Mechanical behavior of the timber–terrazzo composite floor

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HIGHLIGHTS

- Mechanical behavior of the terrazzo flooring.
- Experimental results from tests performed on real scale structures differing for the Venetian floor.
- Experimental data used to develop a predictive analytical model.
- Peculiarities of the traditional structural system are described.
- Terrazzo provides the floor with significant extra-stiffness and extra-strength.

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ABSTRACT

The mechanical behavior of the timber–terrazzo floor is investigated in this paper. The presentation refers to the traditional Venetian floor; however, the research was comprehensive and hence the results of this paper include any timber floor finished with terrazzo flooring.

The first part of the paper presents experimental results from laboratory tests performed at different load stages on two real scale masonry buildings, differing only for the presence of the Venetian floor. The experiments also included inducing damage artificially.

The experimental data were then elaborated to describe peculiarities of the traditional structural system. The test results presented in the paper prove that the terrazzo is an important load-bearing component, since it provides the floor with substantial extra-stiffness and extra-strength. The test results also prove that even a high level of damage does not reduce significantly the stiffness of this type of floor.

Research activity was then directed toward analytical modeling. The second part of the paper presents how the experimental data were used to construct a predictive theoretical model, whose reliability is proven by the good agreement between the results from the model and the findings from the tests. The model can be used to assess the stiffness and load-carrying capacity of timber–terrazzo floors and as a basis for floor rehabilitation.

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1. Introduction

This paper deals with the terrazzo flooring that rests on timber floors, and analyzes the mechanical behavior of the structural system that derives from the composition of terrazzo, beams, and boards.

The term “terrazzo” derives from the Italian “Terrazza”. The definition of terrazzo over the centuries is: a form of mosaic flooring made by embedding chips in a matrix and polishing.

In a terrazzo floor, the chip is the ingredient that acts as aggregate (i.e., inert materials). The chips are screened to various sizes. Traditionally, the chips were made of small pieces of marble, granite or other minerals such as quartz, quartzite, and river gravel.

Today, the chips may also be of onyx, glass, smalti or synthetic types.

In a terrazzo floor, the matrix is the ingredient that acts as a binder to hold the chips in position. Traditionally, the matrix was made of mortar (either hydraulic or non-hydraulic lime mortar). Nowadays, the matrix may also be made of cementitious, modified-cementitious or resinous materials.

The terrazzo is poured in place, cured, ground, and polished to achieve a smooth surface.

The terrazzo was invented by Venetian construction workers. Nevertheless, it was the evolution of patient works of art attributed to the first Roman age, where the floors were cemented with lime, according to a Greek procedure that had been then perfected in Italy. The Venetian terrazzo was introduced as a low cost durable flooring system using marble chips from upscale jobs and goat milk as the sealer, which originally were usually set in clay to surface the patios around the living quarters.
The use of the terrazzo changed over the years and after few centuries it was used as high-grade flooring, widely specified by Venetian architects for its aesthetic and decorative characteristics as well as for its durability. Thus, we find the terrazzo in the vast majority of the Venetian buildings. Nevertheless, this type of floor is also used nowadays all over the world.

In historical buildings [1], the slab that forms the terrazzo flooring rests on timber beams and boards. According to the technical history of Venetian architecture, in the designers’ intent the timber beams and boards were the structure of the floor, while the terrazzo slab was a non-load-bearing element devoted to obtaining the flat surface as well as to providing the flooring with aesthetic quality. However, the comparison between historical timber floors with and without [2] the terrazzo suggests that not only has the terrazzo a structural role in the floor structure, but that the designers knew and considered that structural role. The Venetian buildings, where the terrazzo is widely used, provide significant examples of the structural role of the terrazzo.

1.1. Venetian buildings structurally considered

Venetian buildings have always been designed and constructed considering three peculiar characteristics — namely, the brackish water and tides of the lagoon, the shortage of available space, and the soft superficial soil layers (silt and clay). The Venetian foundation system was designed and constructed so as to adequately cope with such adverse environment [3].

The soft soil entailed that the masonry walls of the buildings had to be supported on pile groups embedded into the soil. Each pile was driven vertically into the ground up to reaching the deep soil layers, which are relatively strong (Fig. 1). Then, a pile cap was constructed on the top of each group of foundation piles to evenly accommodate the building that the piles had to carry. The pile caps consisted of timber boards, called “madieri” (Fig. 1 shows a single-layer-board system, i.e. one layer of “madieri”).

Bricks were then laid onto the madieri and covered with special waterproof clay, called “tera da savon” (in Venetian vernacular), so as to obtain the basis of each wall. Moreover, a vertical layer made of Istrian stones was placed on the side of the walls facing the canal (Fig. 1). In so doing, contact between the masonry and the water of the lagoon was prevented.

Some continuous courses of Istrian stones, called “cadene”, were placed above the middle see level, in order to create waterproof layers that protected the upper parts of the wall from the rising moisture (Fig. 1). Moreover, the face of each wall in contact with the lagoon water was protected from the aggressive atmospheric agents by spreading hydraulic lime plaster onto (Fig. 1). However, the above-described system improved the performance of the foundation system but not enough to provide a building with adequate capacity to cope with the soft soil.

In order to allow the walls to withstand the differential settlements of the ground, special techniques had also to be used for the superstructure. In some cases, the longitudinal walls (parallel to the canal faced by the building) were not connected to the transverse walls (Fig. 2a), in order to allow the movements of the walls to occur without causing any cracks. In these cases, tie-rods were placed, in order to compensate for the lack of connection between longitudinal and cross walls (Fig. 2b). The tie-rods prevented the out-of-plane collapse mechanism of the walls from occurring and therefore allowed the walls to be slender although without connections at the vertical edges [4,5].

One technique that was always used in Venetian buildings to withstand soil settlements was to use weight-saving construction elements. To this end, the walls were relatively thin (high slenderness ratio) or perforated, and bricks were preferred over stones. Where possible, moreover, the walls were replaced by columns.

In so doing, the vertical structures were space-saving as well, which fulfilled another requirement — namely, to occupy as little space as possible [3].

In order to obtain weight-saving floors, timber beams and boards [6–18] were preferred to masonry vaults and spandrel fill (Fig. 3). The floor-system also included a timber beam, called “rema”, which was placed onto the top of the wall (transverse to the floor beams) to protect from the rising damp the floor beams that rested on (Fig. 3). Conversely, except for the churches, the masonry vaults were used in few Venetian buildings only. Therefore, the curved components of the Venetian buildings consist of members having the appearance of an arch or a vault though not of arch or vault construction (false vaults). A vault-like was made of wattle and daub hung to timber curved beams, which, in turn, were hung to the timber beams of the floor (Fig. 3b). The wattle and daub surface was plastered. Contrary to a masonry vault [19], this system neither is heavy nor transmits any horizontal thrust to the walls.

While the floor’s structure of the Venetian buildings met the weight-saving criterion, conversely, the flooring did not meet this criterion. In fact, the Venetians architects and builders usually used the terrazzo for the flooring of both rich and ordinary buildings, which is a particularly heavy type of flooring. The terrazzo was laid onto the timber boards, which had been nailed to the timber beams; its thickness was never less than 130 mm and often surpassed 200 mm, even up to 250 mm (sometimes more). It is to note that those values refer to the average thicknesses of the terrazzo slabs, since the timber floors that the terrazzo was poured onto were not flat but warped (i.e., cupped).

The typical Venetian Terrazzo floorings can be grouped into three types — namely, lime terrazzo, pastellone, and cement terrazzo. The lime terrazzo was composed of a first layer called “sottofondo”, made of lime and stone or pieces of bricks, whose thickness ranged from approximately 80 to 110 mm. Hence this flooring was named after the first layer. Over this, there was a second layer, called “coprifondo”, made of lime and dust of bricks, whose thickness was from 20 to 50 mm. Over this, there was the final layer, called stabilitura, made of pieces of marble; this third layer was thin (10–20 mm).

The pastellone differed from the lime terrazzo for the second layer, which was made of lime together with powder of brick and marble and had thickness from 10 to 150 mm, and for the third layer, called “pasta”, which was made of lime together with powder of brick or/and marble and was thin (10–20 mm). Hence, this flooring was named after the third layer. The cement terrazzo differed from the lime terrazzo only for the binder, i.e., cement in lieu of lime. Hence, it was named after the binder.

According to the building materials that typify the layers composing the terrazzo and to the way it is composed, the unit weight of a terrazzo ranges from 3.2 kN/m² to 4.5 kN/m². Thus, not only is the weight of the terrazzo high, but above all the terrazzo is drastically heavier than all the other types of non-load-bearing components of the floor as well as of every other building component, either load-bearing or non-load-bearing [20,21].

Hence, the terrazzo seems to be in flat contradiction to all the other construction elements of the Venetian buildings [3]. That analysis suggested that the terrazzo was also uses as load-bearing component of the floor.

2. Research significance

The research presented in this paper aimed at identifying the structural role of the terrazzo flooring in the load-carrying capacity and service-load deflection of floors. Activity was directed at analyzing if the terrazzo provides the timber structures that it rests on
with composite behavior [16,21–26] which guarantees extra-stiffness and extra-strength [5,6,8,10], as well as at carrying out research to help reduce the incidences of structural failure [1,5,7,15,27–35] of timber–terrazzo floors, so as to extend the operating horizons of this flooring system.

Those objectives were pursued by means of laboratory tests on full-scale specimens. The experimental observation and the elaboration of the test results provided the main mechanisms that govern the behavior of the timber–terrazzo floor. Since those findings are comprehensive, they can be generalized and applied to any timber–terrazzo floor, including to interpret the mechanical behavior of this type of floor.

Those findings were also used to develop a predictive theoretical model whose assumptions were derived directly from the experimental data. This analytical model takes into account the contributions that the terrazzo provides the floor with, and therefore the model predictions are reliable.

The model, which this paper presents from the assumptions to the final equations, can be used to provide existing timber–terrazzo floors with adequate behavioral characteristics (stiffness and strength), using the minimal amount of structural work and without altering the way the building reacts to applied loads. Ultimately, the paper provides the means to assess the structural conditions of this type of floors and helps understand how to
rehabilitate existing timber–terrazzo floors simultaneously guaranteeing safeguarding and conservation [1,6–10,24,27,29–38].

3. Experimental tests

This research was based on laboratory tests devoted to detecting experimentally the contribution that the terrazzo provides a timber floor with. The laboratory tests were also devoted to detecting how damage to the timber affects the behavior of the floor.

In order to identify the structural role of the terrazzo, the experiments were performed on two real scale structures differing only for the presence of this Venetian flooring system (Fig. 4). More specifically, the first structure included a floor made of timber beams with transverse timber boards nailed onto (single layer); the second structure included the same timber beams and boards plus the terrazzo on the boards. These floors were subjected to distributed and concentrated downward loads; the differences in behavior were only due to the terrazzo.

3.1. Specimens

The behavior of a timber floor also depends on the supporting vertical structures, since the restraint conditions are dictated by the masonry walls that the floor rests on and is fixed into. In particular, the end-restraint of a timber beam depends on the thickness and brick pattern of the wall underneath the beam as well as on the stresses that the wall above transmits to the end of the beam. Therefore, in order to reproduce the real behavior, the specimens had to avoid scale effects and had to include the masonry walls that support the floor as well as the walls above, including the compression transmitted to the floor’s edges and walls underneath.

Therefore, two full-scale two-story one-bay specimens were designed and fabricated (Fig. 4); the two specimens had the same overall dimensions while they differed from one another (Fig. 5) only in the presence of the terrazzo on the first floor. The total span was 3.24 m, the width 2.85 m, the total height 4.23 m (the height of the first floor was 2.28 m).

The second floor of each specimen was only meant to provide the walls above the first floor with weight, so that the end-restraints of each first floor reproduced the real restraints of historical buildings.

The first level of each test specimen was made up of the floor (first floor) and two supporting masonry walls (first-story walls) having thickness of 250 mm (Fig. 5). The second level was made up of the floor (second floor) and two supporting masonry walls (second-story walls) having thickness of 125 mm (Fig. 5).

All the masonry assemblages were made of brick units and mortar (Fig. 4). The geometry of the walls, the brick pattern, and the mortar composition reproduced the load-bearing masonry walls of historical buildings (Fig. 5).

Timber beams were placed along the top of the first-story masonry walls (i.e., at the intrados of each first floor; Figs. 5 and 6). These transverse timber beams (i.e., directed perpendicular to the span), which collected the ends of the longitudinal timber beams, were the “rema”, which is a recurring component in historical buildings. The width of each rema was 125 mm, i.e., half the thickness of the masonry wall it was inserted into (Fig. 7).

The first floor of each specimen (Fig. 6) was composed of eight parallel timber beams placed 0.35 m apart (one-directional floor), labeled from B1 to B8. Each timber beam had square cross-section with side of 100 mm (Fig. 6).

Each timber beam was accommodated into the entire thickness of the supporting wall. Hence, each timber beam rested for 125 mm onto the rema and for 125 mm onto the masonry wall (Figs. 4, 5 and 7). These transverse timber beams (i.e., directed perpendicular to the span) were connected to the beams with numerous nails, which prevented the former from sliding relatively to the latter (Fig. 6).

The two free edges of the boards (i.e., the two edges perpendicular to the walls) were not in correspondence with the edges of the two perimeter beams (i.e., B1 and B8), but the boards overhung the beams (Fig. 6).

A single-layer timber board was placed onto the beams in the transverse direction. Hence, the boards were perpendicular to the beams they rested on (i.e., normal to the span (Figs. 5). Every timber board had thickness of 30 mm and was connected to the beams with numerous nails, which prevented the former from sliding relatively to the latter (Fig. 6).

The second-story masonry walls were built after having finished the first floor. In so doing, the masonry filled the gaps between the timber beams of the first floor, so that the beams resulted to be fixed into the walls.

The second floor of each specimen was identical to the timber system of the first floor (Fig. 8), i.e., beams and boards. However, the thickness of the second-story masonry walls was 125 mm. Consequently, the second floor was provided with a support different from the first floor, since the latter rested on 250-mm-thickness walls. For that reason, the rema was not placed into the second-story walls. Ultimately, the second floor rested directly on the masonry for a length of 125 mm (Fig. 9).

Once completed the second floor, timber wedges were driven between the extrados of the rema and the intrados of four first-floor-beams, on one side of the floor of each specimen (Fig. 7). These wedges were meant to be progressively removed, so as to progressively modify the end-restraint of the beams.
Therefore, the wedges made it possible to reduce the degree of restraint that the wall provided the beam ends with, which is the main effect of damage on a timber beam. In so doing, damage and its evolution could be reproduced in some tests.

At this point, while the first specimen was completed, the second specimen was finished pouring the terrazzo onto the first floor (Figs. 5 and 6). It is to note that the terrazzo was not poured onto the second floor (Figs. 8 and 9).

Ultimately, the two specimens had the same masonry structure, second floor, and timber structure, while they differed from one another in the presence of the terrazzo on the first floor (Figs. 5, 6 and 8).

The dimensions of each brick that composed all the walls were 250, 125, and 55 mm. The courses of the brickwork that composed the first-story walls were made of two wythes of bricks with the units running horizontally (i.e., stretcher bricks), bound together with bricks running transverse to the wall (i.e., header bricks). The courses of the brickwork that composed the second-story walls were made of one wythe of brick only (stretcher bricks).

The mortar of all the walls was composed of lime (3/12), Portland cement (1/12), sand (1/3) and water (1/3). The thickness of the horizontal and vertical mortar joints was approximately 10 mm. They were made flush the brick’s face.

Masonry elasticity modulus was determined, although it was not involved in the interpretation of the test results; it resulted to be 1767 N/mm².

The timber elements were made of fir-tree. The elasticity modulus of the timber was determined as well, since it is essential to interpret the results from the tests [2,7–9,16–18,26,38–40]. The elasticity modulus of the timber was obtained by performing compression and tension tests on six samples made of the same fir-tree used for the floors. The average value of the elasticity modulus obtained from the tests resulted to be 8454 N/mm².

The terrazzo was built pouring three layers, one onto another. The lower layer was the “sottofondo”, whose thickness was 80 mm and whose unit weight was 2.02 kN/m². This layer rested onto the timber boards. The layer midway was the “coprifondo”, whose thickness was 35 mm and whose unit weight was 0.44 kN/m². The upper layer was the “stabilitura”, whose thickness was 15 mm and whose unit weight was 0.26 kN/m². Hence, the total thickness of the terrazzo was 130 mm (Fig. 6b), which is the typical terrazzo’s thickness of Venetian buildings, especially when the timber system is flat (not warped). The composition of each layer and the unit weight of the components are summarized in Table 1.

The test included the determination of the terrazzo elasticity modulus too, which is essential in order to interpret the test results [41–44]. The elasticity modulus of the terrazzo was obtained by performing compression tests on four cylinder specimens with 200 × 500 mm dimensions, which were made and cast in the same way as the terrazzo poured onto the floor. The elasticity modulus of the terrazzo resulted to be 1213 N/mm².
2. This stage did not surpass the theoretical elastic limit of the timber used. In so doing, the test set-up consisted of a stiff beam that converted the force of the steel cable (tendon) into two forces applied to the beams B4 and B5, respectively. Therefore, the test results were deemed to be accurate.

3.2. Test set-up

For the test set-up, four screws were used in each specimen, in the masonry wall. The second load consisted of a steel cable (tendon), which was applied at a distance of 0.36 m from one of the support masonry walls (Fig. 11). The tendon was tensioned by a hydraulic jack, so as to induce a concentrated load applied to the beams B4 and B5. The bottom of the tendon was fixed to a steel beam, which, in turn, was anchored to the foundation system of the laboratory (Fig. 11). The tendon was fixed to a steel beam placed onto the extrados of the first floor; a hole had been drilled through the timber boards, to let the tendon pass through. In order to obtain two localized loads, two bricks were placed between the steel beam and the timber boards (Fig. 11). The steel beam was then fixed to the boards with four screws. In so doing, the test set-up consisted of a stiff beam that converted the force of the tendon into two forces applied to the beams B4 and B5, respectively.

No loads were applied to the second floor, which hence contributed to the tests with its own weight only.

Displacement transducers were mounted on telescoping poles and placed at the interface of the floors, to measure the deflection profile due to the loadings (Figs. 11 and 12). Displacement transducers were installed at the common boundary between terrazzo and timber boards, to measure the relative displacements (slips) under load. Strain gages were installed on the end of the timber beams, to measure the curvature of the beams at the end-restraints. Displacement, slip, and strain measures were taken during the entire tests.

The measuring equipment was connected to a data acquisition system, which controlled the jack and recorded the measures from the displacement transducers and strain gages.

The data that were collected include the maximum vertical displacement (deflections) as well as the deflections of numerous points of the floors, which provided many load-deflection relationships, the slips, which showed whether the terrazzo and the timber system exchanged in-plane shear force or were independent of one another, and the curvature of the ends of the beams, which revealed the actual restraint that the walls provided the beams with. The test included the surveying, the cracks in the slab of terrazzo at each loading level. Crack survey determined the density of cracks and the locations of cracks due to each load [39–48].

3.3. Test methodology

As above-mentioned, the test methodology consisted of subjecting the two specimens to the same test program. In so doing, the structural role of the terrazzo could be observed. The test program was composed of five stages, which differentiated from each other in the loading and/or the presence of the timber wedges. The same measures were taken during the five stages for the two specimens (Fig. 12).

Stage 1: The uniformly distributed loads (Subsection 3.2) were applied onto the extrados of the floor (Fig. 10). The sacks of sand were laid so as to form a layer, then a second layer, finally a third layer. In so doing, three levels of uniformly distributed load were applied to the first floor at stage 1 — namely, 1.0, 2.0, and 3.0 kN/m². This stage did not surpass the theoretical elastic limit of the timber material.

Stage 2: At the end of stage 1, the concentrated load was applied to the first floor (Subsection 3.2). During the second stage, hence, the first floor of each specimen was subjected to the action of the downwards force induced by the jack plus the uniform load of 3.0 kN/m². The concentrated load was gradually increased from zero up to 20.0 kN. This stage slightly surpassed the elastic limit of the timber, which theoretically was reached for 18.8 kN.

Stage 3: The first floor was unloaded; i.e., first the jack was unloaded and then the three layers of sacks of sand were removed from the extrados of the floor. This stage aimed at detecting the residual deflection (Fig. 12).

Stage 4: This stage and the last one were devoted to damage. Two of the timber wedges that had been placed between the beams and the rema were removed (Fig. 7) — namely, the wedges at one side of the two central beams of the first floor (i.e., under the beams B4 and B5). In so doing, the effects due to decay were simulated, since timber decay usually results in a reduction of the cross-section of the ends of beams. The first floor was then unloaded, in the same way as stage 2.

Stage 5: The first floor was unloaded and two other wedges were removed from the ends of the beams — namely, the wedges at one side of the span of the beams next to the central ones (i.e., B3 and B6). The first floor was then loaded in the same way as stage 2 (i.e., as stage 4).

3.4. Experimental results

The maximum deflections of a beam due to the loadings of stage 1 occurred at midspan. The maximum deflection of a beam due to the loadings of stages 2, 4, and 5 occurred at a point located between the midspan and the distance of 0.33 m from the right support wall (0.33 m was the distance of the force from the wall; Figs. 11 and 12). In order to provide a synthetic representation of the floor’s behavior, the figures presented herein do not show the maximum deflections of each beam due to each load, since these deflections occurred at different positions from each other. Conversely, the figures show the deflections of the beams at a distance of 0.36 m from the midspan. In fact, it was proven that the transverse axis at a distance of 0.36 m from the midspan collects the deflections that are closer to the maximum for each beam under each load than any other transverse axis. Ultimately, all the figures show the deflections of the “reference points”, which are the points of the beams that lie on a transverse axis passing at a distance of 0.36 m from the midspan.

Some of the experimental results are shown in Figs. 13–20. More specifically, Figs. 13–16 show the deflections of the representative points at each stage (i.e., deflection versus position), while Figs. 17–20 for all the stages (load versus deflection). In each figure, the graph “a” refers to specimen 1 and “b” to specimen 2; the comparisons between the graphs “a” and “b” show directly the contribution of the terrazzo to the service-load deflections.

During stage 1, the beams exhibited only marginal differences in behavior from each other. During stages 2, 4, and 5, the deflections were reasonably symmetric with respect to the longitudinal axis (the axis passing midway the beams B4 and B5). Therefore, the test results were deemed to be accurate.
The measures of the slips collected for specimen 2 (with terrazzo) were elaborated to obtain information about the composite behavior of the structure. These elaborations proved that the slab of the terrazzo shifted significantly with respect to the timber boards, which suggested that no significant composite action existed in this floor.

Crack survey showed that, during all the stages, the terrazzo exhibited only few and short cracks, which opened at the bottom of the terrazzo slab, whose depth was much lower than half the thickness of the slab. This result suggested that the terrazzo slab did not reduce its stiffness during loadings.

The experimental strain showed that, during all the stages, the ends of the beams did not exhibit any considerable strain, which suggested that the beams rotated freely relatively to the masonry walls they rested on. Accordingly, the end-restraint was always a hinge.

No substantial residual deformations were observed. In particular, the deflections measured at stage 3 were practically zero, which suggested that the loadings had induced marginal or no inelasticity. Also the deflections measured during stage 5, before applying the new load, were substantially zero.

The comparisons of the deflection profiles due to the concentrated loads only (obtained by subtracting the contributions of the uniform loads from the experimental deflections measured at stages 2, 4, and 5) showed that the curvatures in the transverse direction of the floor without terrazzo were significantly greater than those of the floor with it. This result suggested that the terrazzo significantly increased the load-sharing mechanism between the timber beams.

### 3.5. Discussion

Under the same load, the floor’s deflections of specimen 1 (that without terrazzo) drastically surpassed those of specimen 2 (that with terrazzo). Since the two specimens differed from one another only for the terrazzo, this comparison proved that the terrazzo had a significant structural role.

More specifically, the deflections of the representative point due to (stage 1) an uniformly distributed load of 1.00, 2.00, and 3.00 kN/m², respectively, were 0.98, 2.11, and 3.38 mm for specimen 2, and 3.83, 7.61, and 11.58 mm for specimen 1. Thus, the terrazzo enabled the first floor to reduce the deflections due to a uniform load by approximately 3.5 times.

Moreover, the deflections of the representative point due to (stage 2) the uniformly distributed load of 3.00 kN/m² and a concentrated load of 5.00, 10.00, and 20.00 kN, respectively, were 3.81, 4.54, 6.02 mm for specimen 2, and 13.51, 16.23, 22.84 mm for specimen 1. Thus, the terrazzo enabled the floor to reduce the deflection due to a uniform load plus a concentrated load by more than 3.5 times.

### Table 1

Composition of the three layers of the terrazzo that was built onto the first floor of specimen 2 (the names of the layers are in Venetian vernacular). Unit weights of the components of each layer, in kN/m².

<table>
<thead>
<tr>
<th>Sottofondo</th>
<th>Caprifondo</th>
<th>Stabilitura</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slaked lime</td>
<td>Crushed bricks and tiles</td>
<td>Slaked lime</td>
</tr>
<tr>
<td>0.42</td>
<td>1.62</td>
<td>0.11</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Powdered bricks</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.33</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Slaked lime</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.12</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Marble chips</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.14</td>
</tr>
</tbody>
</table>

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**Fig. 10.** Uniformly distributed load on the first floor. The load was obtained with sacks of sand. Three layers of sacks were laid in three subsequent steps, so as to obtain three levels of load.

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Under the same load, the floor’s deflections of specimen 1 (that without terrazzo) drastically surpassed those of specimen 2 (that with terrazzo). Since the two specimens differed from one another only for the terrazzo, this comparison proved that the terrazzo had a significant structural role.

More specifically, the deflections of the representative point due to (stage 1) an uniformly distributed load of 1.00, 2.00, and 3.00 kN/m², respectively, were 0.98, 2.11, and 3.38 mm for specimen 2, and 3.83, 7.61, and 11.58 mm for specimen 1. Thus, the terrazzo enabled the first floor to reduce the deflections due to a uniform load by approximately 3.5 times.

Moreover, the deflections of the representative point due to (stage 2) the uniformly distributed load of 3.00 kN/m² and a concentrated load of 5.00, 10.00, and 20.00 kN, respectively, were 3.81, 4.54, 6.02 mm for specimen 2, and 13.51, 16.23, 22.84 mm for specimen 1. Thus, the terrazzo enabled the floor to reduce the deflection due to a uniform load plus a concentrated load by more than 3.5 times.

### Table 1

Composition of the three layers of the terrazzo that was built onto the first floor of specimen 2 (the names of the layers are in Venetian vernacular). Unit weights of the components of each layer, in kN/m².

<table>
<thead>
<tr>
<th>Sottofondo</th>
<th>Caprifondo</th>
<th>Stabilitura</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slaked lime</td>
<td>Crushed bricks and tiles</td>
<td>Slaked lime</td>
</tr>
<tr>
<td>0.42</td>
<td>1.62</td>
<td>0.11</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Powdered bricks</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.33</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Slaked lime</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.12</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Marble chips</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.14</td>
</tr>
</tbody>
</table>
Fig. 12. Displacement transducers used to measure the deflections of the timber beams and of the floor.

This result was expected from the qualitative perspective only, while from the quantitative perspective the differences in deflections were much more than expected. In fact, on one hand, the stiffness and strength of the portion of terrazzo included into the tributary area of a timber beam were considerable. On the other hand, however, the terrazzo was not connected to the timber structure by any mechanical element. In particular, no stud shear connectors or bars had been used, and thus the connection between the terrazzo and the timber boards was provided only by interlocking and friction, which were marginal. Moreover, the tensile strength of the terrazzo was low.

The deflection data collected during the load tests were also analyzed in order to evaluate the deviations from linearity of the load–deflection relationship. This analysis showed that both the floors exhibited substantial linear behavior, which was consistent with the marginal residual deflections that had been found at stage 3. More specifically, the deflections of specimen 2 with terrazzo deviated from linearity more than those of specimen 1, but these deviations were however minor. Considering that specimen 1 was without terrazzo, non-linearity of specimen 2 was attributed to some inelasticity exhibited by the terrazzo. Considering that to exhibit the greatest deviations from linearity were the maximum deflections while the other deflections exhibited deviations much lower, nonlinearity was attributed to local effects because of imperfections related to load distribution, shape of the structure, and support conditions.

In order to gain insight into the composite behavior, the experimental slips were compared to the slips derived from modeling the structure as layered without connections. The comparison showed that the interface between terrazzo and timber reduced the relative displacements only marginally, i.e., the slips approached the layered limit. Therefore, no considerable in-plane shear stresses were transferred at the common boundary between terrazzo and boards.

Ultimately, no composite action existed in the floor and therefore the behavior of the floor was the result of the bending stiffness of the timber system and the terrazzo only, but not of the coupling between them. That result was consistent with the cracks observed in the terrazzo, which were few, short, and not deep; i.e., the cracks did not reduce the stiffness of the slab.

With concentrated load (stage 2) applied to the two central beams, the differences in deflections between the two central beams and the other beams of specimen 1 were much greater than those of specimen 2 at any given distance from the wall. For instance, under a force of 20.0 kN (plus the uniform load), the difference in maximum deflections between a central beam and a perimeter beam was 12.6 mm for specimen 1, while it was 1.85 mm for specimen 2. That result proved that the terrazzo had another structural role — namely, it provided the floor with significant two-dimensional behavior. Accordingly, the terrazzo increased the stiffness of the structure not only in the longitudinal direction of the floor but also in the transverse direction.

The deflection profiles from the tests were analyzed using the model of continuous elastic beam resting on elastic supports (i.e., linear springs). In that model, the beam reproduced the transverse behavior of the floor, while the springs reproduced the timber beams. Since all the geometric and mechanical parameters were known except for the width of the ideal beam, this parameter was obtained by calibrating the theoretical deflections against the test deflections. The best agreement between experimental and theoretical deflection profiles was obtained for a width of the ideal beam equal to half the span of the floor.

Ultimately, a point of the floor with terrazzo deflected much less than the same point of the floor without terrazzo; i.e., the ratio between the two deflections was much less than unity for all the points of the floor. While under uniform load the ratio between the two deflections did not depend on the point, under concentrated load the ratio strongly depended on the point; the greater its distance from the force center, the greater the ratio. Hence, the timber–terrazzo floor had significant two-dimensional composite behavior, which was provided by the bending stiffness of the terrazzo slab, although no in-plane (longitudinal) shear actions were transferred between the terrazzo and the timber structure.

Since specimen 2 reproduced the typical terrazzo flooring, the above results can be generalized to the historical floors with terrazzo.

The analysis of the test results obtained at stages 4 and 5 allowed the structural effects of damage to be detected.

The specimens after the removal of the timber wedges from the two central beams (stage 4) did not exhibit significant differences in behavior from the stage before (stage 2). More specifically, the deflections of stage 4 (Figs. 15 and 19) were larger than those of stage 2, but the increases in deflection were moderate for specimen 1 (Figs. 14a, 15a, 18a and 19a) and minor for specimen 2 (Figs. 14a, 15a, 15b, 18a and 15b). The results obtained during stage 5 were almost the same as stage 4 (Figs. 14b, 15a and 19).

Since the curvatures at the end of the timber beams were almost zero already during stage 1 and 2, the increase of deflections observed during stage 4 and 5 was not due to any downgrading of the end-restraint. Thus, the deflections increased because the reduction of the beam ends shifted the center of the contact stresses exchanged by wall and beam towards the external of the wall cross-section, which increased the span. This interpretation was supported by the data, which confirmed that the increase of the beam end span caused the beam’s deflections to increase approximately of the values that had been measured.

The decrease of slopes in deflections observed at stages 4 and 5 proved that the initial connection, i.e., at stage 1 and 2, already behaved as a hinge. Ultimately, the connection between the timber beams and the masonry walls were hinges both with and without the wedges.

That result was consistent with the fact that the ends of the timber beams exhibited significant rotations during the loadings already at stages 1 and 2.

Considering that the end-restraints of the specimens reproduced the typical connection of a timber floor to the supporting walls in historical buildings, the experimental results support two general conclusions. The typical end-restraint of a timber floor, with or without terrazzo, can be modeled as a hinge, which is simultaneously a conservative and a realistic assumption.

Damage to timber beams [2,7,9,11,17,18,40], whose main effect is a reduction of the end cross-section, reduces moderately the stiffness of the timber floors and marginally the stiffness of timber–terrazzo floors. Nevertheless, the reduction in cross-section due to damage implies a reduction in shear strength and in the capacity of the timber beam to connect the opposite walls it rests on; moreover, damage can propagate towards the midspan [6,8,16,33,50,52]. Therefore, damage has to be detected and eliminated [10,12,15,28–30]. However, according to the test results, the increase in deflection is not the way to detect damage to timber floors, especially if they present the terrazzo flooring.

4. Analytical modeling

The test results were used to construct an analytical model that predicts the service–load deflection and stress behavior of timber floors finished with terrazzo flooring. The mechanical assumptions of the model were derived directly from the results of the laboratory experiments (Section 3).

The model presented here was also used to predict the deflections and stresses of timber floors without terrazzo, as specimen 1, although the novelty of this model only lies in its ability to describe the behavior of the timber–terrazzo floor. However, simulating the two laboratory experiments with the same mathematical model allowed unbiased interpretations of the observed behaviors to be obtained.

The reference structure is composed of longitudinal timber beams spaced a given distance apart from each other, transverse timber boards with no gap in between one another, and terrazzo slab onto the boards (Figs. 21 and 22). The reference structure is
symmetric with respect of the longitudinal axis passing through the center of the floor (i.e., to the axis midway the two central beams). Nails connect the boards to the beams, which prevent any considerable sliding of the former relatively to the latter (monolithic behavior of the timber system). Conversely, no elements connect the terrazzo to the timber system; i.e., the former is not restrained to the latter. The reference structure is subjected to vertical static load, which can be uniformly distributed and/or concentrated (Figs. 21 and 22).

The diagram of the reference structure (Figs. 21 and 22) refers to specimens 1 and 2, and the formulation presented herein reproduces directly the geometry of the floors that were tested — namely, eight timber beams, symmetric with respect to the axis midway the beams B4 and B5, subjected to symmetric loads. Nevertheless, the reference structure is general and therefore the formulation can be extended to floors composed of a different number of timber beams and to any type of loads.

Modeling the timber–terrazzo floor consists of addressing three basic issues — namely, (1) how the timber floor and the terrazzo slab work together in the longitudinal and transverse directions, (2) whether a wall prevents the end rotation of the timber beam that rests on it or not and, in case, up to what extent, (3) and how the terrazzo provides the floor with stiffness.

Regarding the first issue, the experimental results showed that no considerable in-plane shear action was transmitted through the common boundary between terrazzo and boards; i.e., no
appreciable composite action existed. That finding, which held true for both the longitudinal and transverse directions and for both uniform and concentrated loads, was consistent with the fact that no connectors joined the terrazzo to the timber system, since the former had been simply poured onto the latter. Moreover, friction strength was almost zero, since the transverse forces were irrelevant in the floor. Thus, the shear action was transmitted only by the interlocking mechanism, whose capacity was marginal [51].

Since this finding is comprehensive, it can be generalized and applied to any timber–terrazzo floor. Hence, the model has to ignore any transmission of in-plane shear action between the boards and the terrazzo (layered behavior of the timber–terrazzo composite floor). Moreover, the model has to consider that, on one hand, timber beams and timber boards are connected to each other, but on the other hand, beams and boards are perpendicular to one another.

Regarding the second issue, the experimental results showed that the ends of the timber beams rotated freely with respect to the supporting walls, since the fibers of the former did not exhibit any significant strain at the ends (i.e., the curvatures of the beams were marginal at the supports). That finding was consistent with the fact that the removal of the wedges from the supports did not increase considerably the deflection of the two floors, which proved that the end-restraints of the timber beams behaved as hinges already in the no-damage state. Ultimately, each connection provided the end of the timber beam with vertical force, but with no significant couple.

Since this finding is comprehensive, it can be generalized and applied to any timber–terrazzo floor. Hence, the model has to reproduce the connection between the end of a beam and the supporting wall with a hinge.
Regarding the third issue, the experimental results showed that the terrazzo followed the deflections of the timber floor it rested on without exhibiting any significant cracks. More specifically, the cracks were small even when the floor reached the timber elastic limit. Hence, the structure found equilibrium before the cracks in the terrazzo propagated significantly, and therefore cracking did not reduce appreciably the bending stiffness of the terrazzo slab.

Moreover, the elastic deflections of the timber floor induced compressive stresses in the terrazzo that were much lower not only than its compressive strength but also than its elastic limit. Ultimately, the terrazzo provided the floor system with its full elastic bending stiffness, in the longitudinal and transverse directions. That finding was consistent with the deflections of the floor finished with terrazzo, which were remarkably lower than those without it. Moreover, that finding was also consistent with the marginal residual deflection found at stage 3 and at the beginning of stage 5.

Regarding the third issue, moreover, the elaboration of the experimental results showed that the transverse behavior of the floor is governed by an imaginary strip whose width (tributary area) is half the floor span, which rests on linear springs that reproduce the stiffness of the timber beams.

Since these findings are comprehensive, they can be generalized and applied to any timber–terrazzo floor. During the elastic deflection of the timber elements, hence, the model has to take into account the full elastic bending stiffness of the tributary areas in both the longitudinal and transverse directions of the terrazzo slab.

Ultimately, the terrazzo slab as a standalone building component would be inadequate; in particular, if it were used as a floor, it wouldn’t guarantee any stiffness and load-carrying capacity. Conversely, the terrazzo as construction material of the floor system helps the timber structure carry the loads, which increases the stiffness and the load-carrying capacity of the floor system.

Accordingly, the terrazzo slab can be envisioned as a grid of adjacent and orthogonal beam strips interconnected continuously along their length, which only bending occurs in, while twisting is minor. The width of the imaginary longitudinal strips is defined.
by the tributary area of each beam. The width of the imaginary transverse strips is equal to half the span of the longitudinal strips; therefore, the transverse strips overlap each other.

Ultimately, the timber–terrazzo composite floor behaves as a grid of strips, interconnected to each other at fictitious nodes. Each strip, which is composed of timber and terrazzo with the two components positioned directly one above another (with their respective centroids vertically above each other), has a certain elastic bending stiffness while its twisting stiffness is negligible. Moreover, the two components do not transmit any in-plane shear stress to one another.

The formulation also includes the damage state of the floor, so that the model possesses all the attributes necessary to provide the designers with the means of predicting the behavior of any historical timber–terrazzo floors. The experimental results showed that damage did not reduce the ability of the end-restraint to transmit bending moment between the timber beam and the supporting masonry wall, since this end-restraint consisted of a hinge already in the undamaged state. Nonetheless, the experimental results showed that the reduction of cross-section at the end of a beam due to damage modified the mutual contact between the beam and the supporting wall, which consequently caused the

![Fig. 19. Load–deflection curves during stage 4. Abscissa: deflection of the reference point. Ordinate: concentrated load applied to the first floor. (a) Specimen 1; (b) specimen 2.](image1)

![Fig. 20. Load–deflection curves during stage 5. Abscissa: deflection of the reference point. Ordinate: concentrated load applied to the first floor. (a) Specimen 1; (b) specimen 2.](image2)
vertical force that the wall provided the beam with to shift towards the outer edge of the wall cross-section. That finding was consistent with the deflections collected during the stages 4 and 5.

Since this finding is comprehensive, it can be generalized and applied to any timber–terrazzo floor. Hence, the model has to reproduce the progression of damage in a timber beam by progressively increasing the span of the beam, from the initial value up to reaching the outer span (i.e., the inner span plus twice the wall thickness).

The experimental results were reproduced by means of four modeling assumptions which allowed the structural behavior to be reproduced — namely, (1) The floor is composed of longitudinal strips, whose width is equal to the spacing of the beams, and transverse strips, whose width is equal to half the span of the beams,
which only elastic bending occurs in, while twisting is zero; (2) The strips of the grid, which are composed of timber and terrazzo, do not transmit any in-plane shear action between the timber system and the terrazzo slab through the common boundary, so that no composite action exists in the structure; (3) The end-restraints of the timber beams are hinges; (4) Damage shifts the application point of each reaction force underneath the ends of the timber beams toward the outer edge of the wall cross-section.

Those assumptions describe the behavior of the timber–terrazzo floor up to the limit of elasticity of the structure, which is dictated by the timber system, since non-linearity due to the terrazzo is moderate, although it starts before than nonlinearity of the timber system.

The behavior of the nth-beam of the floor according to the assumptions is described in the diagrams of Figs. 21 and 22.

According to the assumptions, the damaged state of the nth beam is modeled by increasing its length \( l_{bn} \) (Fig. 21e and f). The application of the model to the laboratory tests increased the span only towards what in Fig. 21 is the right support, since in the tests damage was applied only to this side of the beams. In these applications, hence, the distance \( l_{bn,2} \) between the right support and the vertical force of the nth damaged timber beam was increased by the length of the wedge (half thickness of the wall). Conversely, the distance \( l_{bn,1} \) (i.e., between the left support and the force) was not changed, since no wedge had been placed under the left support of the tested beams. When the model is used to reproduce a floor whose timber beams are affected by damage on both the sides, the span of the damaged beams has to be increased towards both the supports.

The fraction of the distributed load that acts onto the nth beam, which depends on the tributary areas, is denoted by \( q \) (Figs. 21 and 22). The fraction of the concentrated vertical load \( V_{bn} \) (Fig. 22c and d) that acts on the nth beam, which depends on the tributary areas and the stiffness of the components, is denoted by \( V_{bn} \) (Fig. 21c–f); i.e., the force \( V_{bn} \) is the fraction of the force \( V_b \) that is applied to the nth beam.

According to assumption 1, the deflection of a generic point of the nth beam that belongs to the piece of beam of length \( l_{bn,2} \) (Fig. 21) can be calculated as the sum of the deflection due to the distributed load \( q \) and concentrated load \( V_{bn} \) that act on the longitudinal strip:

\[
\eta_{intn,1} = \frac{q \cdot x^4}{24 \cdot E \cdot J} + \frac{q \cdot l_{bn} \cdot x^3}{12 \cdot E \cdot J} + \frac{V_{bn} \cdot l_{bn,2} \cdot x^2}{6 \cdot E \cdot J} - \frac{V_{bn} \cdot l_{bn,2} \cdot x}{6 \cdot E \cdot J} + \frac{V_{bn} \cdot l_{bn,2}}{6 \cdot E \cdot J} \left( \frac{t_{bn,2}^2}{6} \cdot x - \frac{t_{bn,2}^2}{6} \cdot x^3 \right)
\]

In Eqs. (1) and (2), \( x \) denotes the distance of the point that is considered from the wall that supports the left end of the nth beam (Fig. 21).

Moreover, \( E \) and \( J \) denote the elasticity modulus and the cross-section moment of inertia, respectively. The term \( E \) is equal to \( E_{Tz} + E_{T} / \sqrt{2} \), where \( E_{Tz} \) and \( E_{T} \) are the elasticity modulus of the terrazzo and timber, respectively, and where \( J_{Tz} \) and \( J_{T} \) are the cross-section inertia moment of the beam and terrazzo, respectively. More specifically, \( J_{T} \) is the moment of inertia of the timber beam section with respect to the centroidal transverse axis; it does not include the timber boards, since the boards are orthogonal to the beams (i.e., the boards’ fibers are directed along the direction that is orthogonal to the direction of the beams’ fibers). Moreover, the inertia moment \( J_{Tz} \) uses the tributary area of the terrazzo; thus, \( J_{Tz} \) is the inertia moment of a rectangular section whose height is that of the terrazzo and whose width is equal to the distance of one beam from another, denoted by \( l_{wb} \) (in the tests, the contiguous beams were at the same distance from one another). In the particular case of floor without terrazzo (specimen 1) \( E \) is equal to \( E_{T} / \sqrt{2} \).

The force \( V_{bn} \) is the unknown of Eqs. (1) and (2), whose obtainment allows the deflection \( \eta \), in turn, to be obtained. According to the grid behavior (assumptions 1), \( V_{bn} \) can be derived referring to a continuous elastic beam resting on elastic supports, i.e., linear springs (Fig. 23). The springs reproduce the timber beams according to the longitudinal strip model; the elastic beam reproduces the transverse behavior of the floor according to the transverse strip model too. The width of the beam cross-section is equal to half the span of the floor (assumption 1). According to assumption 2, the beam is composed not only of terrazzo but also of timber boards. In fact, the boards are transverse and therefore the fibers of the boards are transverse too.

Ultimately, the moment of inertia of the elastic beam on springs is the sum of the moment of inertia of the terrazzo cross-section and of the board cross-section. The width of each cross-section is equal to half span; the thickness of each cross-section is equal to the actual thickness of the component.

The beam resting on spring model involves two unknowns — namely, the moments \( M \) in the beams at the intersection with the supports (springs), and the deflection \( \delta \) of the supports (Fig. 23a and b).

The symmetry exhibited by the structure and the absence of moment at the first and last intersections reduce the number of unknowns from 16 to 7 (the formulation is developed for a floor with 8 beams), which are the bending moments at the intersections with the supports from 2 to 4, denoted by \( M_{B2}, M_{B3}, M_{B4} \), and the deflections of the supports from 1 to 4, denoted by \( \delta_{B1}, \delta_{B2}, \delta_{B3}, \delta_{B4} \). More specifically, the symmetry condition implies that \( \delta_{B1} = \delta_{B4}, \delta_{B2} = \delta_{B3}, \delta_{B} = \delta_{B2} \) and that \( k_{B1} = k_{B2}, k_{B2} = k_{B3}, k_{B3} = k_{B4}, k_{B4} = k_{B5} \) (Fig. 23a and e; b and f). Moreover, the non-twisting assumption implies that \( M_{B6} = M_{B7} = 0 \).

The equilibrium and angular compatibility conditions allow the 7 unknowns to be found. The 7 equations necessary to obtain the 7 unknowns are herein formulated using the displacement method, where a vertical displacement is assumed to be positive if it is directed downwards and a rotation is assumed to be positive if it is clockwise:

\[
\delta_{B1} = \frac{M_{B2}}{k_{B1} \cdot l_{wb}}
\]

\[
\delta_{B2} = \frac{M_{B3} - 2 \cdot M_{B2}}{k_{B2} \cdot l_{wb}}
\]

\[
\delta_{B3} = \frac{M_{B2} - 2 \cdot M_{B3} + M_{B4}}{k_{B3} \cdot l_{wb}}
\]

\[
\delta_{B4} = \frac{V_{B} - M_{B3} - M_{B4}}{k_{B4} \cdot l_{wb}}
\]

\[
\frac{\delta_{B2} - \delta_{B1}}{l_{wb}} + \frac{l_{wb}}{6 \cdot E_{Tz} / J_{Tz}} \left( -2 \cdot M_{B2} \right)
\]

\[
= -\frac{l_{wb}}{6 \cdot E_{Tz} / J_{Tz}} \left( 2 \cdot M_{B2} + M_{B3} \right)
\]

\[
\frac{\delta_{B3} - \delta_{B2}}{l_{wb}} + \frac{l_{wb}}{6 \cdot E_{Tz} / J_{Tz}} \left( -2 \cdot M_{B3} - M_{B2} \right)
\]

\[
= -\frac{l_{wb}}{6 \cdot E_{Tz} / J_{Tz}} \left( 2 \cdot M_{B3} + M_{B4} \right)
\]
The vertical deflections $\delta_{Bn}$ of the nth beam provided by Eqs. (3)–(9) allows the concentrated vertical load $V_{Bn}$ shared by the nth beam to be determined:

$$V_{Bn} = k_{Bn} \cdot \delta_{Bn}$$

(14)

where $k_{Bn}$ is the stiffness of the beam provided by Eqs. (10)–(13).

Finally, the values of $V_{Bn}$ provided by (14) have to be plugged into Eqs. (1) and (2). In so doing, the deflection $\eta$ of any point of the floor with any pattern of loading can be obtained.

The internal actions can be obtained by calibrating a stress–strain model against the deflections obtained with this model. The model calibration guarantees that, when operating in the linear range, the accuracy of such a new model is almost the same as that of this model.

Since the model is analytical, it also shows the influences of the terrazzo on the deflections of the floor as well as the role of the terrazzo in the distribution of concentrated loads between the timber beams.

5. Application of the analytical model to the tests

The analytical model was used to run simulations of the laboratory tests. The elasticity modula that had been obtained from the tests of timber specimens and terrazzo specimens (see Subsection 3.1) were plugged into the model, which was then solved for the values of $q$ and $V_B$ of stages 1 and 2 (see Subsection 3.3).
The model was also used to run simulations of the damaged state. In these simulations, the span of the timber beams that had been subjected to artificial damage during stages 4 and 5 (i.e., B3, B4, B5, and B6; see Subsection 3.3) was increased with respect to the original value, according to the modeling assumptions (see Section 4).

The analytical results are shown in Figs. 24–29. More specifically, in their part a Figs. 24–26 reproduce the tests of specimen 1, and Figs. 27–29 of specimen 2. In their part b, these figures present the analytical results together with the experimental results reproduced analytically, so as to provide directly the comparisons between test and model. It is to note that the model is analytical and thus the formulation depends only on the representativeness of the assumptions. Thus, those comparisons only verify that the assumptions synthesize accurately and exhaustively the mechanical behavior of the timber–terrazzo floor.

The comparisons between the results from the analytical model and from the tests show that the model reproduces accurately all the displacements of the specimens in the undamaged condition. Not only is this true for the one-dimensional deflections induced by uniformly distributed loads, but this is also true for the two-dimensional deflections induced by concentrated loads. More precisely, the agreement between analytical and experimental curves for stages 1 and 2 is good for the points away from the maximum deflection, whereas it is fair for the maximum deflection as well (Figs. 24–29).
From a qualitative to quantitative perspective, the deflections of the “representative point” (Section 3.4) predicted by the model of specimen 2 (that with terrazzo) for a distributed load of 3.00 kN/m² and a concentrated load of 5.00, 10.00, and 20.00 kN (stage 2) are 4.31, 5.10, and 6.69 mm, respectively. Considering that the corresponding experimental values were 3.81, 4.54, and 6.02 mm, respectively, the differences between the analytical predictions and the measured deflections are of about 10%. This percentage confirms that the model guarantees a reasonable level of accuracy.

It is to note that the deflections predicted by the model of specimen 1 for the same loads were 12.41, 14.21, and 21.44 mm, respectively, against experimental deflections of 13.51, 16.23, and 22.84 mm; thus also these differences were of about 10%. It can be concluded that the deviations between predictions and actual deflections are not due to how the terrazzo was modeled, but to some local effects of timber.

The accuracy of the model of the damaged state is lower than that of the undamaged state, although it is sufficient to provide reliable estimations. For specimen 2 (Figs. 28 and 29), in fact, the differences between the model predictions and the test results were within 30%. For specimen 1, these differences were within 40% (Figs. 25b and 26b); i.e., the model of the floor without
Fig. 28. Specimen 2; stage 4. (a) Deflections of the reference points obtained from the analytical model. (b) Comparison between the analytical predictions and the experimental deflections measured for the reference points during stage 4.

Fig. 29. Specimen 2; stage 5. (a) Deflections of the reference points obtained from the analytical model. (b) Comparison between the analytical predictions and the experimental deflections measured for the reference points during stage 5.
terrazzo was less accurate. The reason is that damage on the floor without terrazzo causes greater effects than to the floor with terrazzo.

The actual deflections of the floor in the damaged state were always lower than the predicted deflections. Thus, the real effects of damage to the timber beams are lower than what assumed in the model. Consequently, the estimations of the model are systematically conservative; hence, the proposed model can be used to assess safety of damaged timber floors.

6. Conclusions

The mechanical behavior of the timber–terrazzo composite floor has been investigated. The first part of this paper has presented experimental results from tests performed at different load stages and with different loadings, on two real scale structures differing only for the presence of the Venetian floor. These results have pointed out the differences in structural behavior between timber floors finished with terrazzo with and without it. Some of the tests also induced damage to timber artificially; the results of these tests have provided information about the structural effects of damage on this type of floor. In the second part of the paper, the experimental data have been used to develop a predictive theoretical model, whose mechanical assumptions have been derived directly from the results of the tests. Finally, the paper has described peculiarities of the traditional structural system.

The results of the tests have shown that the terrazzo slips almost freely with respect to the board that it rests on. Consequently, no significant shear action is transmitted at the common boundary between the timber board and the terrazzo. Hence, no composite action exists in this type of floor.

Nevertheless, the results of the tests have also shown that the terrazzo shares a significant fraction of the load and that this contribution is provided for at least the entire elastic range of the timber system.

Hence, the timber–terrazzo floor, on one hand, is neither a laminated nor a sandwich. In fact, no in-plane actions are transferred between the components. Therefore, the floor’s stiffness and load-carrying capacity are equal to the sum of the stiffness and load-carrying capacity of the components, and not greater, as it would occur in an actual composite structure.

On the other hand, however, the terrazzo has been proven to be a load-bearing component. Therefore, this floor type consists of a structure whose components are both the timber system and the terrazzo slab, although no composite action is transmitted between the timber system and the terrazzo slab. As a result, the terrazzo creates a load-sharing mechanism between the components, which makes the terrazzo share the loads applied to the floor in proportion to its bending stiffness. Moreover, the terrazzo also creates a load-sharing mechanism between the timber beams, which makes the terrazzo distribute part of the load to all the longitudinal beams.

The reason why the terrazzo slab is a load-bearing component of this floor is that the terrazzo does not crack appreciably during the elastic displacements of the timber system. In particular, even for the floor deflection that makes the timber attain (and surpass) its elastic limit, the terrazzo usually exhibits only marginal cracks. Hence, cracking does not reduce considerably the bending stiffness of the terrazzo.

Since the thicknesses of the typical terrazzo floorings are great, the load fractions usually shared by the terrazzo floorings are significant. In particular, the load-sharing mechanisms provide the timber floor of historical buildings finished with terrazzo with much greater stiffness and strength than the same floor without terrazzo. These mechanisms explain why many historical floors have functioned well during the centuries although the timber beams are small. In particular, these mechanisms prove that the presence of the terrazzo drastically reduces the deflections of the floor.

The experimental information from the full-scale structures has allowed the behavior of the timber–terrazzo floor to be described comprehensively by few statements, which have been adopted as mechanical assumptions. Based on these assumptions, an analytical model has been developed, which predicts the linear behavior of timber floors with terrazzo as well as which provides mechanical interpretations of the behavior.

The good agreement between the results from the model and the results from the tests has proven that the mechanical assumptions reproduce closely and exhaustively the actual behavior of this type of floor. In particular, the main assumptions whose validity has been confirmed by the comparisons between theoretical and experimental results are that the terrazzo and the timber are not capable of transmitting to one another any in-plane shear action through the common boundary, that the terrazzo provides the floor with its entire bending stiffness, that in the transverse direction the floor behaves as an elastic beam resting on elastic supports having a certain width, and that the twisting action in the terrazzo slab is negligible.

Another conclusion of this research is that damage to timber beams does not reduce the stiffness of a floor. In fact, damage affects mainly the end of the beams, since it is due to moisture and contact to outer environment. From the structural perspective, damage to a timber beam reduces the end cross-section, which, in turn, reduces the rotational stiffness of the connection, since the end is not fixed into the wall any longer. However, the reduction of the end cross-section has marginal effects on the stiffness, since the connection behaves as a hinge even when the beam is not damaged, and it has no effects on the strength, unless it is substantial. The main major effect of the reduction of the end cross-section is that the contact stresses between a beam and the supporting wall shift from the inner edge to the outer edge of the wall cross-section. This behavior causes the span of the beam to increase. However, the increase in deflection and the decrease in strength due to this effect are not substantial.

That result shows that damage has opposite effects on the safety of timber beams. On one hand, damage does not produce any significant extra deflection, since it usually affects the ends. On the other hand, the increase of deflection does not point out the reductions of the shear capacity of the beam. As a result, if a beam is on the verge of collapsing since damage has reduced the shear-load-resisting capacity of the beam’s ends, its deflection does not exhibit this dangerous condition. However, the terrazzo mitigates this risk, since it can share the load’s fraction not shared by the beams.

Ultimately, the terrazzo slab that finishes the timber floors of many historical buildings has to be considered as a load-bearing element of the construction, in particular of the floor.

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