THREE FOOTBRIDGES

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Summary

The aim of the present paper is the illustration of one realization and two footbridge designs, actually elaborated by the author as :

1) Footbridge called "Ponte della Pace" (Bridge of Peace) over the Reno river, Casalecchio di Reno (Bologna), located approximately 500 m downstream of the road bridge on the Porrettana road and approximately 1100 m upstream of the bridge of the south-west Freeway.

2) Footbridge over the A13 Bologna-Padua motorway, connecting the R.5.4d Dozza area and via Tuscolano.

3) Footbridge "Canonica", Casalecchio di Reno (Bologna), approximately 500 m upstream of the south-west Freeway area.

Keywords: Conceptual design, suspension, cable-stayed, detail design.

1.   Footbridge over the Reno – Bridge of Peace

The footbridge built over the Reno river is a pedestrian and bicycle path and has an approximately 100 m free span.

From the town planning viewpoint, it contributes to the definition of a pedestrian and bicycle connection route playing a major functional and symbolic role.

Also in terms of the recovery of the identity of the town, the selected location allows those who cross the footbridge to directly enjoy important venues of the Casalecchio town structure, in particular the S. Martino church, the ancient brick wall and the ancient Scaletta, S. Luca and Verrocchio docks of the Reno canal, and the Eremo di Tizzano church(fig_1).
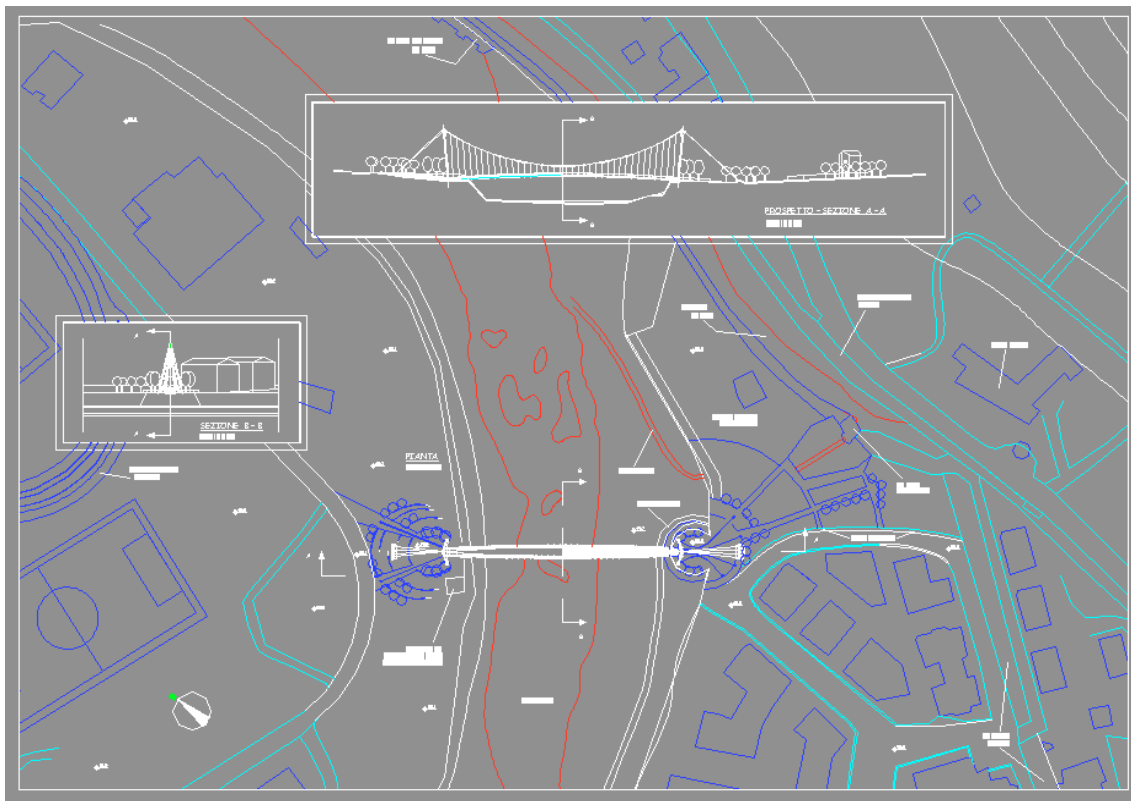
Fig. 1 General setting.

The architectural and structural project took into in particular account the functional, environmental and economic limits set by the Clients.

Based on those specifications , after a comparative typological analysis, a pre-tensioned suspension bridge was selected, which allows to eliminate the deck structures with longitudinal flexural rigidity (which minimises the environmental impact) and supports the wooden floor simply by means of transversal bent beam elements (gondole), which in their turn hang from the fully locked carrying cables by means of spiral cables stays.

The structural solution basically consists of:

- one main spatial carrying cable system ;
- one system of stabilising ropes with opposing curvature;
- two anchor frames with gravity foundations.

1.1   The main supporting system

The main supporting system is composed of two carrying cables with a 98 m free span and 15 m sag. Both carrying cables are constructed with spiral high resistance individual wires plus Z-shaped external wires (locked coil system) cables, protected from corrosion through galvanising and having a $\phi=60mm$ nominal diameter.

In order to achieve a stable system also in terms of the lateral forces due to the wind, such carrying cables were arranged according to a space pattern envisaging diagonal lines, at first implementing a natural equilibrium setting (State 0) depending on the load distribution and the linear constraint conditions.

This configuration mainly originates from the shape of the deck structure, the width of which ranges, according to a double parabola, between 2.50 m at the springing and 6 m in the centre line, which, through the very deck structure, ensures a wind bracing function outside the vertical plane (fig_2).
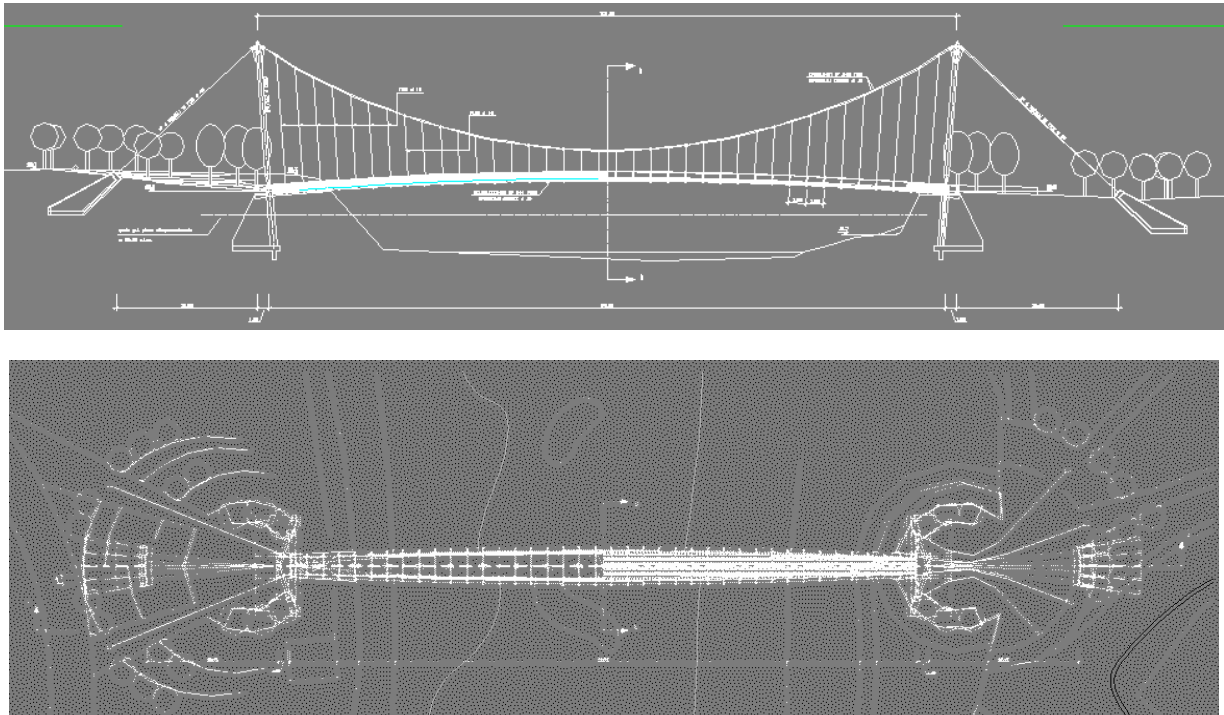
Fig. 2 Plan view

The sag rods connecting the deck structure and the carrying cables are composed of ϕ=16mm – 19mm galvanised fully locked spiral ropes; they hold the deck structure every 2.50 m by connecting to enclosed Fe 430 D steel transversal beams with variable span and convey the stress to the carrying cables through special friction grips.

The deck structure is 98.00 m long between the anchor frames and is in ad-hoc treated 0.07 m thick, 0.20 m wide and 5.00 m long larch wood tables.

The fillets are laid longitudinally with reference to the crossing direction of the pathway, placed one next to each other with a few millimetre span to allow the flow of water and the usual expansion of wood itself (fig_3).

Fig. 3 Full daylight and night views of the footbridge

1.2 The stabilising system

The stabilising system is composed of cables with opposing curvature arranged along the external perimeter of the deck structure. The cables, with a 40 mm nominal diameter, have an initial pre-stressing force of 500 KN,

The stabilising cables allow achieving a double-effect vertical system, thus generating a tension- structure response system, unlike the traditional stabilisation by gravity of merely hanging decks.

Due to the shape design of the deck, the stabilising cables have a spatial double curvature in the vertical and horizontal planes so as to achieve an effective response against the gravitational loads and the lift and drag actions due to the wind (fig_4).

The stabilising cables are anchored to a foundation in reinforced concrete.


Fig. 4 Details
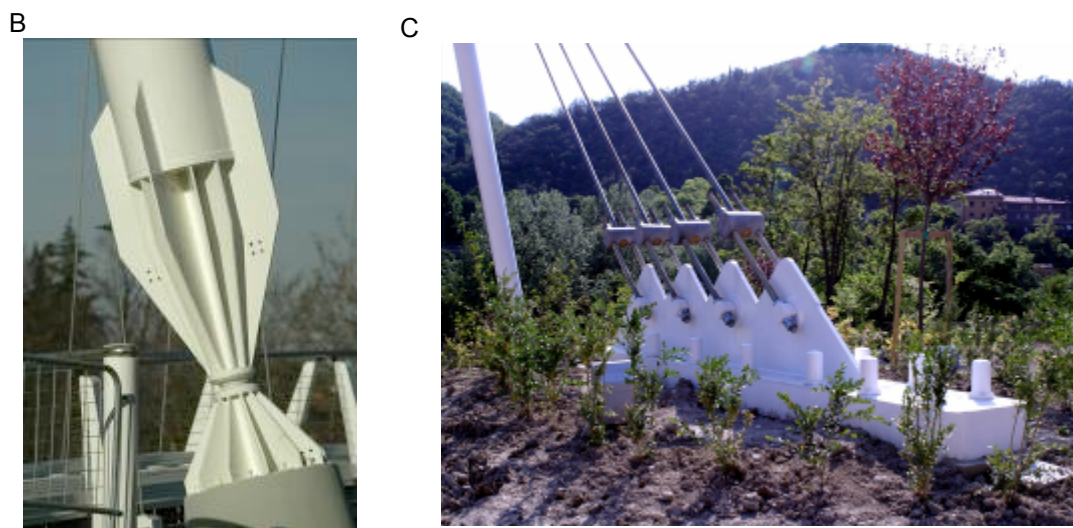
1.3 Anchoring supports

The tensioned structure system formed by carrying and stabilising cables generates tension stress at the sides, with horizontal and vertical components, which are balanced and conveyed to the ground through an anchoring system. The present project implemented an anchoring frame system composed of two "A"-shaped steel columns and a guying composed of four stay ropes with 40 mm diameter, fan arranged on the longitudinal vertical plane (fig_5).

The carrying cables meet in the anchoring point at the top of the support columns, where a particular hinge-pin structural device was developed which allows to connect the carrying cables, the stay ropes and the A-shaped columns, thus automatically leading the various components to a state of equilibrium in operating conditions and facilitating assembly operations as well.

The A-columns are approximately 22.00 m tall above the ground and are built with S 355 steel circular hollow structural section, 711.2 mm diameter and 12 mm width, hinged at the base.

A
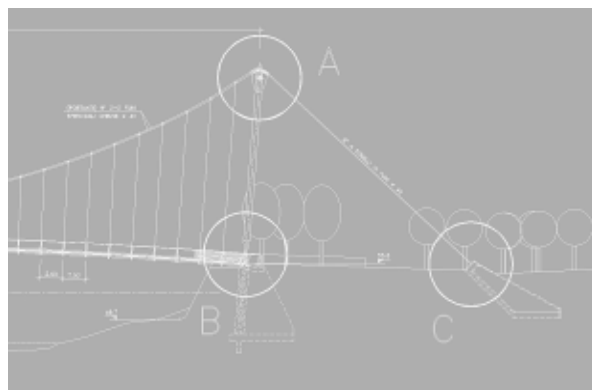
Fig. 5 The anchoring support

1.4 The foundations

The column forces are transmitted to the reinforced concrete foundation system.

Based on the geotechnical properties of the site, direct-type foundation solutions could be implemented.

The stay-cable forces, generated by the structural system response, is counterbalanced by gravity foundations, typically used in cable-stayed and suspended bridges. The gravity cable stay anchorage foundations are located approx. 22-23 metres away from the columns described above, where the equilibrium of forces is achieved vertically through the weight of the foundation itself and horizontally through the combined contribution of friction and a certain soil passive pressure share.

The foundation of the columns may be compared to a retaining wall loaded vertically by the columns and horizontally by the stabilising cables.

2. Footbridge crossing the Bologna-Padua A 13 Highway

2.1 Description of the structure

Also in this case, in the light of the functional, environmental and economic bounds set by the clients during the preliminary project, a comparative typological analysis was conducted, leading to illustrate the various solutions through interactive graphic techniques, 3-D solid rendering and environmental impact simulations.

Based on the results achieved, a solution was implemented envisaging a tied structural support system and internal stay-ropes (fig_6).

Additionally, this solution allows minimising the assembly time, which is particularly important in the light of the location within the city area.

The final project stage was implemented according to different sub-typologies so as to streamline the planimetric and altimetric arrangement and fundamental structural parameters, as well as, in the light of the aesthetic impact considered, match the building cost analysis with the allocated budget.

The structural solution developed during the final design phase mainly consists in:

- a three hinged arch main support structural system with counter-stressed tie mechanism;
- an internal fan-shaped cable stay system supporting the deck structure;

- a double-effect pre-stressed transversal stabilising system through cables with opposing curvature;
- a foundation system composed of reinforced concrete side walls on fill embankment.
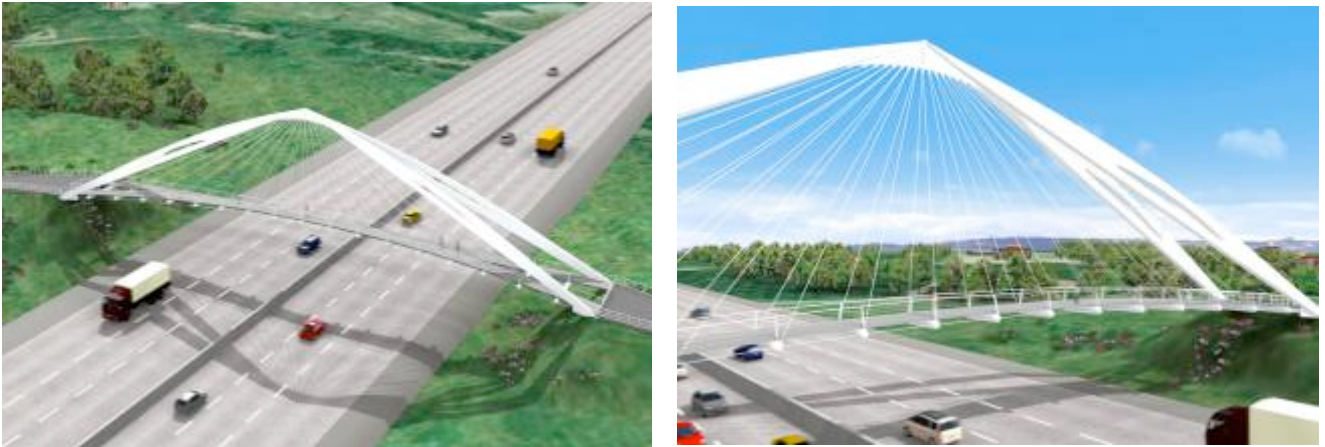
Fig. 6 Graphic simulations of the project
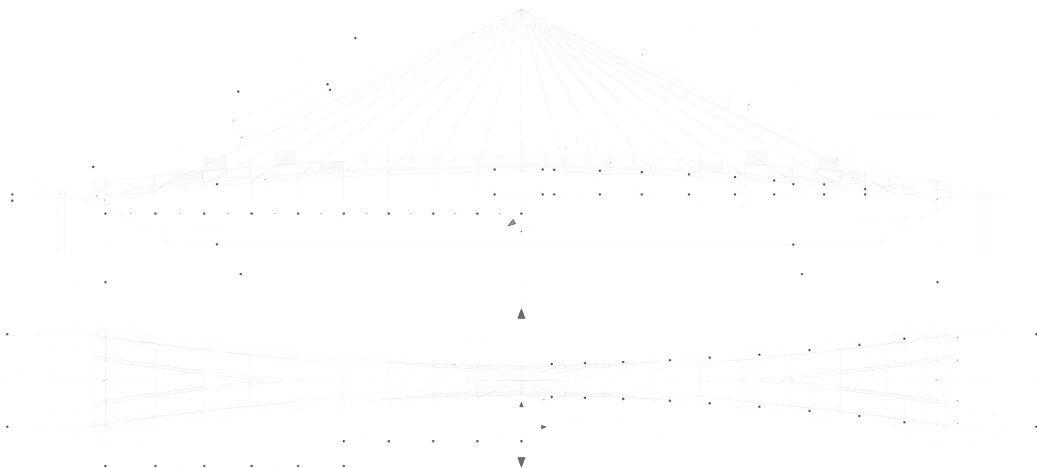
Fig. 7 Plan view

2.2   The main supporting system

The main supporting system is composed of two inclined "A"-shaped frames, contrasting in the centre line, so that, between the side supports, they exceed a 90 m free span, with a 20 m arch rise. The minimum free height of the deck structure is 6 m from the motorway level.

The frame support points have 10 m separation at the sides. The horizontal forces generated by the supporting mechanism - which is very similar to a three-hinges arch - is balanced by a high-resistance steel spiral cable system. The deck structure, is marked by a 3% rise of the free span, achieved through the geometric configuration and the mutual contrast with the internal stay rope system.

The main frame members "legs" are realized of S 355 steel with box cross-section through automatic welding of differently thick flat members; they are shaped with a variable section so as to achieve an optimum configuration with reference to the stress distribution and the stability problems of the plane and outside the main flexure plane(fig_7).

2.3   The secondary or local supporting system

The secondary supporting system is composed of a fan shaped stay-cable system converging at the crown and a "chain" system of flat members of S 460 steel, placed following the deck geometry. The stay-ropes are of the locked coil strand type, with high-resistance s 160 Mpa individual wires, class B galvanising, with a nominal diameter ranging from ϕ=40mm to ϕ=28mm. The stay-ropes are anchored where the stabilising cables and the warp cross girders meet a constant 5m centre spaces.

A

B
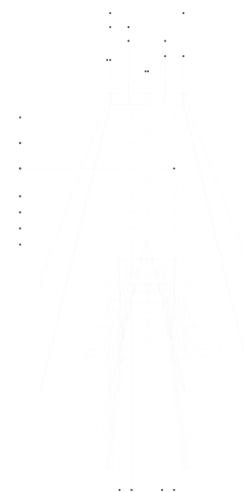
Fig. 8 A.Sezione trasversale B.Sezione e particolare del nodo in sommità

2.4   The stabilising system

Along the external perimeter of the deck structure, 42 mm diameter stabilising ropes with opposing curvature are arranged (4 per side), with a pre-stressing level forces of 4 x 305 KN.

The stabilising cables are shaped equipped with bending components in the vertical and horizontal planes so as to achieve an effective response against the gravitational loads and lift and drag stress due to the wind.

In the vertical plane, the stabilising rods are connected to the intermediate stay-ropes by means of intermediate thrust piles and operate as a chain eliminating the thrust generated in the main arch mechanism. The curvature of the cables in the vertical plane is achieved by a centre-line arch rise amounting to 3% of the free span, thus achieving an initial pre-stress state in the case of permanent loads.

According to the project, the ropes follow the variable development of the bridge structure, featuring a 2.50 m centre minimum width up to 10 m at the springings.

2.5   The foundation system

The structural system generates boundary forces at the footbridge sides with mainly vertical components. Horizontal reactions mainly depend on the longitudinal and transversal drag components due to the wind and

seismic action (seismic intensity: s=6) considered as minimum reference dynamic load used to calculate the size of the wind-bracing systems and the boundary constraints.

The external reactions of the structural system are balanced by two open abutments in reinforced concrete, covered by reinforced fill embankment so as to minimise the visual impact. The foundation is of the deep drilled-in caisson type.

2.6 The external anchoring system

Four vertical supports are located at the base of the main frames resting on side piers, ensuring the vertical equilibrium and rotational stability around the horizontal longitudinal axis, the following elements are arranged at the top of the foundation abutments:

a) 2 horizontal transversal restrain located on the longitudinal axis of the pathway;

b) 4 visco-elastic damper actuators for horizontal dynamic restrain conditions under a specific constitutive law, specially designed to control structural response under seismic actions. On the other hand, the visco-elastic actuators allow the horizontal displacements of the support details caused by "slow" actions such as loads due to crowd, snow and thermal changes.

Fig. 9 Appoggio del puntone sulla spalla

2.7 Technical instructions on the assembly and start-up operations

Owing to the peculiar traffic conditions, the assembly of the footbridge must be carried out on the via Tuscolano side, regardless of the traffic directions, and its fully completed version must be placed on the reinforced concrete abutments through handling in the night-time. This operation, allowed by favourable conditions on the building site, is aimed at minimising the uncertainties affecting the safety plan during the planning and working stages and the duration of the traffic interruption.

3. Footbridge over the Reno river – "Canonica"

Also the new footbridge in Casalecchio di Reno is aimed at connecting the two banks of the Reno river and has a 100m maximum free span.

The structural architecture conceptual design is inspired by the shape of a swan, in particular its lightness and elegance, and resorts to materials such as steel, capable of ensuring a favourable weight-resistance ratio, and a series of original structural solutions aimed at minimising the weight of the structure and,

consequently, the total cost of the work.

Fig. 10 General setting and graphic simulation of the work

The deck structure includes a reinforced concrete slab on 9 cm tall corrugated steel metal sheet and is supported by transversal elements arranged at a constant 2.5 m centre line which convey the load of the deck structure on a box girder with polygonal section, the extremities of which are hinged and supported by a

series of stay-ropes in 4 sections.

The solution implemented, i.e. the use of a reinforced concrete slab instead of the traditional orthotropic plate is aimed at ensuring stability to pedestrian dynamic actions, as well as greater stiffness to the deck structure on its plane; this advantage is achieved by implementing a composite steel-concrete section trough stud connection between the concrete layer and the steel box supporting structure.

The section of the bridge deck varies:, the cross section starts at the left bank support from a minimum value of 2.5 m and then increases while approaching the right bank to reach a 6 m width at the stay-rope holding antenna (located approximately 80 m away from the left bank), where the "pathway" is divided into two symmetric 3 m wide parts, in their turn supported by cantilever beams projecting from a box girder located in a lateral position.

Going from the right to the left bank, also the two beams supporting the deck structure progressively increase their cross section until the point where they are hinged in the central abutment, then they continued in an inclined position to form the antenna supporting the stay-ropes.

The stayed inclined column is composed of two box sections, reaches a 25.05 m maximum height with 44 degree angle towards the centre line of the bridge. Four stay-cables depart from the top and support the deck structure by means of 4 adequately stiff transversal beams anchored to the deck structure by means of triangular shaped plate elements capable of preventing any parasitic flexures affecting the bridge deck.

The cable axial forces are oriented towards the anchoring structures after being deviated in a zenith point corresponding to the connection point among the deck beam, the antenna and the two box girders . following, in plan view, the development of the box girders.

4.   General remarks on the vibration behaviour of footbridges

Footbridges are generally characterized by a low ratio between permanent loads and live loads and, at the same time, remarkable free spans. Under such conditions, the structural systems and typologies, normally implemented on footbridges, show a dynamic behaviour marked by natural frequencies very close to the values perceived by human beings. As noted earlier by direct observations in Albert Bridge about breaking step warnings; by Hugo Bachman (Vibration Upgrading of Gimnasia, Dance Halls and Footbridges-Structural Engineering International 2/92)) and the synchronisation effect, already known by Christian Petersen (Dynamik der Baukonstruktionen; Gruppen und synchronisatioseffekt- Vieweg 1996).

The technical literature suggests avoiding frequency ranges included between 1.6 ↔ 2.4 Hz. and 3.5 ↔ 4.5 Hz. The performance side, at "human comfort" level, is accounted for in the Eurocode n. 3 Design of Steel Structures - Part2: Steel Bridges, as the service limit state. The provisions dealing with anthropic stress and the relevant performance comfort level have recently been considered unreliable.

Numeric analyses in dynamic conditions of the time and frequency domain, subject to the action of elements simulating synchronised anthropic actions, were implemented on all three projects so as to limit the induced accelerations within acceptable values.

Moreover, experimental on site tests may be provided according paragraph 8 of EC3-" Design assisted by testing – tests during execution in order to take account of actual conditions experienced e.g. for measurements of frequencies, or damping". Tests may show the necessity of vibration mitigation trough use of a TMD (tunned mass dampers) system and/or dampers so as to be able to modify the dynamic characteristics of the structure during the building stage and, consequently, avoid the typical resonant dynamic vibrations.

Reference

[1]   Majowiecki Massimo "Cycle and pedestrian crossing on the river Reno", *Costruzioni Metalliche*, Anno LVI, No. 4, 2004, pp. 40-49.