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Some structural design issues on a timber bridge for pedestrians

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Abstract

The use of wood in timber bridges is increased over the past 20 years, mainly since wood is a renewable and sustainable resource. Nevertheless wood is a natural engineering material that is prone to deterioration caused by fungi decay, insect attack and temperature. For wood and wooden bridges there is in fact a strong correlation between durability of the material and bearing capacity. Deformations in a timber structure are often a good indicator of the structural condition.
Within this context, in this study some structural issues dealing with the design of a timber bridge for pedestrians are investigated. In a first step, the bridge shape is designed taking into account various aspects: timber as a bridge material; properties of structural wood products; rain systems for preservation and protection; wearing surfaces for timber decks in order to ensure durability; static and dynamic loads; static scheme. In a second step, the bridge shape is optimized by a procedure based on the calibration of natural modes of vibration.

Keywords: timber bridge; conceptual design; durability; modal analysis; model updating.

1. Introduction

Until the sixteenth century, wooden bridges were mainly used for provisional constructions due to their

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vulnerability to atmospheric agents - the singular case of the Bassano del Grappa bridge by Palladio, still practicable thanks to careful maintenance, represents an example.
From the second half of the nineteenth century onwards, materials such as iron, steel and reinforced concrete were preferred with respect to timber. Nevertheless in recent decades, in many European countries, the employ of wood in constructions and specifically in bridges, was rediscovered thanks to: the great sensibility of this material to environmental sustainability, the optimization of engineered wood such as glulam and related connections, the development of more performing methods of protection [1].

Italy is also experiencing this phase, in particular in the use of glulam bridges adopted for pedestrian and cycle paths. The architectural choice of the uncovered bridge mainly characterizes these structures, directly exposed to atmospheric agents and inevitably destined to premature deterioration of structural components due to the biological nature of wood [2]. According to Eurocode 5 [3], these structural components should be assigned to the service class n. 3, but also this expedient, as proved by the conservation state of many existing bridges, may not be sufficient. On the contrary a correct design approach, including durability devices, could be fundamental in order to guarantee a good duration in time. For example in other countries, such as U.S.A. [4], there was an attention to avoid directly exposed parts, preferring covered bridges [5].

In this context the proposed study deals with the multi-objective design of a timber pedestrian bridge, taking into account all the main aspects of the design process: architectural conception, structural components, load-bearing system, durability, technology, maintenance items.

2. Conceptual design

The proposed study deals with the design of a pedestrian and cycle timber bridge over the Gravina torrent, in Apulia (Italy). The first criterion for satisfying technical feasibility, was the span, equal to 45 m; the position of supports was influenced by the topographic characteristics of the site and by the profiles of obstacles (Fig. 3*a*).

In fact boundary conditions (ground profile) and, in particular, the span length to be covered, significantly affect the choice of structural system, the structural height and the placement of a bridge (Fig. 1 [6]).

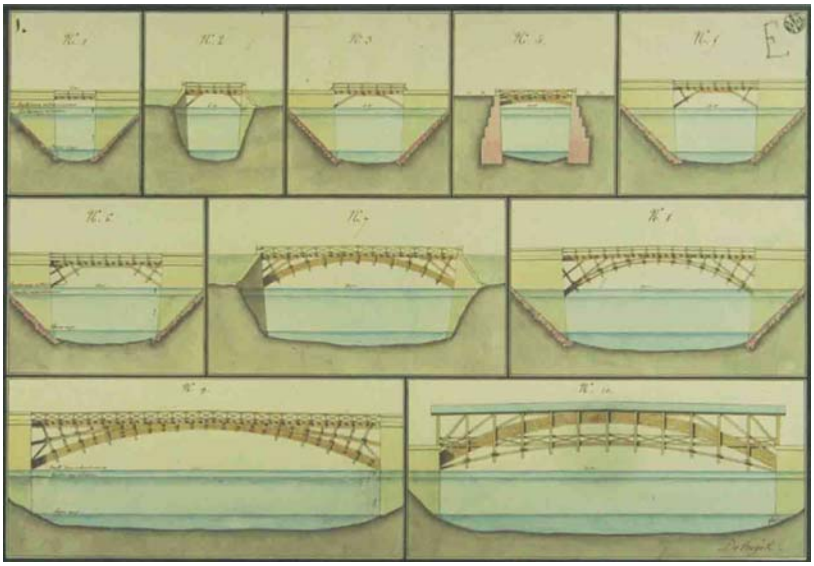


Fig. 1. Influence of boundary conditions on the choice of a bridge structural system. “Concours de architecture presso l’École des Ponts et Chaussées”, 1818. Student: Marie Fortunè de Vergés [6].

Focusing on the timber bridge object of this study, the first selected longitudinal profile was an arch lower-chord truss scheme (Fig. 2*a*) and was chosen since able to provide suitable structural heights. It easily allowed to reach the foundation from the river level up to the road one. However the resulting structure was very light, susceptible to oscillations (vertical and horizontal) and with little torsional rigidity [7]. So this proposal was abandoned at the aim to reduce the values of maximum bending forces.

The obvious solution was to adopt an arch lower-chord strut system with V-struts (Fig. 2*b*). On the one hand this second solution better solved the environmental impact of the foundations and led to smaller bending moment effects, but on the other it did not enable to satisfactorily fulfill robustness and durability requirements.

For these reasons, a covered Pratt-type truss system was finally selected, by assuming the lower chord as cycle path level and the upper chord as roof (Fig. 3*b*). Such a scheme well fits in the natural environmental scenario around the Gravina torrent, dominated by the concept of horizontality. In order to both increase the stiffness and improve durability, a secondary steel truss was placed on the main laminated-timber Pratt-type truss.

As to the installation aspects, the bridge is located in an area where the most common construction site vehicles cannot be used, i.e. crane trucks and / or telehandlers and the use of a specifically designed crane would risk being as expensive as the entire work. For these reasons, assembly via a helicopter would be appropriate.

The structure should therefore be divided into parts (to be assembled on site) with a weight equal to the maximum capacity of the chosen vehicle (for example the maximum capacity of the AS 332 Super Puma model - helicopter for aerial work - is 45 kN).

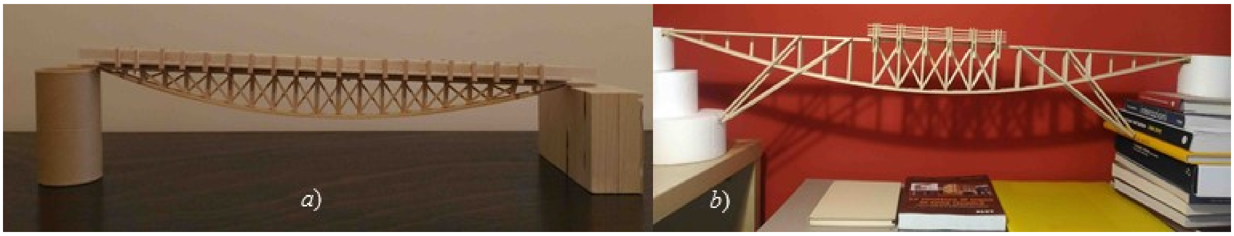
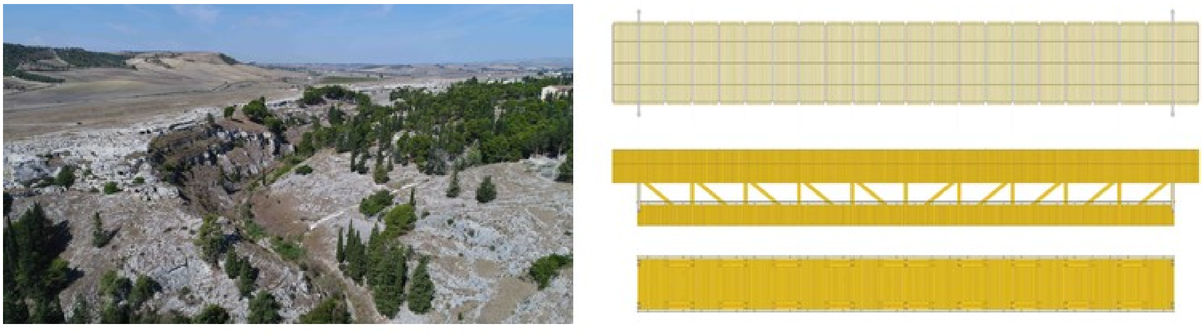


Fig. 2. First longitudinal profiles for the timber bridge: *a*) arch lower-chord truss scheme; *b*) arch lower-chord strut system with V-struts



a) b)

Fig. 3. *a*) Topographic characteristics of the site in proximity of the Gravina torrent; *b)* Final longitudinal profile chosen for the bridge.

2.1. Design for durability

"The durability of a structure is its ability to remain suitable for use during its useful life, provided it is adequately maintained" according to Eurocode 0 [8]. The UNI EN 1001-2 [9] standard defines the durability of wood and wood-based products as the *"resistance of the material to degradation induced by wood-borne organisms"*, including molds and fungi that cause its degradation by attacking the material under certain humidity conditions.

Eurocode 5 [10] defines three important service classes in order to assign the resistance and deformation values of the structural components, and therefore of the entire timber construction.

The evaluation of the moisture content is important for biological durability, therefore the European Standard EN 335 [11] defines five use classes, i.e. five environmental conditions in which the wood can be found. The concept of use class is related to the probability that a wooden element is attacked by biological agents and mainly depends on its moisture content that should not exceed a percentage equal to 20%. The two classification systems differ in the consideration of the effects of humidity in the wood, being of the mechanical type and of the biological type respectively. It should be noted that the classes of service and those of use are not performance classes, therefore no indications are given on how long time the wooden structures will remain in service. Similarly codes in force do not furnish any precise method in order to assess durability. In addition to the above mentioned codes, the European Standard EN 350-2 [12] just provides information about natural durability of the wood species existing in Europe, while the European Standard EN 460: 1995 [13] indicates the requirements for wood corresponding to each use class.

Within this framework, in this study the following approach is suggested to properly account for durability: 1) definition of the design durability; 2) individuation of the use class according to [11, 12]; 3) choice of a design strategy, including protection measures and maintenance plan; 4) verification of durability on the basis of the rules proposed in [14].

The above strategy was applied to the pedestrian bridge object of this study. Durability was chosen in function of the service life of the bridge, assumed equal to 50 years. Successively, focusing on the environmental context where the construction is planned, the 3rd use class was set, corresponding to a moisture content > 20% and so with wood elements vulnerable to the attacks of fungi and insects.

The consequential choice of the service class depended not so much on the design environmental conditions - being the structural components in laminated wood totally protected by the roof - but from the predictable conditions that could involve structural element, if the "water barrier" created by the lining vertical wooden staves were lost. Furthermore, the Gravina stream, which flows below the bridge at about 10 m, although often dry, can lead to a moisture content >85%. For these reasons, it was decided to design the bridge according to service class 3. On the basis of the above observations, the larch was chosen as wood species for the bridge structure.

Focusing on the design strategy for wood protection, it was fundamental to work on the cross section of the bridge, trying to apply the so-called 4D rule, known for the design of wooden buildings in the American context, but more recently also in Europe [14]. The spatial reticular steel truss, being cantilevered, protects the timber truss from atmospheric agents. The inclination of rain, assumed at an angle equal to 60° with respect to the vertical axis, is the design parameter according to which the cross section of the bridge was modeled.

The hot-galvanized steel truss was calculated to withstand also maintenance loads, avoiding the need to mount a scaffold to inspect the bridge; as a consequence the side vertical panels were designed, in turn, to be easily removed from the top.

Being constituted by juxtaposed and overlapping staves, vertical panels absolve the dual role of constituting a "water barrier" and of creating shading, so as to avoid the phenomenon of delamination. The wooden vertical panels were forecasted in Accoya®, a molecularly-modified acetylated wood, characterized by a very low capacity to absorb water. Accoya® is associated to the highest durability class (1), corresponding to a service life equal to 50 years.

According to the above design strategy for durability, on the basis of the rules proposed in [14], the bridge should not be directly exposed to rainfall under normal service conditions and thus the moisture content and temperature should not reach the values activating the wood decay [2, 15].

In addition, it is supposed that just occasionally the bridge could lie under conditions of air humidity greater than 90% and temperature higher than 20°C, especially during summer storms. The construction details of the bridge do not allow to avoid such moisture absorption. Nevertheless, considering that the aforementioned conditions are not frequent and that ventilation of structural elements and nodes is guaranteed, it can be assumed that the absorbed humidity could be easily released in a natural way.

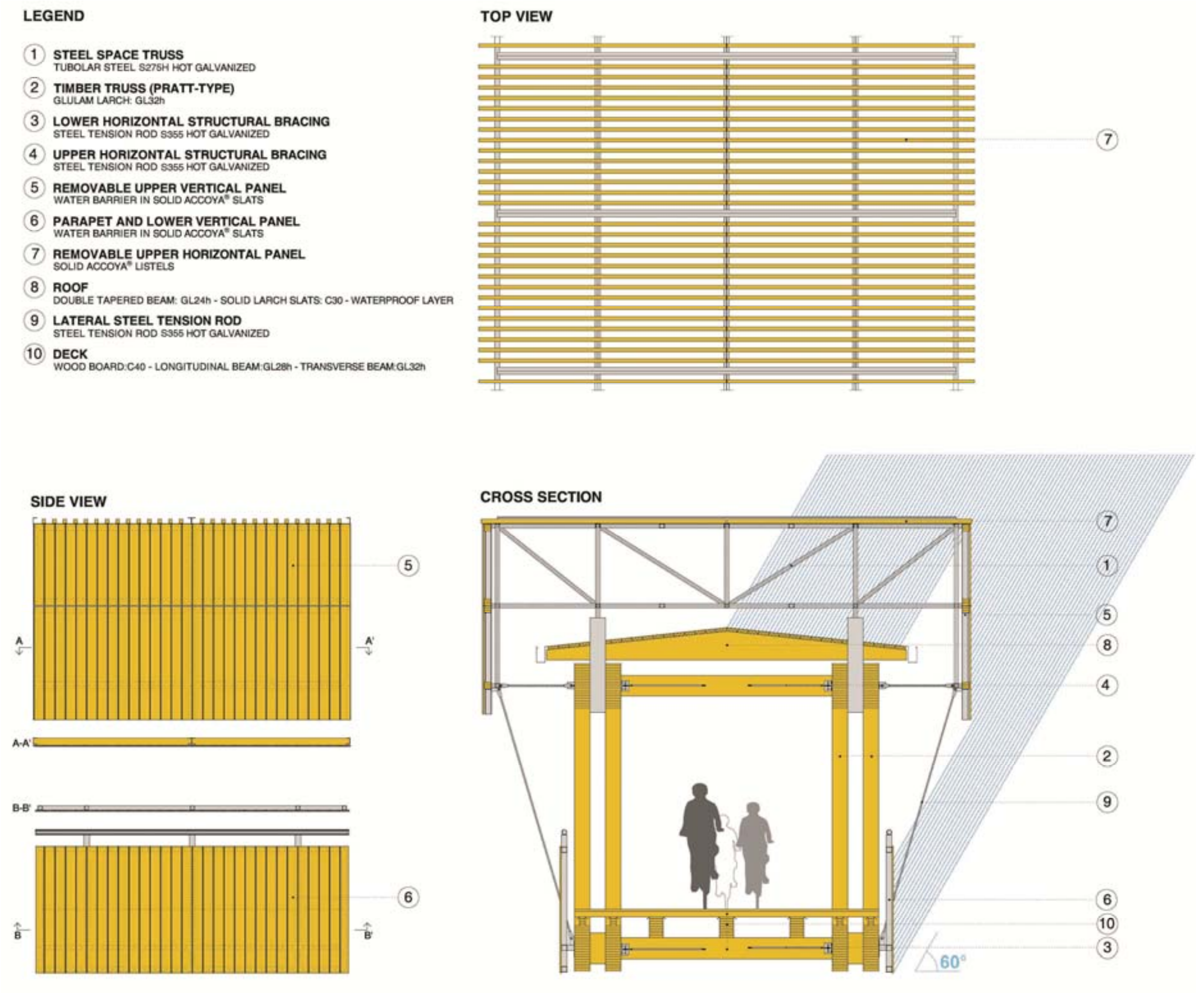


Fig. 4. Design for durability of the timber bridge

3. Structural behaviour

Structural verifications were carried out according to the code prescriptions provided by: Italian technical code [16], Eurocode 5 [3], CNR-DT 207 R1/2018 [17].

The materials used in the project are: solid larch C30, C40 [18] and glulam larch GL24h, GL28h, GL32h [19] for wood; *ii*) S275H and S355 [16] for steel. The choice of the wood species significantly affects the structural performances of each element. The bridge belongs to the 2nd category, therefore the considered traffic actions are: a concentrate load equal to 10 kN with a 0.10 m side square-footprint used for local verifications (load diagram 4); a crowd load, including dynamic effects, equal to 5 kN / m^2 (load pattern 5); a roof maintenance overload equal to 0.5 kN / m^2; a crowd thrust, pushing on the handrail, equal to 1.5 kN / m.

The structural permanent loads of all elements were determined by a finite element calculation software. The specific weight of the chestnut wooden floor constituting the planking level is given by 4.84 kN / m^3, while the one of the accoya® covering is equal to 5.1 kN / m^3.

The main load-bearing system is constituted by two laminated-timber Pratt-type truss longitudinal beams, that support the transverse frame (deck), the wooden roof and the steel spatial truss system. The steel space system includes tubular trusses in both longitudinal and transversal directions, with square-hollow or circular cross-sections, in order to suitably overcome constructional issues. The values of the main mechanical properties of materials, used for numerical simulation, are reported in Table 1.

A three-dimensional finite element model of the bridge was built by using RSTAB of the Dlubal software. Only structural elements were included in the model, whereas non-structural elements were considered as extra masses. The model has a total of 928 nodes and 2721 frame elements. The modeling of the glulam truss was carried out by schematizing the joints as rigid nodes.

Table 1. Mechanical properties of materials.

	GL24h	GL28h	GL32h		S275H	S355
$\mathbf{f_{t,0,k}}$ [kN/cm^2]	1,92	2,23	2,56	$\mathbf{f_{yk}}$ [kN/cm^2]	27,5	35,5
$\mathbf{f_{c,0,k}}$ [kN/cm^2]	2,4	2,8	3,2	$\mathbf{f_{tk}}$ [kN/cm^2]	43	51
E [kN/cm^2]	1150	1260	1420	**E** [kN/cm^2]	21000	21000
γ [kN/m^3]	4,2	4,6	4,9	γ [kN/m^3]	78,5	78,5

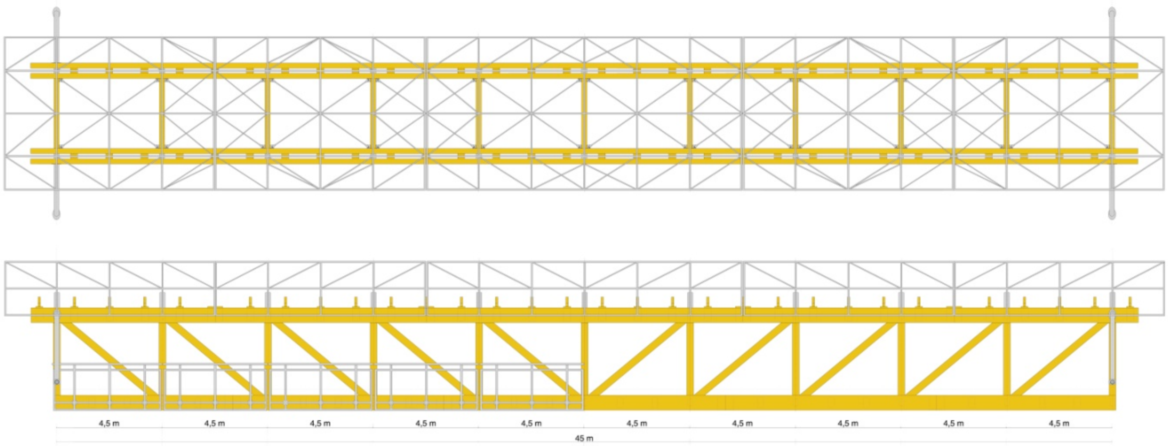


Fig. 5. Structural system of the timber bridge over the Gravina torrent

3.1. Modal analysis and model updating

The results of the modal analysis are summarized in Table 2. In particular Table 2 shows the fundamental modes of vibration in the transversal (y) direction (T = 0.335 s), in the vertical (z) direction (T = 0.218 s) and in the torsional direction around the longitudinal axis (x) (T = 0.239 s; $m_{@jX}$=191285,51 kg·m^2). The torsional mode of vibration around the longitudinal axis is depicted in Figure 6a; it can be observed that the corresponding cross-section deformation is non-homogeneous and assumes a rhomboidal shape.

In order to avoid such a deformed configuration, lateral steel tension rods were added on both sides of the bridge, along the entire span, so conferring stability to the horizontal section (Figs. 6b). The results of the modal analysis of the new model are reported in Table 3; Fig. 6b shows the cross-section deformation of the torsional mode of vibration (T = 0.197 s; $m_{@jX}$=466015,09 kg·m^2), resulting homogeneous after the above adjustment. Moreover it can be argued that the modal participating mass ratios of the fundamental modes of vibration in the three directions are significant (~ 70%), so indicating that there is no excessive dispersion of mass among too many oscillation modes and that the structure is well organized [20, 21].

Nevertheless from Table 3 it can be noted that the value of the natural period of the fundamental vertical mode of vibration (T=0.219 s) is near the one of the torsional mode of vibration (T=0.197 s), and consequently if vertical mode occurs, also the torsional one could simultaneously activate, causing dangerous effects for the structure. So it is suggested to introduce in the model the additional steel cables represented in Fig. 6c and 7, in order to make the translational and the torsional modes of vibration asynchronous. The results of the modal analysis after this second model updating are reported in Table 4.

Table 2. Results of the modal analysis of the original model

Mode	Modal mass	Effective modal mass						Modal participating mass ratio			Natural frequency	Natural period
nr.	M_i [kg]	m_{eX} [kg]	m_{eY} [kg]	m_{eZ} [kg]	$m_{@jX}$ [kg.m^2]	$m_{@jY}$ [kg.m^2]	$m_{@jZ}$ [kg.m^2]	ρ_{meX}	ρ_{meY}	ρ_{meZ}	f [Hz]	T [s]
1	21094,16	0,00	50308,99	0,00	4158,60	0,00	2,28	0,000	0,662	0,000	2,989	0,335
2	15913,94	0,00	6975,04	0,00	191285,51	0,00	120,83	0,000	0,092	0,000	4,178	0,239
3	34247,83	0,00	0,00	54767,57	0,77	118,43	0,00	0,000	0,000	0,721	4,580	0,218

Table 3. Results of the modal analysis after the first model updating

Mode	Modal mass	Effective modal mass						Modal participating mass ratio			Natural frequency	Natural period
nr.	M_i [kg]	m_{eX} [kg]	m_{eY} [kg]	m_{eZ} [kg]	$m_{@jX}$ [kg.m^2]	$m_{@jY}$ [kg.m^2]	$m_{@jZ}$ [kg.m^2]	ρ_{meX}	ρ_{meY}	ρ_{meZ}	f [Hz]	T [s]
1	32600,03	0,00	58121,09	0,00	679,33	0,01	0,21	0,000	0,763	0,000	3,169	0,316
2	34323,16	0,00	0,00	54911,96	0,78	118,15	0,00	0,000	0,000	0,721	4,576	0,219
3	13592,08	0,00	6,53	0,00	466015,09	0,00	903,17	0,000	0,000	0,000	5,083	0,197

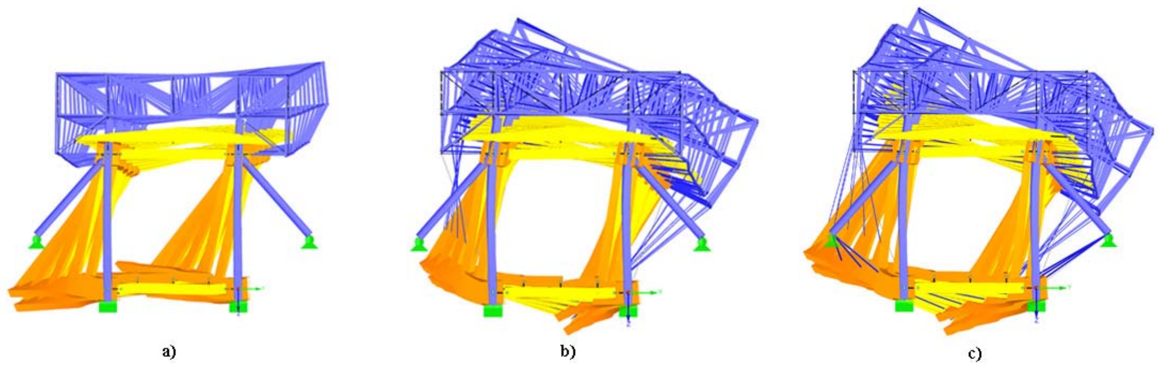


Fig. 6. Cross-section of the torsional modal shape: a) original model (2nd mode of vibration, T=0.239 s; $m_{@jX}$=191285,51 kg·m^2); b) after the first model updating (3rd mode of vibration, T = 0.197 s; $m_{@jX}$=466015,09 kg·m^2); c) after the second model updating (3rd mode of vibration, T = 0.17 s; $m_{@jX}$=421632,16 kg·m^2);.

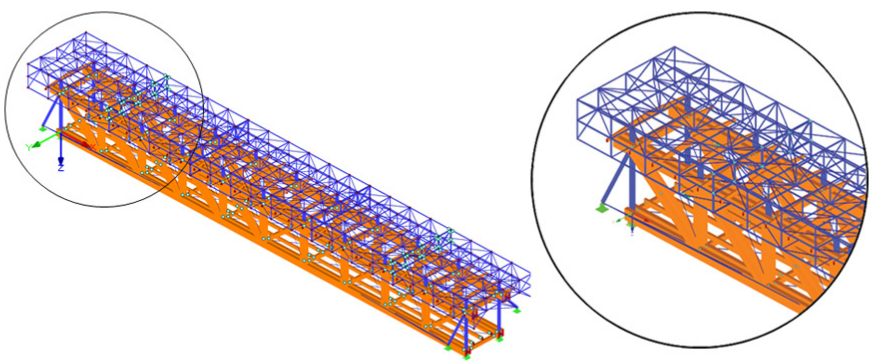


Fig. 7. Three-dimensional model after the second updating

Table 4. Results of the modal analysis after the second model updating

Mode	Modal mass	Effective modal mass						Modal participating mass ratio			Natural frequency	Natural period
nr.	M_i [kg]	m_{eX} [kg]	m_{eY} [kg]	m_{eZ} [kg]	$m_{@jX}$ [kg.m^2]	$m_{@jY}$ [kg.m^2]	$m_{@jZ}$ [kg.m^2]	ρ_{meX}	ρ_{meY}	ρ_{meZ}	f [Hz]	T [s]
1	19268,17	0,00	51966,17	0,00	32594,13	0,00	84,55	0,000	0,675	0,000	3,721	0,269
2	34445,37	0,00	0,00	55375,46	0,77	116,31	0,00	0,000	0,000	0,720	4,635	0,216
3	18015,99	0,00	4181,06	0,00	421632,16	0,00	1309,30	0,000	0,054	0,000	5,890	0,170

4. Conclusions

In the proposed study a novel methodology to carry out the conceptual design of a pedestrian and cycle timber bridge was proposed and described, proving its efficacy. A possible bridge over the Gravina river, in Apulia (Italy), was considered as case study.

In a first step, the structural scheme of the bridge, the materials and the covering systems were chosen taking into account multiple aspects, nor of which negligible: boundary conditions, structural behavior, durability, constructional issues. Successively a two-step model updating was carried out. That is the finite element model of the bridge was corrected on the basis of the modal analysis, by introducing additional steel cables, in order to reach two main objectives: *i*) an homogeneous cross-section modal shape in corresponding of the torsional mode of vibration; *ii*) translational and the torsional modes of vibration asynchronous.

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