

EXPERIENCES ON FOOTBRIDGE CONCEPTUAL DESIGN VS. DYNAMIC PERFORMANCES

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Summary

This paper presents five experiences on footbridges design with a particular focus on the behaviour under the dynamic pedestrian excitation in its different aspects: frequency, amplitude, perception and comfort.

In the first footbridge, a special stay arrangement allows for a quite high modal frequencies, so that pedestrian excitation is reduced; in addition, the stay arrangement induces a geometric non-linearity which avoid large resonance amplitudes.

In the second one, the aesthetic properties and the structural typology reduce the human perception of vibrations, with respect to other typologies, even if it is quite flexible, light and characterised by a low inherent damping ratio.

The third and the fourth footbridges are characterised by a mass-stiffness values and ratio that allow to strongly mitigate the pedestrian dynamic excitation, without limiting the aesthetics values of the structure. In addition, the deck plant-shape (for the third one) or dimensions (for the fourth one) allow to obtain horizontal modal frequencies out of the excitation range.

Finally, in the fifth footbridge, a very low cost dissipative material is added within the deck structure, so reducing significantly the vertical excitation; in addition, the stay arrangement increases the horizontal stiffness of the deck and reduces the horizontal excitation possibility.

Keywords: footbridge; pedestrian excitation; aesthetic; comfort; damping.

1. Introduction

With new technologies and new materials, over recent years, the trend in footbridge design has been towards increases flexibility and lightness. As a consequence, they are prone to vibration induced by human activities and can suffer severe vibration serviceability problems, particularly in the lateral direction. This phenomenon has been evidenced by the excessive lateral vibration of many footbridges worldwide.

During walking on a structure, pedestrians induce dynamic time varying forces on the floor. These forces have components in all three directions, vertical, lateral and longitudinal and they depend on parameters such as frequency, walking speed and steep length. Dynamic forces induced by pedestrians are therefore highly complex in nature. Several studies have been performed in order to quantify pedestrian walking forces and it is still a research argument the response of a structure under dynamic loads induced by more persons and/or in crowded conditions.

Figure 1 shows critical conditions (due to resonance) for walking-running vs frequencies of vertical, transversal and longitudinal vibrations. As a matter of fact longitudinal vibration are rarely observed in practical cases because of the high axial stiffness of the bridge deck and the commonly applied restraints.

The typical pacing frequency for walking is around 2 steps per second, which gives a vertical forcing frequency of 2 Hz. Slow walking is in the region of 1,4-1,7 Hz and fast walking in the range of 2,2 - 2,4 Hz. This means that the total range of vertical forcing frequency is 1,4-2,4 Hz with a rough mean of 2 Hz. Since the lateral component of the force is applied at half the footfall frequency, the lateral forcing frequencies are in the region of 0,7-1,2 Hz.

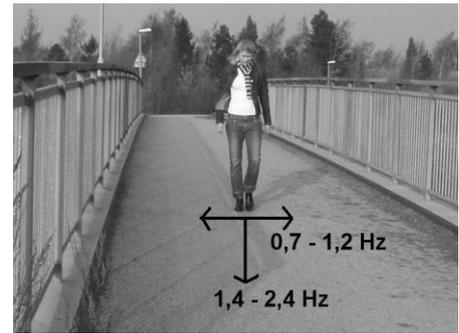
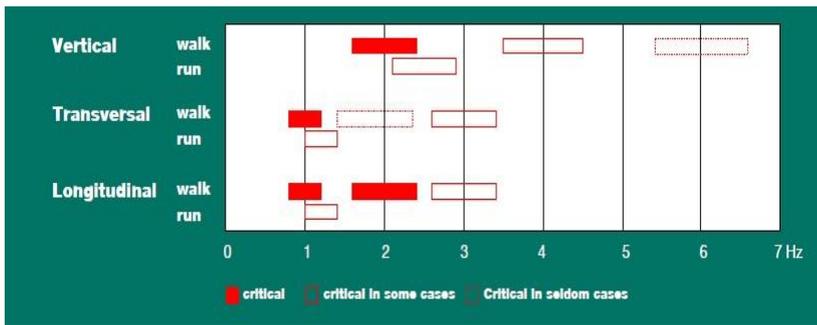


Fig. 1 Critical regions for pedestrian excitation of footbridges (left); typical excitation frequencies ranges (right)

In theory, vibrations can cause discomfort to pedestrians and the deterioration of the footbridge's structural integrity. Unfortunately, present bridge design codes do not provide exhaustive guidelines and information to address such vibration problems and to investigate the dynamic characteristics of slender footbridges under human induced loads. International standards, usually provides comfort criteria in terms of maximum acceleration (in some cases as a function of the frequencies), even quite different among themselves, as shown in figure 2. The Eurocode provide, for instance, the following recommended maximum acceptable acceleration (m/s^2) of any part of the deck: 0,7 for vertical vibrations; 0,2 for horizontal vibrations due to normal use; 0,4 for exceptional crowd conditions. It also states that a verification of the comfort criteria should be performed if the fundamental frequency of the deck is less than: 5 Hz for vertical vibrations; 2,5 Hz for horizontal (lateral) and torsional vibrations. Finally it provides that when the comfort criteria are not satisfied with a significant margin, it may be necessary to make provision in the design for the possible installation of dampers in the structure after its completion.

Practically, different variables introduce uncertainties in the task:

- The dynamic input is quite unknown in both shape and amplitude; researches are still ongoing on this subject.
- The perception and assessment of motion and vibration are not only subjective and, therefore, different for each pedestrian, but also related to some "environment" factors. For instance, some researches demonstrated that users of pedestrian bridges that are located near hospitals and nursing homes, may be more sensitive to vibrations than hikers crossing a pedestrian bridge along a hiking trail; it was also observed that the percentage of individuals feeling disturbed while crossing a sturdier-looking footbridge, is four times higher than for a lighter-looking footbridge.
- Horizontal excitation is a typical lock-in phenomenon and usually occurs only significantly crowd conditions; hence, in most cases it can be inopportune to base the design on this criterion.
- The inherent structural damping (which is essential in determining the vibration amplitude and the auto-excitation condition) is quite variable and it depends not only on the basic material and joints typology but also on non-structural elements and on the oscillation amplitude.

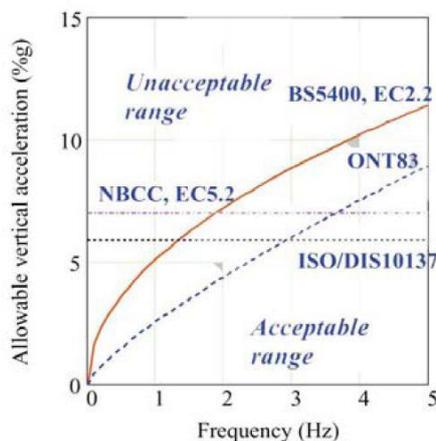


Fig.2 Different comfort criteria for vertical acceleration

Hence, the design criterion based on the natural structural frequencies (which is often adopted and suggested, consisting to avoid that structural modal frequencies "fall" in the critical ranges) can strongly and unnecessarily penalize both economical and aesthetical aspects.

In the paper, some design experiences made by the authors will be presented: economical, lightness and (maybe) aesthetic results can be achieved without incurring in significant vibration problems related to pedestrian excitation.



Fig.3 View of a construction stage (left) and of a final night view (right) for the footbridge crossing the Bologna-Padova A13 highway

2. A footbridge across the Bologna Padova A13 highway

The footbridge crossing the Bologna-Padova A13 highway (figure 3) was built on the outskirts of Bologna and it spans about 90 meters. The structure is totally made of steel and cables and it has been designed in order to be subjected mainly to axial-membrane stresses.

The main structural system is composed of 4 box girders (in compression) and external tense cables. All together they form a three dimensional structural system where horizontal forces are absorbed by cables that are raised about 26 meters from the ground. The tension ropes are arch shaped and they remain parallel to the bridge deck. The deck is suspended by a radiating cable system which extends from the top of the main structural system. The mutual distance between cable anchorages on the deck is about 5 meters.

Due to the inclined directions of the cables, the horizontal internal forces are self-balanced by a local structural system made of compressed trusses, which have a circular hollow section and are parallel to the main ropes.

The result is that the footbridge is a sort of “portal” to enter the city, with a light deck and slender in its geometric proportions. The total weight and the features of the structural system (statically “closed”) also have interesting advantages: the bridge can be assembled close to the highway area and then finally moved to its final place, thus minimizing interference with the traffic below.

The stay arrangement allows to obtain quite high modal frequencies (as shown in figure 4 and as confirmed by experimental tests aimed to the dynamic characterisation of the structure) so that pedestrians excitation is avoid in most “walking conditions”. In addition, the stay arrangement induces a geometric non-linearity which avoid large resonance amplitudes; hence, the vibration amplitude is small also in “running conditions” as proved by the actual response of the structure.

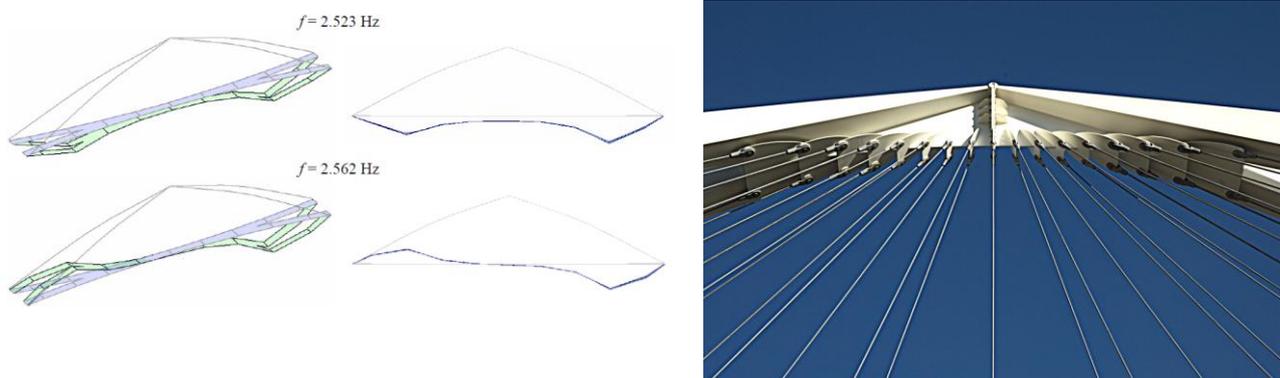


Fig.4 Representation of identified modal frequencies and shapes (left); detail of the upper cables connection (right)



Fig.5 View of the suspended footbridge over the river Reno (left) and the anchoring support (right)

3. A suspended bridge over the river Reno in Casalecchio - Bologna

This footbridge was built over the river Reno along a cycle-pedestrian path and is characterised by an approximately 100 m free span (figure 5 and figure 6). After a comparative typological analysis, a pre-tensioned suspension bridge was selected, which allows to eliminate the deck structures with longitudinal flexural rigidity (to minimize the environmental impact) and to supports the wooden floor simply by means of transversal bent beam elements, which in turn hang from the fully locked carrying cables by means of spiral cables stays.

The structural solution basically consist of: a main spatial carrying cable system; a system of stabilizing ropes with opposing curvature; two "A" shaped pylons; two anchor frames with gravity foundations.

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 galvanizing and having a 60 mm 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.

The stabilizing system is composed of cables with opposing curvature arranged along the external perimeter of the deck structure. These cables allow achieving a double-effect vertical system, thus generating a tension-structure response system, unlike the traditional stabilization by gravity of merely hanging decks.



Fig.6 Full daylight (left) and night (right) views of the suspended footbridge over the river Reno in Casalecchio-Bologna

The structural typology and arrangement is so that many vibration modes fall in the frequency range typically excited by pedestrian in the vertical direction. This is confirmed by the experimental dynamic identification as shown in table 1. The dynamic identification also showed that the inherent modal damping is quite low, typically being lower than 1%, so that vertical vibration are quite large as demonstrated both during the dynamic tests and the normal use of the bridge.

Nevertheless, as already stated in introduction, the lighter-looking typology induce people to “well accept” even quite large vibration without any significant reduction of the comfort perception, as widely demonstrated over more than seven years of use.

On the other hand, thanks to the plan curvature of the stabilizing cables the horizontal frequency is relatively high in absence or with few persons, so that during the common use of the bridge horizontal vibration have never been observed. Horizontal excitation has occurred only during the opening day, with the bridge completely crowded and hence with a big mass (lower frequency) and large exciting forces.

Tab.1 Summary of the modal identified characteristic

<i>Modal shape</i>	<i>Freq. [Hz]</i>	<i>Damp. [%]</i>	<i>Modal shape</i>	<i>Freq. [Hz]</i>	<i>Damp. [%]</i>
<i>Flex Asymm</i>	<i>0,55</i>	<i>1,8</i>	<i>Flex Symm</i>	<i>2,6</i>	<i>2,9</i>
<i>Flex Symm</i>	<i>0,83</i>	<i>2,0</i>	<i>Tors Symm</i>	<i>2,6</i>	
<i>Tors Asymm</i>	<i>1,06</i>	<i>0,93</i>	<i>Flex Asymm</i>	<i>2,65</i>	
<i>Tors Symm</i>	<i>1,55</i>	<i>0,8</i>	<i>Tors Symm</i>	<i>3,18</i>	<i>0,4</i>
<i>Flex Symm</i>	<i>1,78</i>	<i>2,5</i>	<i>Flex Symm</i>	<i>4,23</i>	<i>1,5</i>

4. A cable stayed bridge over the River Reno in Casalecchio - Bologna

In this paragraph a second footbridge across the river Reno in Casalecchio is presented (figure 7 and figure 8). The structure is a asymmetric single tower cable-stayed bridge. 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 minimizing the weight of the structure and, consequently, the total cost of 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 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. The antenna is located approximately 80 m away from the left bank, where the "pathway" is divided into two symmetric 3 m wide parts, which in turn are 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 incline column is composed of a box section, 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 5 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.

The solution implemented, i.e. the use of a reinforced concrete slab instead of the traditional orthotropic plate is aimed to provide stability against 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. In addition, the use of a concrete slab contribute to increase the inherent structural damping and the dead to live loads ratio with a subsequent reduction of the pedestrian induced vibration.



Fig.7 Views of the cable stayed bridge over the river Reno in Casalecchio-Bologna

A second design aspect that influence and strongly mitigate the dynamic excitation of the bridge, in particular the horizontal pedestrian excitation, is the “Y-shaped” plan: this imply that the longest span behaves as a beam which is simply supported at one end and full fixed at the other end. Hence, the horizontal frequencies of the bridge is practically out of the excitation range (except for fully crowded conditions).

5. A cable stayed footbridge at Piraeus in Athens

This footbridge (figure 9) is essentially made up of a 43 m span box-girder-deck, vertically supported and laterally restrained by secondary truss structures (which also support the stairs which are necessary for reaching the deck) and by a system of cables, linked to a pylon.

The deck box-girder is a composite (steel-concrete) beam. The lower and the lateral panels are made from steel plates, while the upper panel is made of a concrete slab, which works also as walking surface.

The secondary structure which supports the front stairs is also used to vertically support the deck at its front end and to restrain the longitudinal, lateral and torsional degrees of freedom of the deck itself. The “V” shaped structure, located at the back end of the deck, is used to vertically support the deck and to restrain the deck torsional degrees of freedom at this end. The secondary structures which support the lateral stairs are also used to laterally restrain the deck and the pylon.

The pylon is a steel box with a linearly variable section; the box section is reinforced by an internal “H” shaped profile. Actually, the first part of the pylon (the first lower side 2 m) is made of a filled steel block.



Fig.8 Upper anchoring of front cables (left) and lower anchoring of back cables (right) of the stayed bridge over the river Reno

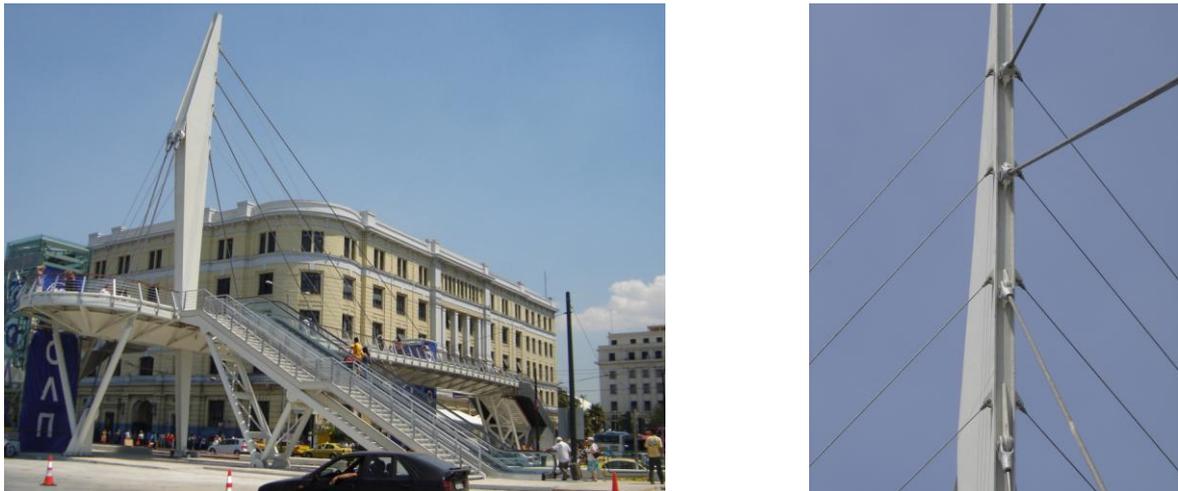


Fig.9 View of the cable stayed footbridge in Athens (left) and the upper cables anchoring (right)

The cable system is composed of: 4 front-located cables, which suspend the deck to the pylon; 2 back-located cables, which restrain the pylon in the longitudinal direction; 8 lateral cables, which laterally restrain the pylon at its upper end. Front and back cables are Steel Wire Full Locked Coil Strand (FLC); lateral cables are Steel Wire Open Spiral Strand (OSS).

From a dynamic point of view this bridge is conceptually similar to the previous one. Vertical vibration are prevented-mitigated thanks to the stiffness, mass and damping contribute of the concrete slab; horizontal vibration are avoided in most service condition thanks to the high horizontal stiffness of the deck box-girder, which in this case is simply supported at both ends but with a relatively low length to width ratio. In addition, different secondary structures are used to stiff the bridge without “shading” the main structure.

6. A cable stayed footbridge in Sassuolo-Modena

This footbridge (figure 10) is located in Sassuolo (Modena) over the river Secchia. The structure is a cable-stayed bridge developed on five spans: three 40 m length spans and two 20 m length ones, that is 160 m total length.

The five spans are supported by four intermediate pylons and by two end abutments. The longest spans are supported at the midspan by a group of cables that suspends the spans to the adjacent pylons. Pylons are placed alternatively on the left side and on the right side of the deck; this strongly characterise the architecture of the bridge and confer torsional and lateral stiffness to the deck. Each pylon is made by a pyramidal box steel beam supported by a concrete pile.

The deck is basically made by a lattice steel beam (diagonal trusses links one lower chord and two upper chords). Above the lattice beam, a secondary steel structure supports the wooden floor. In order to avoid “parasitic” actions on the secondary structure, the secondary structure is linked to the main girder by mean of slotted bolt connections.



Fig.10 Full daylight and night views of the footbridge in Sassuolo (Modena)

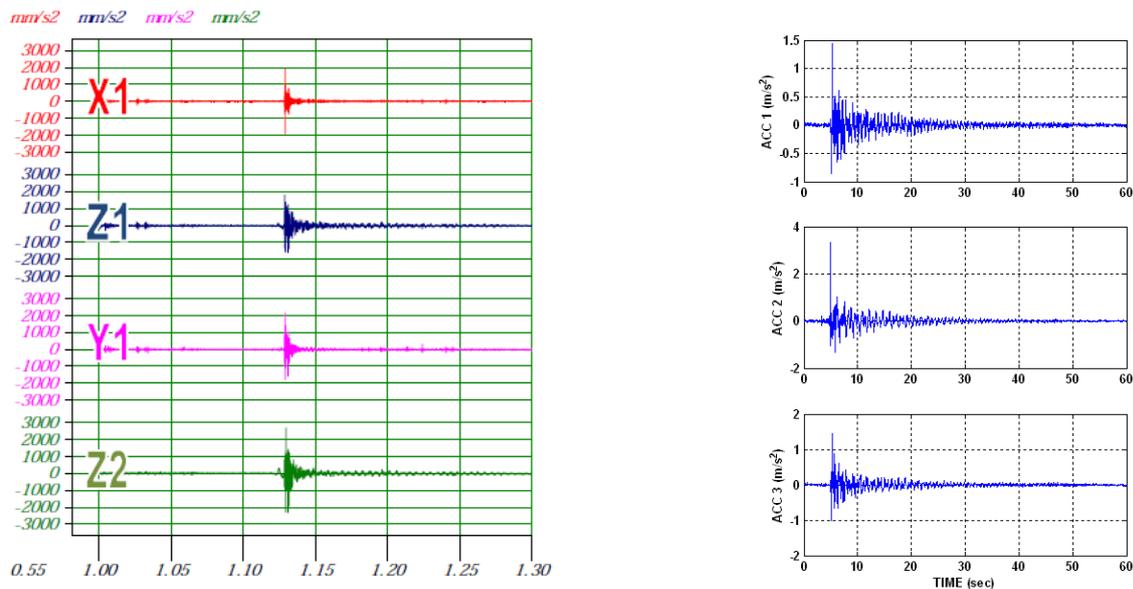


Fig.11 Accelerograms under impulsive excitation for the Sassuolo (left) and Casalecchio suspended (right) footbridges

A thin (5mm) rubber foil is placed within this connection (between the main and the secondary structure) to avoid friction. As a matter of fact this rubber foil behaves as a highly dissipative connection, so inducing damping in the structure. Thanks to this added damping, the bridge does not suffer pedestrian dynamic excitation (no vibration has been appreciated even during the opening ceremony, with bridge fully crowded). The higher inherent damping was kept also during the dynamic characterisation tests; this is clearly shown in figure 11, where accelerograms under impulsive excitation are compared for the suspended footbridge in Casalecchio and the present one.

7. Conclusion

This paper presented five experiences on footbridges design with a particular focus on the behaviour under the dynamic pedestrian excitation in its different aspects: frequency, amplitude, perception and comfort.

It was shown as the design criterion based on the natural structural frequencies (which is often adopted and suggested, consisting to avoid that structural modal frequencies “fall” in the critical ranges) can strongly and unnecessarily penalize both economical and aesthetical aspects.

In the paper, some design experiences made by the authors have been presented to demonstrate that economical, lightness and aesthetic results can be achieved without incurring in significant vibration problems related to pedestrian excitation. This can be achieved during the conceptual design stage by acting on different structural and non-structural aspects: the use of “stiff geometries”, the exploitation of geometric non-linearities, the use of composite concrete-steel members, the exploitation of secondary and/or non-structural elements to introduce stiff and/or damping, ... up to the lighter-looking typologies where vibrations are better accepted by users.

8. References

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