Diagnostic tests and numerical simulations for the preservation of two stone stairways in the historic centre of Genoa (Italy)

A. Brignola, A. Del Grosso, S. Podestà, S. Resemini & G. Riotto
DICAT, Department of Civil, Environmental and Architectural Engineering, University of Genoa, Italy

ABSTRACT: The study focused on the experimental investigations and numerical analyses regarding the staircases in the interior of two historical buildings (named Caffa and Metellino) in the refurbished area of the docks of Genoa harbour (Italy). Those stairways are made up of stone elements (pink granite of Sardinia Island) and show a particular constructive technique that allows the monolithic steps to be linked together, providing an overall behaviour among steps of a flight and among flights. This technique, suggested by the prescription (or rule of thumb) of various ancient building manuals, allows the stress field to be distributed on each element and it was modelled by means of FEM, in order to verify the effect of this technical measure relative to various load cases. The numerical simulation, carried out through a detailed non-linear solid model of the flights of steps, was preceded by an exhaustive diagnostic campaign (in situ and laboratory tests), useful in order to define, both through direct and indirect tests, the mechanical parameters to be adopted. The obtained results were crucial to preserve the staircases without performing any structural intervention that would have been useless (if not harmful), modifying the architectonical and historical value of the original structure of the stairways.

1 INTRODUCTION

The recent renewal of the dock area of Genoa harbour (Italy) led to the renovations of various historical buildings used as industrial warehouses. The interventions determined the need of verifying the existing structure reliability, with reference to the new end use and the current technical building rules, aiming to preserve their architectonical features.

In this study, the work focused on the experimental investigations and numerical analyses regarding the staircases in the interior of two important buildings (named Caffa and Metellino) in the upgraded area. Those historical stairways are made up of stone monolithic steps.

The constructive technique, suggested by the prescription of various ancient building manuals (de Belidor 1729, Breymann 1885) and implying a particular moulding on each step edge, leads to the structural interaction among the elements. In this way, an overall behaviour of the flights may be achieved.

Nevertheless, current technical building rules do not take into account this constructive technology (monolithic stone elements) for stairs. So, no clear reference is given to the material behaviour that has to be assumed or safety checks which have to be satisfied.

Moreover, even if the constructive details are recommended by ancient rules of thumb and they are effective from the static point of view, a detailed analysis is needed, because no simplified models seem to well reproduce the effect of this technical measure.

The numerical FEM simulation, carried out through a detailed non-linear solid model of the flights of steps, was preceded by an exhaustive diagnostic campaign, useful in order to define, both through direct and indirect tests, the mechanical parameters to be adopted and the presence of crack patterns or defects in each single step.

The obtained results were crucial to preserve the staircases without performing any structural intervention that would have been useless (if not harmful), modifying the architectonical and historical value of the original structure of the stairways.

2 THE HISTORICAL DOCK AREA OF GENOA AND ITS RENEWAL

Since the 13th century, the city of Genoa (Italy) was already a thriving maritime township in the northwestern Mediterranean Sea.

The historical dock area (“Darsena”) of the Old Port was built from the 11th century and it was subjected to various modifications and re-organizations during the ages, in relation to the evolution of the port and the town. Since the first of 14th century, the “Darsena” was organized in order to handle the galleys of the Genoese Republic; moreover, there are warehouses for
the galley repair (“Darsena delle galere”) and storage of goods (“Darsena del vino” or “delle barche”).

In the Renaissance age, during the restoration of the naval dock yard of the Genoese Republic, a tract of the sea water was filled in and the quarters (“Quartieri”) grew up on the new land (Fig. 1).

These are distinct large buildings of a significant architectonic value, due to the excellent expertise in the design of the architects and the skilfulness in building of the craftsmanship.

In the very inside of the docks, the Quartieri Caffa and Metellino were built (Fig. 2). These two twin palaces are connected to each other through a huge glass gallery (Fig. 3), which the main part of their appeal is ascribed to. The morphology of the two buildings is similar, but significant differences, which the peculiarity of each palace is due to, may be noted. In particular, the stairs compartments, being key-points for the ancient end use of the buildings (storehouses) and are object of this study, show the same structural typology, typical of Genoese architecture (Franco 1995), but they are differently located in plan (Fig. 4).

In the last decades, thanks to various funds obtained by Genoa city in relation to important events (Columbus celebrations in 1992, G8 meeting in 2001, European Capital of Culture in 2004), the area of the historical docks was deeply modified. Nowadays, the Faculty of Economics and the “Galata Maritime Museum” are based in the old quarters; from 2004, Caffa, Metellino and Tabarca buildings were restored and they currently house a contemporary music centre (studios, auditorium, etc.) and contemporary-art complex (devoted to permanent exhibitions, artist atelier, bookshop and other shops), as well as a civic centre, having a multifunctional room for exhibitions and meetings, to be used by local associations.

The modification of their end use led to a complete verification of the static behaviour of the previously mentioned palaces. In particular, this work may be included into this ambit, among which the main staircases of Caffa e Metellino palaces are under investigation.
3 THE STAIRCASES OF CAFFA AND METELLINO PALACES

The staircases of Caffa and Metellino palaces are made up of stone elements (pink granite of Sardinia Island) and show a particular constructive technique that allows the monolithic steps to be linked together, providing an overall behaviour among steps of a flight and among flights.

The lack of indications, in current technical building rules, about how to model and verify the static behaviour of stairs made up of monolithic stone elements rules led to perform in depth analyses.

Numerical FEM simulations through a detailed non-linear solid model of the flights of steps and an exhaustive diagnostic campaign, aimed to characterize the material mechanical parameters and to identify the presence of defects in the stone elements, were carried out. Besides that, an accurate historical investigation about the ancient building technology in case of monolithic stone stairways seemed to be very important.

3.1 Historical and technological aspects

In many ancient building manuals, technical characteristics and constructive details of the monolithic stone stairways are described. Generally, they are made up of large freestone elements. In his treatise “Wooden, stone and brick stairs” (1885), Breymann wrote “Using freestones, one may obtain very strong, durable and nice stairs and also very easy to build”. In a few words, he highlighted the main features of this typology. In Figure 5, the original drawings are shown.

The section shapes of the step are various: starting from the simpler rectangular profile, up to more elegant ones, characterised by moulding, carving or special intrados outline, aiming to give a more aesthetic sight from below, but also to facilitate the flight construction.

The way through which the steps are laid one upon the other depends on the support typology of the step edges: they can be fixed in the masonry walls on each side or they can be simply supported by beams, walls or arches.

According to Breymann, in case of fixed supports of the edge, having at least an insertion depth equal to 10–12 cm, the step overlapping could be only necessary to hide the back of the element and ensure the laying clearance; the overlapping distance may be minimal (4–6 cm, as in Figure 5, image 466). If, on the contrary, one or both the edges of the step are free-standing, the element superposition is needed to avoid relative displacements among them. In this case, an almost 2 cm moulding has to be trimmed. The shape can be various: the profiles in Figure 5, images 464 and 465, aim to avoid the movement of the step, by means of a of 2–3 cm backing. The same scope may be identified in the 6 cm trim shown in Figure 5, image 467.

The geometry of the staircases in the interior of Caffa and Metellino palaces is ascribable to this last typology. However, in the examined stairs, the superposition of the shaped steps, regards elements having their edge fixed in the walls for about 20 cm (Fig. 6). So it can be presumed that those structures, relying on both the housing in the masonry walls and the overlapping of the steps through the moulding, show a good behaviour in relation to loads applied on them.

According to what specified in the “Traité théorique et pratique de l’art de bâtir” (Rondelet, 1802), the behaviour of the open staircases, that are stairs only supported by the moulded shape of the steps, is independent from the presence of a beam propping up...
the parapet: “The step chase along the walls and the landing constraint [at turn of stairs] provide, together with the moulding and the superposition, an ingenious system that stands up well without beams … [omissis] … It is essential observing that in stairs without beams, when the mouldings are not sufficient, the minimal movement can lead the step to rotate and slide out of the mouldings if: 1st their chase in the wall is not sound, 2nd it does not have a sufficient depth, 3rd as a consequence of the movement, the steps fail along their span. The beams added to the stairs, in any way they are built, have the advantage of fixing the steps at each end, preventing them to slide out of the mouldings, being constrained by the wall, on one side, and by the beam on the other”.

Therefore, from what Rondelet suggested, the granite staircases of Caffa e Metellino palaces are in agreement to the rules of thumb. Moreover, standing that the elements are fixed in the walls on both sides, the troubles described by Rondelet should be presumably warded off.

Nevertheless, even if the constructive details are recommended by ancient rules of thumb, more detailed studies are needed to enforce that they are effective from the static point of view.

3.2 Geometry of the staircase

The analyses focus on the staircases in the interior of Caffa and Metellino palaces. Those stairways are made up of stone monolithic steps and the previously described constructive technique allows these elements to be linked together. In Figure 7a-b, an overall view of the staircase is proposed.

The geometry considered for each single step is representative of the most part of the stone elements. In fact, each flight is sensibly similar in terms of dimensions and very low scatter was found by the survey analysis of the complete staircases in the two palaces.

On the safe side, the most conservative hypotheses on the geometry were assumed. In Table 1, data of the geometric model are reported, focusing on the dimensions significant for the FEM model; the nomenclature is in Figure 7c.

The free span of the step results from the detailed in-situ geometric survey, while its total length derives by a realistic hypothesis (enforced by examples of similar constructive typology in other case studies) of a 0.2 m deep insertion in the masonry walls on each side.

This aspect was however a posteriori partially confirmed by the information obtained by technicians working on the building restoration, who directly checked the considerable chase depth of the stone step in the walls.

4 EXPERIMENTAL CAMPAIGN

The lack of indications, in current Technical Building Rules, about the mechanical parameter of monolithic stone elements led to perform detailed experimental tests.

During renewal works, some slabs, with the size of half a step, were found. Some of them were used directly for bending destructive test.

Table 1. Geometry of the stone step.

<table>
<thead>
<tr>
<th>Dimensions</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Total height H (m)</td>
<td>0.19</td>
</tr>
<tr>
<td>Total depth B (m)</td>
<td>0.39</td>
</tr>
<tr>
<td>Moulding height h (m)</td>
<td>0.05</td>
</tr>
<tr>
<td>Moulding depth b (m)</td>
<td>0.05</td>
</tr>
<tr>
<td>Total length (m)</td>
<td>3.4</td>
</tr>
<tr>
<td>Free span L (m)</td>
<td>3.0</td>
</tr>
</tbody>
</table>
Table 2. Results of compression tests.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Diameter (cm)</th>
<th>Length (cm)</th>
<th>( f_c ) (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slab 1/2</td>
<td>7.3</td>
<td>14.6</td>
<td>143.36</td>
</tr>
<tr>
<td>Slab 2/1</td>
<td>7.3</td>
<td>14.6</td>
<td>109.43</td>
</tr>
<tr>
<td>Slab 3/1</td>
<td>7.3</td>
<td>14.4</td>
<td>129.98</td>
</tr>
<tr>
<td>Slab 3/2</td>
<td>7.3</td>
<td>14.7</td>
<td>133.80</td>
</tr>
<tr>
<td>Slab 3/3</td>
<td>7.3</td>
<td>14.6</td>
<td>138.58</td>
</tr>
<tr>
<td>C 1</td>
<td>7.3</td>
<td>14.5</td>
<td>96.05</td>
</tr>
<tr>
<td>C 3</td>
<td>7.3</td>
<td>14.6</td>
<td>99.39</td>
</tr>
<tr>
<td>M 1</td>
<td>7.3</td>
<td>14.5</td>
<td>100.35</td>
</tr>
<tr>
<td>M 2</td>
<td>7.3</td>
<td>14.5</td>
<td>110.38</td>
</tr>
</tbody>
</table>

Mean 117.92  
Standard Deviation 18.48  
5% Percentile 97.39

From the others, we obtained cylindrical samples that were used to determine uniaxial compression strength, uniaxial tensile strength and density (it turns out to be 2618 kg/m^3).

As well as these partially destructive tests, sclerometric, direct and indirect ultrasonic tests were carried out (non-destructive tests).

The extensive experimental campaign aims to obtain a statistical characterization of mechanical parameters and, possibly, to identify local defects in the steps.

Considering the age of the structure and the material, which the stairs are made up of (not commonly used in modern constructions), this kind of analysis was considered essential to preserve these attractive buildings in their original form and, at the same time, to ensure a suitable safety level.

4.1 Test set-up and data processing

For the sake of brevity, in the following, only the tests that were used to define numerical analysis parameters are reported. Setup, data processing and results of these tests are described.

4.1.1 Compression tests

The cylindrical samples were subjected to compression test to identify the uniaxial strength. The failure point is the loss of proportionality between the constant load increment and the deformation.

In Table 2, uniaxial compression strength, diameter and length for each sample are reported.

4.1.2 Indirect tensile tests ("Brazilian" tests)

In order to estimate the ultimate tensile strength, the so-called “Brazilian tests” were performed, according to UNI EN 12390-6/2000. These tests are based on the fact that a cylinder subjected to a line load on two opposite diameters will break due to the orthogonal tensile strength (Fig. 8).

In Table 3, uniaxial tensile strength, diameter and length for each sample are shown.

4.1.3 Ultrasonic tests

Ultrasonic tests provide a measurement for the “time of flights” of ultrasonic waves in the material. Hypothesizing the wave paths, the velocities may be obtained. They were used to verify the structural element homogeneity, localize possible reduction of material properties (e.g. cracks or cavity) and to estimate the value of Young’s modulus.

During experimental campaign, two different type of ultrasonic test were performed: direct test (i.e. receiver and emitter are placed on two opposite side of the step) and indirect test (i.e. emitter and receiver are placed on the same side of the step).

4.1.3.1 Direct ultrasonic tests

Direct tests were carried out near the landing at turn of stairs, where the sensor can be placed on the two opposite side of the steps. The resulting velocity was processed to obtain the p.d.f. (probability density function), as in Figure 9, and to estimate the
4.1.3.2 Indirect ultrasonic tests

Indirect ultrasonic tests were performed on every single step of the two stairways, in order to obtain a wide set of values that may represent a significant statistical sample.

The “time of flight” was obtained placing the receiver on the “first column” (the black one in Figure 10) and moving the emitter in the other three different positions on each step.

The processing phase of these tests is a little more complex than the direct ultrasonic ones, due to difficulty in the estimation of the wave path. For this reason, it was decided to divide the data in three different sets, one for each horizontal distance between the sensor (i.e. 70 cm, 140 cm, 210 cm). In this way, the possible error in the path estimation was minimized.

Figure 9. Probability density function of direct ultrasonic velocity of Metellino palace.

Figure 10. Indirect ultrasonic test setup.

dynamic Young’s modulus that turns out to be around 30,000 MPa (mean value) with modest variability.

4.1.3.2 Indirect ultrasonic tests

Indirect ultrasonic tests were performed on every single step of the two stairways, in order to obtain a wide set of values that may represent a significant statistical sample.

The “time of flight” was obtained placing the receiver on the “first column” (the black one in Figure 10) and moving the emitter in the other three different positions on each step.

The processing phase of these tests is a little more complex than the direct ultrasonic ones, due to difficulty in the estimation of the wave path. For this reason, it was decided to divide the data in three different sets, one for each horizontal distance between the sensor (i.e. 70 cm, 140 cm, 210 cm). In this way, the possible error in the path estimation was minimized.

For each distance, the p.d.f. of the velocity was obtained (Fig. 11) and the extreme values were analyzed in detail. It results that the state of preservation of the stair is essentially homogeneous.

Thanks to this wide experimental campaign, the results of the following numerical analyses can be reasonably extended to the whole stairways of both the palaces.

5 NUMERICAL ANALYSES

In order to assess the structural safety of the ancient stone stairways of Caffa and Metellino palaces, a set of numerical simulations, using the code ANSYS rel. 8.0, were performed.

The numerical analyses have a double role. On the one hand, they are useful in evaluating stress and strain fields in case of the loads prescribed by the Italian Technical Building Rules (2005). On the other hand, these simulations were carried out aiming to assess the safety coefficient (in terms of load multiplier) with reference to live loads. Those may be due, for example, to crowding.

In order to come through the computational effort required, the FEM model simulates an assemblage of six steps. Nevertheless, this is representative of the overall behaviour of one stairway.

In particular, aiming to study the static behaviour of the steps in the middle and at the end of the staircase, it was checked that adding other elements does not influence (conceptually and quantitatively) the behaviour.

5.1 General description of the FEM model

The numerical simulation, preceded by an exhaustive diagnostic campaign and geometrical survey, is particularly useful when dealing with the historical heritage.
In this framework, the development of very accurate models is generally required, both in case of service loads (for which cracks formation may represent a condition to avoid) and ultimate limit state. In fact, non-linear analyses may give information, by means of incremental analysis, about the collapse, but the models should be able to reproduce the limited tensile strength and possible crushing of stone material, the frictional behaviour on the contact surface of the moulding.

To this aim, the modelling was carried out through a detailed non-linear solid model of the flights of steps, focusing on effectively describe the interface behaviour.

Brick elements (SOLID65) are used to model the stone material of the monolithic steps. The frictional behavior on the contact-planes (horizontal and vertical) of the moulding is simulated by CONTACT52 elements.

In Table 4, the basic information about the FEM model, made up of 34630 elements and 41124 nodes, are provided.

The boundary conditions of FEM model are intended to simulate two situations, related to different hypotheses of interaction between the step and the masonry walls:

- Model A: displacements along Y and Z axes are avoided on the bottom surface of the steps, in correspondence of the insertion surface of the step (0.2 m in depth) in the wall. This condition aims to simulate structural fixed ends (Fig. 12).
- Model B: displacements along Y and Z axes are avoided on the bottom of the steps, in correspondence of the chase of the step in the wall. A line of nodes only (0.2 m in distance from each ends of the step) is constrained, in order to enable the rotation, aiming to simulate structural hinges.

The actual condition is intermediate between the analysed ones; due to the chase depth in the walls, it is probably better described by Model A.

Moreover, the steps at both ends of the flight need to be realistically constrained. On the bottom one, the vertical support of the masonry arch below (Fig. 7b) and the horizontal constraint of the floor have to be simulated. On the top step, instead, horizontal constraints are needed to model the interaction of the step and the landing at turn of stairs, made up of stone slabs having the same thickness. All this kinds of constraints behave obviously as compression-only elements.

5.1.1 Mechanical parameters

The pink granite stone mechanical characteristics are derived by the experimental test campaign previously described.

In the FEM simulations, in the elastic range, a linear isotropic constitutive law was assumed. This kind of behaviour can be appropriate to satisfy the requirements of the safety check, serviceability and ultimate limit state, of the Technical Rules (2005).

The values of the mechanical characteristics assumed correspond to the average of the statistical distribution of each quantity (in case of Young's modulus $E = 30,000$ MPa, the value is derived by the experimental tests on the stone of the Caffa palace).

Moreover, the non-linear behaviour is modelled through the CONCRETE model (enclosed in the ANSYS 8.0 library), whose constitutive law simulates the limited tensile and compressive strength of stone material. The failure surface in the stress domain is represented by a law that depends on the hydrostatic stress, as Mohr-Coulomb or Drucker-Prager ones. Cracking along three orthogonal axes and crushing are allowed and five failure-surface parameters have to be assigned. If only two ($f_t$ and $f_c$) are set, the failure surface is defined as in Willam and Warnke (1975).

The non-linear parameters in terms of strength values are obtained as the 5% percentile of the stochastic distribution of the experimental results. In the model, the uniaxial tensile strength is set $f_t$ equal to 7.52 Mpa and the uniaxial compressive strength $f_c$ to 97.39 Mpa.

The stiffness parameters of the contact element on the interface of the step moulding are assumed to simulate the interaction effect (equivalent Young's modulus equal to 30,000 MPa). Being difficult to have an estimation of these quantities, it was verified that their variation among a pre-defined range does not significatively affect the results.

The frictional coefficient on the contact surface is set equal to 0.5.
5.2 Scheme of the numerical simulations

Two analysis phases were carried out: in the first one, the load cases prescribed by the technical rules (ultimate and serviceability limit state) were imposed and, in the second one, the behaviour related to incremental loads was studied.

**Phase 1**: on the two models (A and B), the following analyses were performed:

- **LC1 (ULS)**: \(1.4 G_k + 1.5 W_{k1}\)
- **LC2 (SLS)**: \(G_k + W_{k1}\)

where \(G_k\) is the dead load and \(W_{k1}\) is the live load (equal to 4 kN/m\(^2\) in case of common stairs);

- **Phase 2**: on the two models (A and B), the analyses carried out concerned the monotonic increase of two load typologies (uniform pressure on every step and transversal line load on the central step), after the dead load assignment.

It has to be noted that, in case of Phase 1, the behaviour is very far from the inelastic range; so, it was verified that the action assignment in two subsequent stages or the concurrent loading did not lead to different results (i.e., the effect superposition is still correct).

In both cases, live loads were assigned to the walking surface of the steps.

5.3 Analysis results

In the following, the main results obtained from the numerical simulations are discussed. Special emphasis is put on the evaluation of interaction effects among the steps.

5.3.1 Phase 1: technical rule requirements

As previously noticed, the analyses results may be useful in order to obtain some information about the serviceability and structural safety of the stairways, according to Italian Technical Building Rules.

In case of SLS, the mid-span vertical displacement is maximum in the central steps of the flight: with reference to Models A and B, it is equal to 0.06 mm and 0.07 mm respectively. Those values are both much lower than the limit displacement \(L/400\) (7.5 mm).

In case of ULS, the stress field in Model B is higher. The extreme values (in terms of average nodal stresses) are reported in Table 5.

From these results, it can be highlighted that the stress state is much lower than the material strength. This is much more significant if one considers that those values are concentrated in very narrow areas, near the constraints: the safety evaluation is amply conservative.

Focusing the attention on longitudinal sections of steps, corresponding to the portion near the supports and the mid-span one, interesting remarks about the structural performance may be obtained (Fig. 13). Checking the direction of minimum principal stress \(\sigma_{III}\), in the the mid-span section, some sort of strut, due to the transfer of compressive forces through the steps, may be identified. This phenomenon appears, thanks to the moulding, in both the models. Along the

<table>
<thead>
<tr>
<th></th>
<th>MODEL A</th>
<th>MODEL B</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\sigma_I)</td>
<td>1.03 MPa</td>
<td>1.76 MPa</td>
</tr>
<tr>
<td>(\sigma_{III})</td>
<td>1.88 MPa</td>
<td>2.67 MPa</td>
</tr>
</tbody>
</table>

Figure 13. Model B – USL stress state. Direction of maximum (a–b) and minimum (c–d) principal stresses.
lateral section near the supports, the behaviour seems instead to be more affected by torsional effects.

The strong interaction among the steps of one flight, revealed by the formation of the strut in the numerical simulations, confirms once more the static intuitions of the ancient builders and engineers.

5.3.2 Phase 2: incremental analysis

After the dead load assignment, two load typologies (uniform pressure on every step and transversal line load on the central step) were monotonically increased.

5.3.2.1 Uniform pressure

With reference to uniform live load, even the nominal action amplified more than 15 times does not cause significant damage pattern in the steps. In case of $W_{k1}$ equal to 72 kN/m², only slight cracking phenomena develop near the supports (Fig. 14).

In both the models, crushing states are not evident and, in fact, during the loading phase, the principal stress $\sigma_{III}$ has not reached the surface of the failure domain. The higher obtained values for $\sigma_{III}$ are 12.6 MPa (Model A) and 22.9 MPa (Model B). Even in this case, the stress peaks are located near the constraints (Fig. 15).

Observing the failure pattern, it can be noted that, in Model A (as Rondelet wrote), the described constructive technique leads these elements to be more effectively linked together.

The force transfer through the moulding is more evident in respect to the other model, in which the rotation of the ends of the step is allowed. In fact, the lower steps are more loaded in compression in correspondence of the mid-span point than the upper ones; this force transfer lead the vertical planes in correspondence of the fixed ends to be subjected to high tensile stresses and cracking develops in the lower part of the flight.

Further increase of the uniform pressure is not investigated, because the hypothesis of fixed constraints at the ends of the step (modelling the effect of the masonry walls) would have been not totally correct. In fact, higher loads in the masonry could
Figure 16. Model A – line load. Direction of minimum principal stress.

have led to local crushing and stiffness degradation of the supports. This condition has not permitted the investigation of the stair behaviour for the highly non-linear range. Nevertheless, this kind of load seems not to affect significantly the safety of the structure.

5.3.2.2 Line load
Assigning the transversal line load on the central step (along X-axis), some information about the non-linear behaviour modification is achieved.

A final value of 7.5 kN/m is reached, pointing out slight cracking located on the central step itself, near the supports.

Also in this case, the highly non-linear range can not be studied, due to the unrealistic boundary conditions which further load increase would have led to.

In Model A, the force transfer through the moulding is less evident in respect to the uniform load (Fig. 16).

In the mid-span section, the strut, due to the transfer of compressive forces through the steps, is not identifiable anymore. Moreover, even the torsion effect near the supports cannot be highlighted.

From the result review, one can put forward that the direction of the minimum principal stress is almost orthogonal to these longitudinal sections. This may be explained through the creation of a transversal line of thrust along each single step (especially the loaded one). In this way, the load is directly transferred to the supports of the step, achieving only partially the overall behaviour of the stairway. Nevertheless, the lower steps seem to interact with the loaded one.

6 CONCLUSIONS

The significance of synthesis and comparison of data from different ambits, in order to obtain a more detailed and more realistic overview of the problem of safety and conservation of historical structures is evident.

This study provided an exhaustive investigation of the two stone stairways of Caffa and Metellino palaces, having the aim of preserving them without performing any structural intervention.

Combining the elements from the in situ and laboratory testing, from the historical studies and from the numerical simulations, it was demonstrated that the original conception of the granite monolithic stairways is amply safe, even in relation the modification of their end use. So, it is clear that no retrofitting intervention is needed.

On the other hand, the contribution of FEM investigations played a fundamental role in achieving another goal: by means of non-linear incremental analyses, the structural effect of an ancient constructive technique (moulding and superposition of the steps of a flight) was examined and understood.

The research confirms that, in this case, the static perception of ancient builders and engineers is essentially validated and it states once more that if a larger part of the past knowledge would have been transferred, useless (and sometimes harmful) structural modifications could be avoided.

REFERENCES

de Belidor B.F. 1729. The engineers’ science by de Belidor with notes by Mr Navier. Italian translation by Luigi Masieri, Milan, Truffi, 1832 (in Italian).