four provisional trestles in the riverbed, consisting of a metal-section lattice structure, which will support the roller conveyor system and the jacks for lifting the bridge. For the same purpose, eight supports will be built in the construction site area on the left bank on the Borgo San Dalmazzo side, specifically prepared to accommodate the structure.

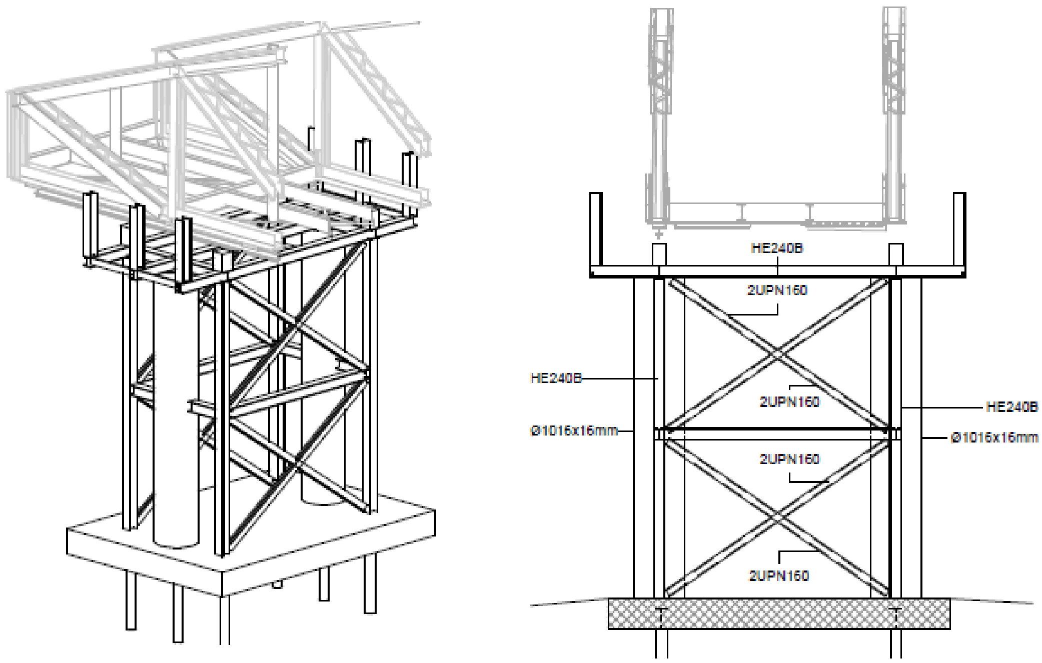
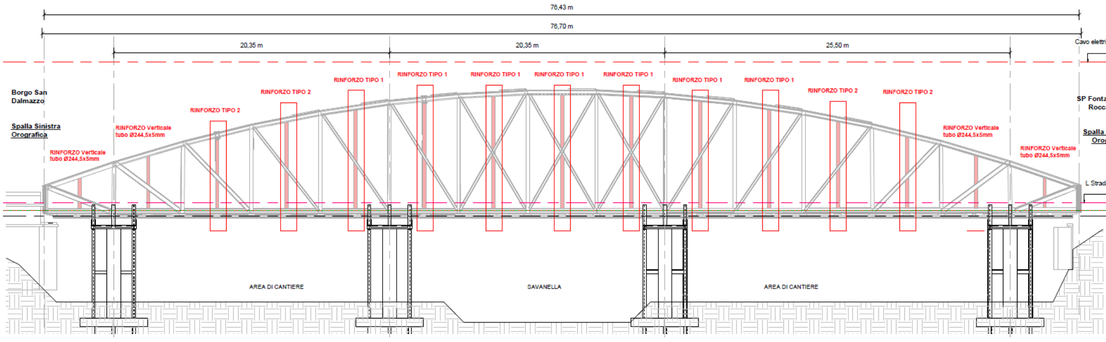


Fig. 6.3 construction details of the provisional system consisting of the riverbed trestles

The second operation consists in the assembly of the system of sliding rails positioned under the lower chords which consist of longitudinal girders featuring a rail-type profile, which will provide the contact surface with the roller to facilitate sliding, and connecting crossbeams.

The third step is to install the internal bracing system made with hollow circular profiles fixed both to the existing structure of the bridge and to the underlying track system, suitably arranged in order to minimize any stresses and deformations to which the structure may be subjected during bridge deck removal and installation.

The configuration of this bracing system has been designed in such a way as to leave a free passageway for a mini-excavator on the bridge deck in order to allow the easy fitting of the braces themselves and at the same time the demolition of the existing paving.



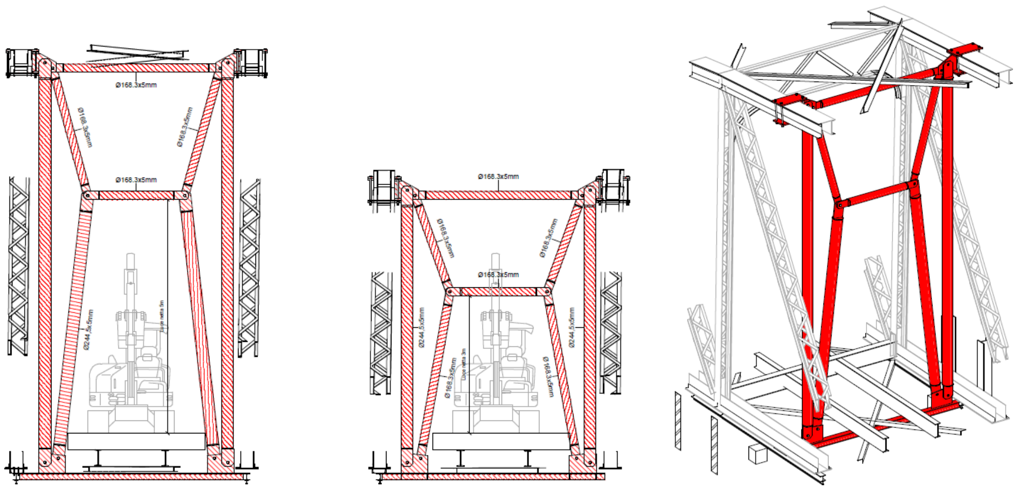


Fig. 6.4 construction details of the bracing system inside the structure

The preliminary operations are completed with the positioning of 16 jacks on the provisional trestles whose characteristics must be the following: capacity 200 kN and minimum stroke 300 mm.

Notes

Contracting Authority: Province of Cuneo - Cuneo Saluzzo Road Sector;

The works are financed by the Ministry of Infrastructure and Transport with Interministerial Decree MIT-MEF 3 March 2020, no. 1. "Securing bridges in the Po basin – Law no. 145 dated 30 December 2018, art. 1, paragraph 891"