# STRUCTURAL AND ARCHITECTURAL DESIGN OF AN INTEGRAL STEEL FOOTBRIDGE

# PROGETTAZIONE STRUTTURALE ED ARCHITETTONICA DI UN PONTE PEDONALE IN ACCIAIO

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## ABSTRACT

The conceptual design of a footbridge to be built over a stream in a little city of Sardinia, Italy, is presented. A particular environmental context has strongly influenced the design of this footbridge, because it is set in a “museum-town” with a number of contemporary artistic works spread in town, along streets. The bridge consists of an embedded beam, 14 metres long, with a strongly variable cross section. The deck is composed of a COR-TEN steel box with an upper concrete slab. Abutments are integrated into the concrete banks of the little channel in which the stream has put in. After the description of footbridge and a discussion about architectural and environmental items, the motivations of design choices are explained and the analysis of structural behaviour is focused.

## SOMMARIO

Si presenta il conceptual design di una passerella pedonale da costruirsi su un rio in una cittadina della Sardegna. Il progetto è stato fortemente influenzato dal contesto ambientale, in quanto si trova in una “città-museo” in cui un certo numero di opere d’arte sono sparse per le vie. Il ponte è costituito da una trave incastrata a cassone con sezione fortemente variabile, di 14 metri di luce. La sezione d’impalcato è composta da un cassone di acciaio COR-TEN e da una soletta superiore in calcestruzzo. Il ponte è integrale cioè connesso integralmente con le spalle, le quali sono poste entro il canale in calcestruzzo che materializza il torrente. A partire dalla descrizione della passerella, si propone una discussione degli aspetti architettonici e strutturali nonché i risultati dell’analisi strutturale preliminare.

## 1 INTRODUCTION

At the end of 2009, the Municipality of San Sperate, near Cagliari in Sardinia, Italy, called a national competition for the construction of a footbridge in the city centre. The chosen place was over the Rio Concias, a little stream crossing the town, which was put into a concrete channel during the second half of the 20th Century. Nowadays an old and precarious footbridge (fig. 1) is placed over the stream in order to connect the city centre with the area where Municipality offices have been built. The competition was called in order to dismantle the old bridge and to build a new one. Results were communicate by the Commission to competitors in the month of April 2010 and the authors won the first prize with their project.

The principal features to be considered in the project regard the particular environmental context in which the bridge has to be built. In fact San Sperate is a “museum-town” with a number of contemporary artistic works spread in town, along streets. So, great attention to architectural items was requested by municipality. On one street along Rio Concias, which has to be connected with the new footbridge, different steel artworks are present with their characteristic brown colour of rust. So, the first design choice was to build a steel bridge of rust colour. Moreover, the presence of two inclined banks drives the authors towards the solution of a steel-concrete composite integral bridge in which abutments are completely inserted into the channel sides. The main span of the bridge, as well as the width of concrete channel, is about 14 meters. Although the existing bridge presents two little intermediate supports into the channel, the best solution was to leave free the stream from piers and to have a unique launch over the stream. It was possible because of the total length is limited.

In this paper the design choices for the realization of this footbridge are explained not only on the structural point of view but also on the architectural and environmental ones. The preliminary structural design is presented and discussed with the critical points to be faced. Some evaluations on structural behaviour and about the design experience are reported.

**Fig. 1:** The old bridge to be dismantled

## 2 ARCHITECTURAL DESIGN CHOICES

The “Rio Concias” marks the topography of San Sperate, a little town placed in the Campidano area near Cagliari, engraving the urban centre. The place in which the new footbridge was to be built is characterized by a curved concrete channel, with two inclined embankments of limited height.

The areas on the two margins see two different realities. On one side, Risorgimento street is a wide road with a large walkway, benches and the steel artworks of the museum-town. On the other side, at a lower altitude on the stream, Rio Concias street is a narrow road without any walkway (fig. 2). The difference between the two margins is then in wideness and altitude of roadways. The existing bridge saves this difference with a little stair. Despite of this, some inhabitants cross the stream with their bicycles, descending or climbing the stairs. So, the main idea was to design a footbridge which could be wider and higher on one side and lower and narrow on the other, as well as the streets it connects, but with a variable profile and a unique inclined and curved deck. So, differences are underlined, becoming the founding theme of the project. The existing bridge is lived by the community every day not only as a passage but also as a meeting point, a fundamental joint of the town social living. Two concrete road bridges, far away from the footbridge, are the only connection points between these two parts of the town.

Steel artworks were the second reason of inspiration with their rust colour: the bridge could be composed of a steel beam element with a superior wood pavement that would be welcoming and favourable to the pedestrian passage.

A bridge that is wide where it is high on the river bed and narrow where it is low. The distance between two inclined banks is saved by the launch of a steel beam with a boxed cross section and a strongly variable height in its geometric profile. It is embedded at the two banks and the abutments hidden behind the channel. The suggestion was to have a bridge which is unitary with the stream, not only integrated in the environment but also “integral” with it.

**Fig. 2:** General plan of the project area

The curved profile varies becoming much higher where the bridge is also wider and the deck has a curved upper line which is soften designed for a better walk-ability. With two little ramps at the two margins and some steps that recall the familiar stair of the previous footbridge, handicapped persons, common pedestrians and cyclists are encouraged to pass over the stream.

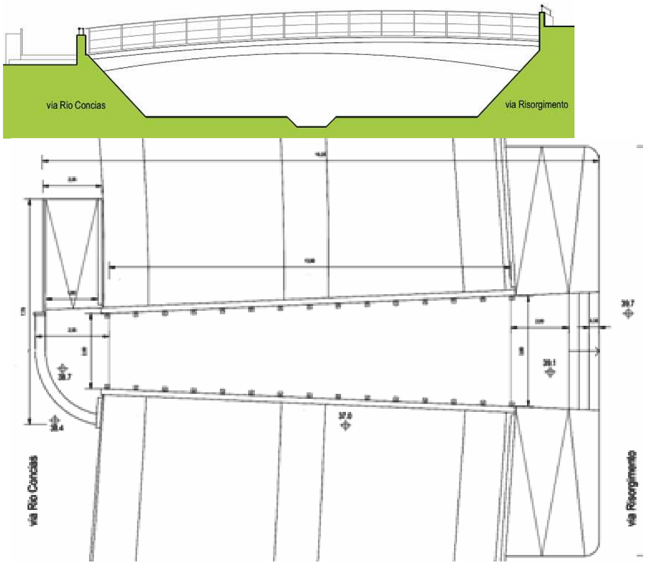

**Fig. 3:** Plan and elevation of the designed footbridge

A superior slab of white concrete completes the footbridge and the different colour underlines the different functions: brown steel for the supporting beam, white concrete for the platform and warm wood for the pavement. The structure can be clearly seen and perceived from pedestrians. The final span length is about 14 m, the maximum wideness of the deck is 3.80 m, the minimum one 2.60 m. Figure 3 shows the geometric characteristics of the bridge.

Pavement has been designed as a wooden parquet while the parapet underlines the main importance of structural shape, being a transparent element made of inox supports and an upper wood handrail. The light squares of parapet recollect to the square shapes of the familiar existing bridge structure (fig. 4).

A fundamental role is played by lightening; a particular attention has been paid to underline with an accent lightening at the same time the up and down parts of the bridge. Pedestrians are often accustomed in seeing only the upper part of the bridge where they walk, without any consciousness about the structure that is permitting their passage. So, behind the bridge lights have to underline the shape and colour, while above the bridge punctual spot lights sign the crossing way and become guide-lights. Figure 5 shows night renders of the structure.

**Fig. 4:** Render of the new footbridge

## 3 STRUCTURAL DESIGN AND CONSTRUCTION CHOICES

The steel bridge assures slenderness and clear shapes but it is subject to time attacks. Rust colour suggests to build the box by COR-TEN steel. The corrosion resistance and the tensile strength of this material are perfect answers to the design requests.

The embedded beam has been designed as an integral abutment footbridge with two stiffen concrete end screens on piles at the ends. This connection between the composite steel-concrete deck and the concrete abutments makes possible the integration with embankments. It is a good technology for bridges of relatively small spans in which thermal strains and axial movements have to be carefully evaluated.

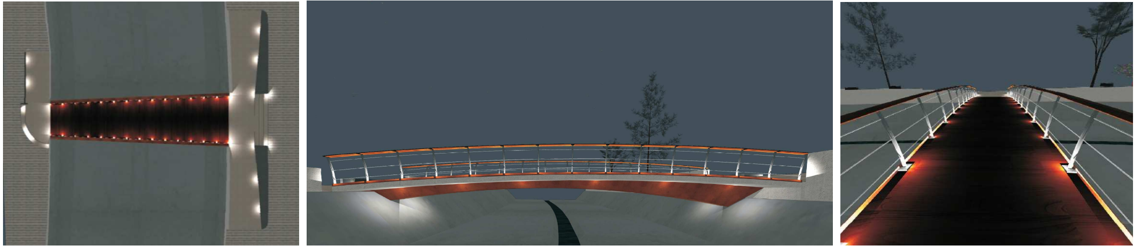

**Fig. 5:** Render of the footbridge. Night vision

The choice to have an upper concrete slab which closes the box girder is related to the need of increasing weight and stiffness. It is very important for vibrations, particularly related to pedestrian motion, in order to avoid lock-in phenomena, i.e. synchronization between pedestrian induced vibrations and the fundamental frequencies of the structure. Moreover a limitation of slenderness and deformations due to static loads has to be achieved with the upper slab. Construction phases have been studied, by considering simple operations in order to respect the prevision budget and the environmental conditions (fig. 6).

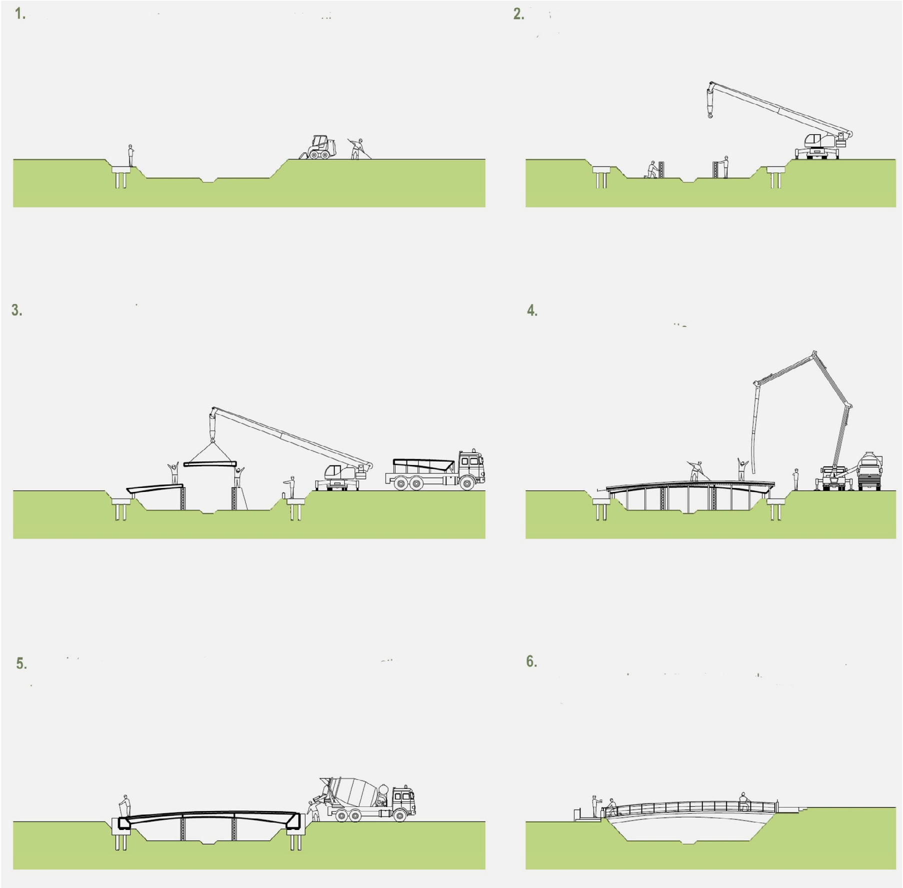

**Fig. 6:** Construction stages: 1. Foundations. 2. Temporary supports. 3. Steel box girder assembling in three parts over supports. 4. Casting of upper slab. 5. Abutment end screens and connections. 6. Provisional supports dismantling and finishing works

After the construction of foundations on piles behind the banks, two provisional supports has to be put into the concrete channel, 1.50 m deep. The steel box is prefabricated in three parts with joints put in the sections of zero bending moments for permanent loads. Bolted joints are connected in situ by the interior side of the box to leave an exterior uniform appearance. In this way steel elements are light and simple to be put on site with a little crane. Internal K steel diaphragms has been foreseen in order to avoid cross section distortion. After the box steel section is completed and the beam is in its definitive position, concrete casting of the upper slab is done on falsework for side cantilevers while on prefabricated slabs of minimum thickness for the internal part between box webs.

End screen walls at the two extremes are cast in situ, connecting the steel box section and the upper slab with abutments through steel connectors and stirrups. Finishing works complete the bridge with pavement, parapet, lightening and inclined ramps.

## 4 STRUCTURAL FEATURES AND PRELIMINARY ANALYSIS RESULTS

The preliminary structural analysis has been done through a Finite Element model by considering the composite steel-concrete structure with a staged construction analysis which reflects the above mentioned construction phases.

Creep effects has been considered through the implementation of CEB Model Code 90 model [1], while permanent and variable loads have been applied on the structure in according with the Italian 2008 Code [2], which is inspired by EuroCodes. About moving loads, they have been considered in a first phase only as a distributed load of type 5, named the “crowd” load.

About integral abutments, the chosen scheme of connections with embankments is the first scheme described by the Steel Construction Institute Technical Report on Integral Steel Bridges [3]. It consists in a “fully integral bridge” with framed end screen abutments, in which bridge deck is embedded to end diaphragm. The framed connection is obtained by concrete circular piles inserted into soil and free into sleeves for the necessary length. This technological detail of extremities has the objective to assure the right deformability of piles and the possibility to have small displacements of pile caps and of end screen walls, related to thermal strains (fig. 7).The idea is similar to that used in some footbridges built in Spain by Sobrino [4], that have longer spans. Other special configurations of abutment-deck connections have been studied for composite arch bridges [5]. Integral abutments have been studied here through the equivalent spring and cantilever models, by evaluating the deformability of piles and the geotechnical characteristics of the clay soil beneath the bridge [3].

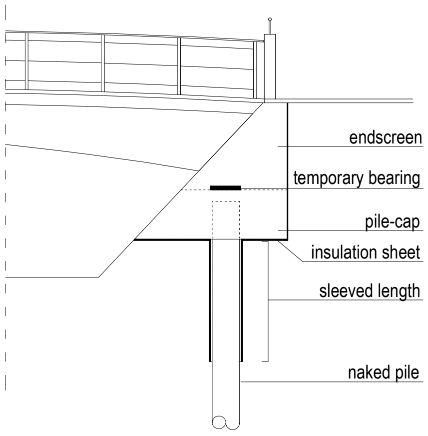

**Fig. 7:** Integral abutment connection

A dynamic modal analysis has been performed in order to know the fundamental frequencies and mode shapes. It has been used not only for seismic evaluations but also to avoid undesirable vibration effects due to pedestrian walking. Particular attention has been paid to slenderness effects on deflections.

A staged construction procedure shows that positive bending moments due to dead loads are important in the early phases when deck is made only of steel box and it is put on temporary bearings. In order to reduce the importance of this moment value, a good choice would be to cast the upper slab together with the end screen wall before to remove temporary supports. In this way the beam can be considered embedded for slab weight and permanent successive loads.

Staged construction has been divided into seven phases:

1) The central part of the steel box is put on temporary supports;
2) the left part of steel box is put on temporary bearings and joined with the central part of box over temporary supports;
3) the right part of steel box is put on temporary bearings and joined with the central part of box over temporary supports;
4) upper slab and connections with end screens are cast;
5) temporary supports are removed;
6) superimposed permanent loads are applied;
7) service life loads are applied.

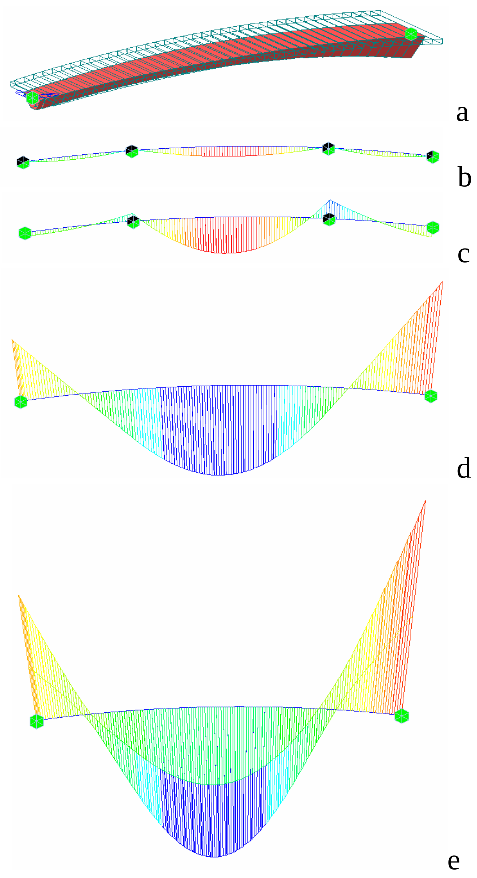

**Fig. 8:** Finite element analysis. a) General view of the model. b) Bending moment diagram at stage 3 before slab casting. c) Integral abutment connection at stage 4. d) Superimposed dead loads at stage 6. e) Maximum and minimum bending moments; permanent and moving loads in service life.

Figure 8 shows bending moment diagrams at different stages for a comparison of values magnitude. It is evident that bending moment grows up in a strong way till the definitive permanent state and after, in service life condition with moving loads. An important role has been played by axial force due to curvature and boundaries; even if the fundamental behaviour of the footbridge is of bending type, a significant arch effect can be obtained by this configuration. Deeper geotechnical studies have to be carried out in the following design stages to establish if foundations can face the expected horizontal forces at the ends. All sections have been verified at this design stage to maximum compressive and tensile stresses.

Figure 9 shows instead the four principal mode shapes obtained by the modal analysis, needed for pedestrian comfort and seismic calculus. Seismic parameters are very low in the Sardinia region and no significant forces have been found. More significance of internal forces due to wind static actions have been found. About pedestrian comfort, frequencies of fundamental modes are very far from the critical values due to crowd walking, being them near 1 Hz. For standard pedestrian traffic with no relevant streams but possible groups on the bridge, no check about synchronization is requested [6]. A good comfort range can be achieved both for vertical and lateral vibrations. Consequently no lock-in phenomena or undesirable vibration effects are expected.

Temperature loads have been considered both as a uniform temperature variation of ±20°C and a temperature gradient between upper slab and lower steel box of 15°C. Deformations have been maintained within the range of ±20 mm of longitudinal displacement, that is the suggested limit for fully integral abutment bridges. They have to be allowed by the deformability of piles and free displacement of end screen walls.

Moreover the maximum value of vertical displacement at midspan found for service loads has been about 1.2 cm, which would be less than 1/1000 of span length.

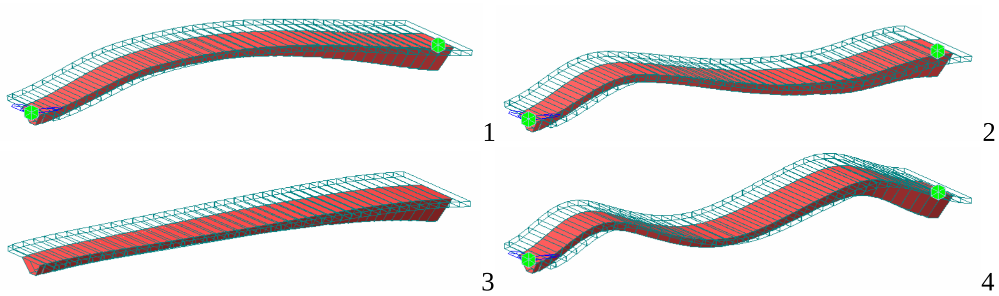

**Fig. 9:** Modal analysis. The first four mode shapes. 1) Longitudinal bending, 9.63 Hz. 2) Longitudinal bending, 21.99 Hz. 3) Transverse bending, 28.01 Hz. 4) Longitudinal bending and axial deformation, 43.83 Hz.

## 5 CONCLUSION

The conceptual design of a steel-concrete composite integral footbridge has been presented. The project won the first prize in a national competition for a bridge to be built in San Sperate, a little town near Cagliari in Sardinia. The architectural constraints have been the fundamental items of this project, because San Sperate is a museum-town. Structural choices have been discussed with reference to the geometry, profile design, composite cross section and integral abutments. Results of preliminary finite element model with staged construction analysis have been presented.

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## KEYWORDS

Footbridge, integral abutments, steel box, composite structure, cor-ten steel