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Structural Behaviour of Damaged Venetian Buildings: Experimental Evaluation

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ABSTRACT: The continuous interaction with the aggressive lagoon environment gives serious problems for the preservation of the historical Venetian buildings. Nowadays many buildings show a severe decay of their structures, that often implies not only an alteration of their architectural image, but also a significant modification of their structural behaviour.

This paper presents some experimental results of a wider research program that investigates the efficacy of the structural functioning of the historical Venetian buildings with reference to the decay of their structures.

Experimental tests were performed on two specimens that reproduced the system masonry walls-Venetian wooden floors without any significant scale effect. During the tests these specimens were progressively damaged, in order to simulate the decay of the structural elements and of their connections. They were loaded with distributed and concentrated vertical loads. The structural behaviour of the wooden floors and of the masonry walls at the increasing of the damage was investigated.

1 INTRODUCTION

It is well known that the building process of the historical Venetian buildings was strictly conditioned by the singular environmental circumstances. The scarce load-bearing capacity of the foundation ground and the interaction with the lagoon water imposed the adoption of specific technical solutions, in order to preserve the integrity of the structures and to guarantee the efficacy of the structural functioning of the buildings.

A foundation system with wooden piles, driven deep into the superficial layers of silt and clay, was conceived in order to found the buildings on the deeper and firmer ground layers, as shown in Fig. 1a (Piana, 1984).

The walls were almost always built with a very big height-to-thickness ratio, in order to contain the loads transferred to the ground. For the same reason and moreover to avoid the transmission of horizontal actions to the walls**,** the floors were almost always built with wooden beams.

The absence of masonry connection among the orthogonal load-bearing walls was needed to permit their different vertical translations in consequence of any different sinking of the foundation ground. The collapses out of plane of the walls were prevented by a system of tie-rods placed at each floor, as shown in Fig. 1c (Piana, 2000).

The protection from the wash of the base of the walls facing the canals was ensured by a layer of Istrian stone blocks that covered the bricks underneath. Moreover some continuous courses of Istrian stone blocks, called “cadene”, were placed at regular intervals in height up to a level above the middle sea level, in order to create some waterproof layers that protected the walls from the rising damp, too, as shown in Fig. 1a .

A further protection from the rising damp of the wooden beams of the first floor was ensured by placing a wooden beam called "rema" below their heads, as shown in Fig. 1b (Piana, 1984).

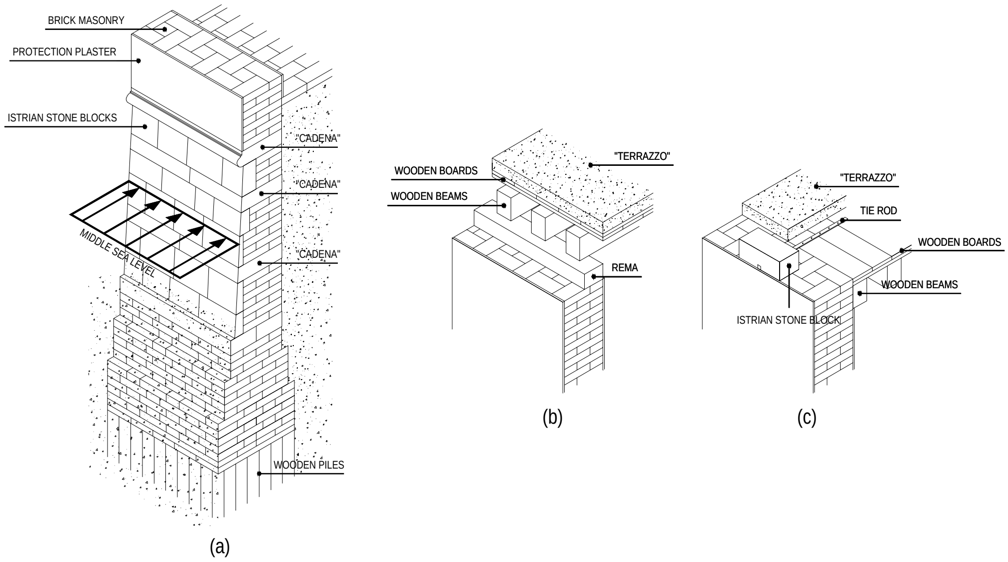

Figure 1 : Building techniques of the historical Venetian buildings.

Despite the efficacy of these technical solutions nowadays many buildings show a severe decay of their structures, partially due to the natural ageing, partially to the modification of the environmental circumstances over the centuries.

The direct contact with the lagoon-water resulting from the increase of the sea level caused the wash of the mortar joints of the brick-walls at the base, and sometimes a significant reduction of their thickness (Zago and Riva, 1981). In this way the rising-damp was emphasized, so that the wooden beams of the first floor show a severe damage even if a rema is placed below.

In some cases also the connection between the orthogonal walls becomes inefficient, because of the oxidization of the tie rods due to the driving rain.

All these alterations provoked a progressive modification of the original structural functioning, with possible severe consequences for the complex equilibrium of the buildings (Zuccolo, 1975).

A research program was made to evaluate the incidence of the described alterations on the structural safety of the historical Venetian buildings.

This evaluation gains a primary importance with respect to the restoration design.

In many cases the rehabilitation of the historical buildings goes through the substitution of some existing parts with new constructive details, that are often repetitive and that often have nothing to do with the historical and constructive reality of the buildings. The result of this design procedure is the levelling down and the standardization of the constructive characteristics, and more widely the progressive loss of the identity of the buildings.

A cognitive effort that combines the qualitative and the quantitative evaluation of the described problems can lead to a design that respects the original structure of the buildings and enhances its residual resources.

This paper presents the first results of experimental tests performed on two specimens, through which we tried to simulate, in simplified way, the condition of the historical Venetian buildings with some of the described problems.

2 OBJECT OF THE EXPERIMENTS

Two simplified models of the system masonry walls-Venetian wooden floors were defined.

The geometrical shape of these specimens was conceived so that they can reproduce the system of the ground and first floor of the historical Venetian buildings preventing any significant scale effect, as shown in Fig. 2.

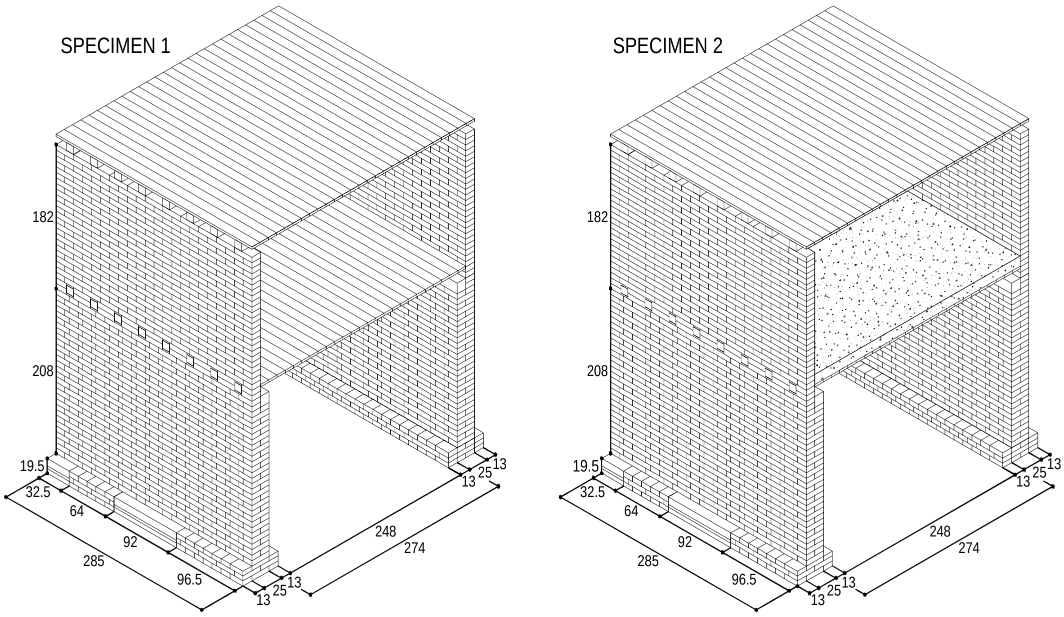

Figure 2 : Geometrical shape of the two specimens.

The masonry walls were built using UNI (ITALIAN standard) bricks, with a mortar prepared mixing equal proportion of sand, water and a binder comprising ¾ lime and ¼ Portland cement 325. The bricks were 25 by 12 by 5.5 centimetres. The mortar joints, made flush with the brick's face, were 1 centimetre thick.

The structure of the first floor was different for the two specimens, as shown in Fig. 3.

In the specimen 1 it was built with wooden beams, on which a simple layer of wooden planks was nailed. This type of floor was employed in the simplest historical Venetian houses; in many cases a second layer of wooden planks was nailed in the orthogonal direction to the first one.

In the specimen 2 a layer of "terrazzo" was arranged on the first layer of wooden planks.

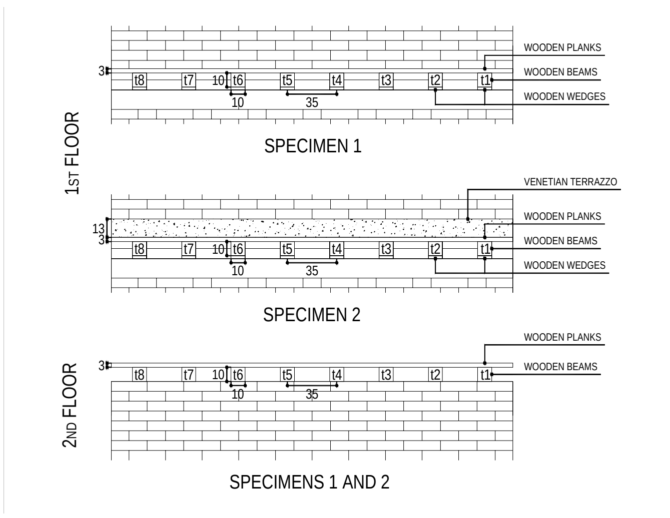

Figure 3 : Structure of the floors of the two specimens.

The terrazzo is the typical Venetian floor, employed both in the monumental buildings and in the council houses. It is composed by three layers: the "sottofondo", 10 centimetres thick, the "coprifondo", 2 centimetres thick, and the "stabilitura", only 1 centimetres thick, as shown in Table 1 (Crovato, 1989).

The terrazzo for the specimen 2 was built with this same composition.

Table 1 : Composition of the "terrazzo"

Sottofondo		Coprifondo		Stabilitura	
Slaked lime	Crushed bricks and tiles	Slaked lime	Powdered bricks	Slaked lime	Marble chips
N/m^2	N/m^2	N/m^2	N/m^2	N/m^2	N/m^2
400	1600	100	300	100	100

The structure of the second floor was the same for the two specimens. It was built with wooden beams, on which a layer of wooden planks was nailed, as shown in Fig. 3.

These specimens were conceived so that they can be modified in order to simulate the described alterations of the material consistency of the structural elements and of their connections.

For this reason the beams of the first floor were put on wooden planks with the interposition of some wooden wedges, as shown in Fig. 4a. These wedges can be removed in order to simulate the reduction of the contact with the wall, when the rising damp provokes the decay of the heads of the wooden beams. On the contrary the beams of the second floor were simply put on the walls.

Moreover one of the two bases of the walls of each specimen was partially built with bricks, partially with wooden planks and parts of wooden beams, with the interposition of wooden wedges under the beginning of the wall, as shown in Fig. 4b. These wedges can be removed in order to simulate a sinking of the foundation ground at the centre and at the end of the wall.

In correspondence of the same wall the horizontal and vertical mortar joints of the first seven courses were partially removed at the beginning of the experimental tests for a depth of five or six centimetres, as shown in Fig 4c, in order to simulate the wash due to the lagoon water.

(a) (b) (c)

Figure 4 : Particulars of the structures of the two specimens.

3 EXPERIMENTAL PROGRAM

The main goals of the experimental program were:

- the evaluation of the behaviour of the first floor built with and without the layer of terrazzo subjected to distributed and concentrated loads, at varying of the contact area between the heads of the wooden beams and the wall;
- the evaluation of the distribution of the compression stress at the base of the masonry walls with respect to these changes of the contact area and when some vertical sinkings of the foundation ground appear at the base.

The experimental program is articulated into four steps, that were equally performed on the two specimens.

The first floor of the two specimens was loaded with distributed and concentrated vertical loads. During the steps the structure of the specimens was progressively modified. The inflection of the beams and the crushing of the masonry wall were measured with continuity.

The steps are synthetically described, specifying for each of these the modifications of the structure of the specimens and the loading conditions:

- 1st step: structure in the original condition, distributed load increased from 1 to 3 kN/m^2, concentrated force keep equal to 0 kN;
- 2nd step: structure in the original condition, distributed load keep equal to 3 kN/m^2, concentrated force increased from 0 to 20 kN;
- 3rd step: removal of the two wedges supporting the two central beams of the first floor, distributed load keep equal to 3 kN/m^2, concentrated force increased from 0 to 20 kN;
- 4th step: Removal of the foundation beams distributed load keep equal to 3 kN/m^2, concentrated force increased from 0 to 20 kN.

The applied loads, and in particular the concentrated force, are increased until a value that avoids the failure of the wooden beams. On the contrary it is to note that the applied loads are very low in order to produce even a little a damage of the masonry walls.

4 TEST SET-UP

The first floor of both the specimens was loaded with distributed and concentrated loads.

The distributed loads were produced with sacks of sand placed at the top of the first floor.

The concentrated load was applied by means of an hydraulic jack, in decentralized position with respect to the vertical axis of the structure, as shown in Fig. 5.

This jack was fixed at its base to a steel beam connected to the floor of the laboratory with chemical plugs. At the top it crossed the wooden planks of the first floor preliminarily drilled, and it was fixed to a second steel beams with four screws. Two bricks were placed between this second steel beam and the top layer of the floor in correspondence of the two central wooden beams, in order to localise the force generated by the jack.

A load cell capable of measuring the applied force was connected to the jack.

Eight differential transducers mounted on telescoping rods were placed at the intrados of the first floor, to measure the inflection of the wooden beams, as shown in Fig. 5. Four differential transducers were placed at the base of the wall, to measure the crushing of the masonry, too. All the measuring equipment was connected to a data acquisition system, that both controlled the rate of application of the concentrated load and the required loading steps, and also recorded the readings from the measuring instruments evaluating them and converting them into graphs.

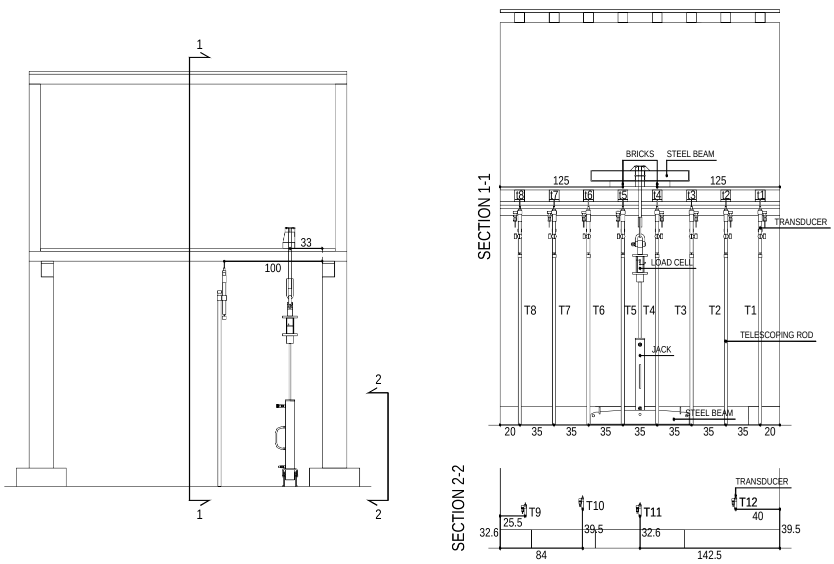

Figure 5 : Experimental set-up.

5 EXPERIMENTAL RESULTS

Given the very limited number of the specimens involved in the tests some considerations must be made with reference to both the purposes of the trial and the validity of the obtained results.

The aim of the tests was not to determine precise values for the inflections of the wooden beams and of the masonry walls at each step, but rather to establish indicative values and behavioural tendencies. The value of the tests is consequently in comparative terms.

5.1 Wooden floors

The comparison of the results obtained in the steps 1 and 2, for the specimen 1, shown in Figs. 6a,b, shows that the inflection of the central beams increases a lot in consequence of the application of the concentrated load, whereas the lowering of the lateral ones remains practically unchanged.

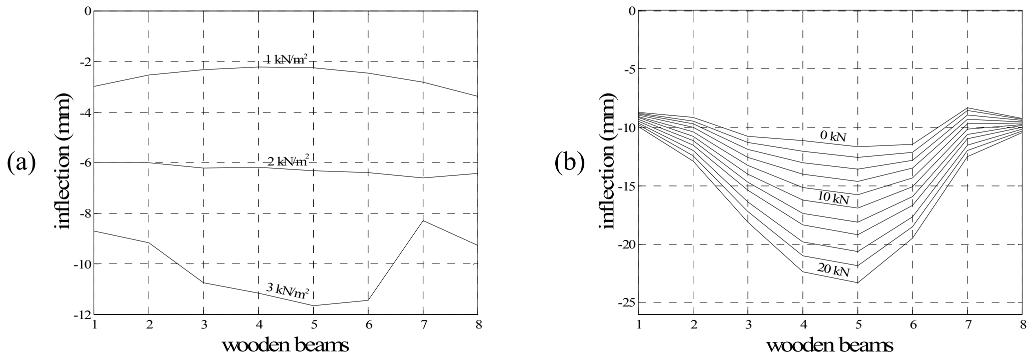

Figure 6 : Inflection of the wooden beams of the specimen 1 in the step 1 (a) and 2 (b) at varying of the distributed load for the step 1 and of the concentrated load for the step 2.

For example, the inflection of the beam 5 at the step 1 with a distributed load of 3 kN/m^2 is equal to 11.65 mm, while at the step 2, when both a distributed load of 3 kN/m^2 and a concentrated load of 20 kN are applied, it is equal to 23.32 mm. Therefore the increase of the inflection in consequence of the application of the concentrated load is equal to 11.67 mm.

On the contrary, the inflection of the beam 1 at the step 1 with a distributed load of 3 kN/m^2 is equal to 8.71 mm, while at the step 2, when both a distributed load of 3 kN/m^2 and a concentrated load of 20 kN are applied, it is equal to 9.93 mm. Therefore in this case the increase of the inflection in consequence of the application of the concentrated load is equal to 1.22 mm.

The comparison of the results obtained in the steps 1 and 2 for the specimen 2, shown in Figs 7a,b, shows that the lowerings of the central and lateral beams are comparable not only for a distributed load, but also for a concentrated load.

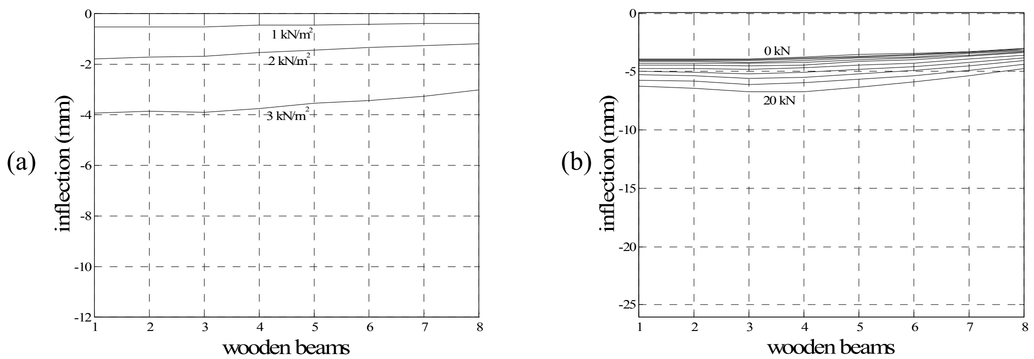

Figure 7 : Inflection of the wooden beams of the specimen 2 in the step 1 (a) and 2 (b) at varying of the distributed load for the step 1 and of the concentrated load for the step 2.

For example, the inflection of the beams 5 at the step 1 with a distributed load of 3 kN/m^2 is equal to 3.56 mm, while at the step 2, when both a distributed load of 3 kN/m^2 and a concentrated load of 20 kN are applied, it is equal to 6.33 mm. Therefore the increase of the inflection in consequence of the application of the concentrated load is equal to 2.77 mm.

In a similar way the inflection of the beam 1 at the step 1 with the distributed load of 3 kN/m^2 is equal to 3.95 mm, while at the step 2, when both the distributed load of 3 kN/m^2 and the concentrated load of 20 kN are applied, it is equal to 6.24 mm. Therefore the increase of the inflection in consequence of the application of the concentrated load is equal to 2.29 mm.

These results indicate that, in the case of the specimen 1, the central beams, that directly support the concentrated force, cannot benefit of the collaboration of the lateral ones, because the wooden planks are not capable to distribute this load so that all the wooden beams equally contribute to support it. On the opposite, in the case of the specimen 2, the layer of terrazzo permits this distribution along the development of the wooden floor, so that all the wooden beams contribute to the load-bearing function at the same way.

The results obtained for the two specimens at the step 3, shown in Figs. 8a,b, show that the removal of the wooden wedges supporting the central beams doesn't modify this behaviour of the two floors.

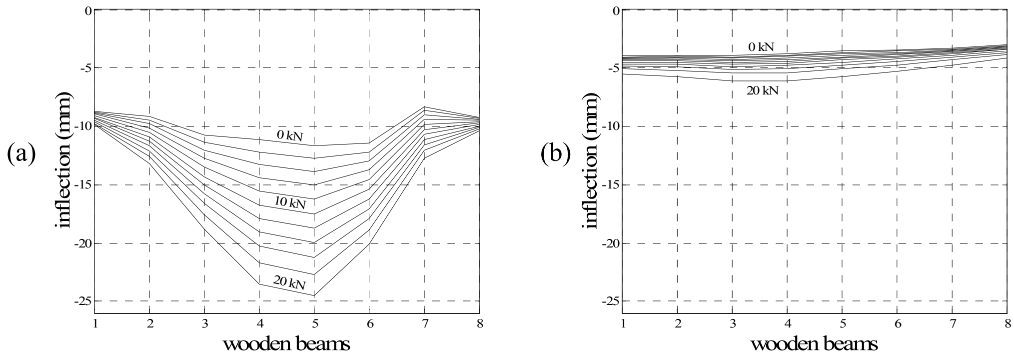

Figure 8 : Inflection of the wooden beams for the specimen 1 (a) and 2 (b) in the step 3 at varying of the concentrated load

In fact the inflection of the central and lateral wooden beams of the specimen 1 at the increasing of the concentrated load is slightly greater than those recorded at the step 2, but the deformed shape of the wooden floor remains the same. The inflection of the central and lateral wooden beams of the specimen 2 is practically unchanged with respect to this recorded at the step 2, so that even in this case the deformed shape of the wooden floor remains the same.

We can conclude that even with a reduction of the contact area of the wooden beams directly loaded from the concentrated load with the wall, no significant variations characterize the functioning of the two floors. In the case of the specimen 1 the existing concentration of the vertical force is only emphasized, while in the case of the specimen 2 the terrazzo continues to ensure the original collaboration among the wooden beams.

In second way, the comparison of the inflection values of the wooden beams of the two specimens shows a substantial difference: the values obtained for the specimen 1 are always greater than those obtained for the specimen 2, under the same load conditions.

This fact doesn't seem comprehensible because the two specimens were built with the same geometry and the wooden beams were equally arranged on the two walls. In second way it doesn't seem comprehensible because the weight of the floor of the specimen 2, that is equal to 2,8 kN/m^2, is greater than the weight of the floor of the specimen 1, that is equal to 0,18 kN/m^2, so that even if the external load conditions are the same for the two specimens, the beams of the specimen 2 are more stressed than those of the specimen 1.

The experimental values of the inflection of the wooden beams for the specimen 1 show that they can be modelled as double-supported beams, stressed by distributed and concentrated loads.

For example, the experimental value of the inflection of the beam 5 for a distributed load of 3

kN/m^2 is equal to 11.65 mm, while the theoretical value in the described boundary conditions and for a Young's modulus of the beams equal to 13000 N/mm^2 is equal to 11.60 cm. This correspondence between the experimental and the theoretical values validates the expressed hypothesis on the boundary conditions, and indicates that the masonry walls at the first floor exert only a weak joint action on the wooden beams.

The same boundary conditions characterize the wooden beams of the specimen 2, because they were equally arranged on the two walls. So we can conclude that the different values of their inflection are probably due to a collaboration of the layer of terrazzo in the load-bearing function of the wooden floor. In other words it behaves not only as a load, but also as a resistant element of the structural section of the wooden floor. This collaboration is not justified from a mechanical connection between the beams and the layer of terrazzo, but its structural effects on the behaviour of the wooden beams are clear.

The experimental value of the lowering of the beam 5 for a distributed load of 3 kN/m^2 is equal to 3.56 mm. We can suppose that this load is really supported by the wooden beam and by the share of the terrazzo put on its top. The share of the terrazzo increases the inertial properties of the floor, so that the inflection of the floor in correspondence of the beam 5 can be calculated supposing a resistant element, that is a beam, with a section constituted by two not connected parts, one of wood and the other of terrazzo. In this hypothesis and for a Young's modulus of the terrazzo equal to 5000 N/mm^2 the value of the lowering is equal to 4.11 mm.

The two values are rather near, so that the expressed hypothesis can be confirmed.

5.2 Masonry walls

The stresses that derive to the masonry walls in consequence of the applied loads are very small, so that the consequent deformations are very limited. Yet the comparison of the values of the lowerings recorded in the four steps, shown in Tables 2 and 3, permits to appreciate the distribution of the vertical loads transferred from the wooden floor at varying of the contact area with the wooden beams and at varying of the boundary condition of the walls at the base.

Table 2 : Experimental results for the masonry wall for the step 1

	Load	Lowerings for the wall of the specimen 1				Lowerings for the wall of the specimen 2			
	kN/m^2	T 9	T 10	T 11	T 12	T 9	T 10	T 11	T 12
		mm				mm			
Step 1	1	0	0	0	0	0	0	0	0
	2	0	0	0	0	0	0	0	0
	3	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01

Table 3 : Experimental results for the masonry wall for the steps 2, 3 and 4

	Load	Lowerings for the wall of the specimen 1				Lowerings for the wall of the specimen 2			
	kN	T 9	T 10	T 11	T 12	T 9	T 10	T 11	T 12
		mm				mm			
Step 2	10	0.01	0.02	0.02	0.02	0.01	0.02	0.02	0.01
	20	0.02	0.02	0.03	0.02	0.02	0.02	0.02	0.02
Step 3	10	0.01	0.02	0.02	0.02	0.01	0.02	0.02	0.01
	20	0.02	0.02	0.03	0.02	0.02	0.02	0.02	0.02
Step 4	10	0.01	0.02	0.02	0.01	0.01	0.02	0.04	0.01
	20	0.01	0.04	0.04	0.01	0.02	0.05	0.06	0.01

The results obtained for the two specimens in the steps 1 and 2 are coherent with the distribution of the distributed and concentrated loads shown from the discussed inflections of the wooden beams of the two floors. In both specimens the inflections of the wooden beams subjected to a distributed load are very similar, with the only exception of the extreme beams, however stressed by a smaller load in consequence of their position.

In same way the recorded lowerings of the masonry walls have the same values, confirming the uniform distribution of the stress also on the base of the masonry walls.

On the contrary when the concentrated force is applied in addition to the distributed load, the lowerings of the wooden beams are different in the two specimens.

The increase of the inflection of the central beams with respect to the lateral ones that characterizes the specimen 1 is confirmed by the distribution of the lowerings of the wall at the base, where the transducer 3, that is positioned in the centre of the base of the wall, records the greatest value of the lowering. In same way the uniform lowering of both the central and the lateral beams shown from the specimen 2 is confirmed by the distribution of the lowering of the wall at the base, where all the transducers still record the same value.

This correspondence between the lowerings of the wooden beams and of the masonry walls is shown also for the step 3, when the wedges that supported the central beams were removed.

With respect to the difference of the lowering values recorded for the wooden beams of the two specimens it is to note that no relevant difference exists between the lowering values recorded for the masonry walls. Nevertheless, given the very small values of the lowerings because of the very limited load, it is possible that the difference was not appreciable from the transducers.

Finally the results of the step 4 for the two specimens evidence that a significant increase of the lowerings is given from the sinking of the foundation ground, simulated through the removal of the wedges and of the wooden beams at the base of the wall. In both specimens the transducers placed in correspondence of the removals record very big values of the lowerings with respect to those recorded from the other transducers.

6 CONCLUSIONS

Notwithstanding the increase of the loads on the vertical structures of the buildings the experimental results evidence the benefits to the structural functioning of the wooden floors due to the presence of the terrazzo.

On the one hand it permits the distribution of the vertical concentrated loads among the wooden beams of the floor, so that no significant difference appears among their deformations. This behaviour of the terrazzo is valid even when some wooden beams reduce their contact area with the wall, for example in consequence of the decay due to the rising damp. In this case the presence of the terrazzo keeps the functioning of the wooden floor unchanged, and therefore the distribution of the stress on the base of the masonry walls.

On the other hand the terrazzo increases not only the load of the wooden floors, but also its inertial properties, and in so doing it increases the load-bearing capacity of the floor and contains the inflection of the wooden beams.

Both the distribution of the vertical loads on the floors and the sinking of the foundation ground is reflected from the lowerings of the masonry walls at their base. In every case it will be necessary to massively increase the vertical loads or to introduce other modifications on the structural elements, as for example a significant reduction of the transversal section of the walls in order to appreciate the reduction of the structural safety of these.

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