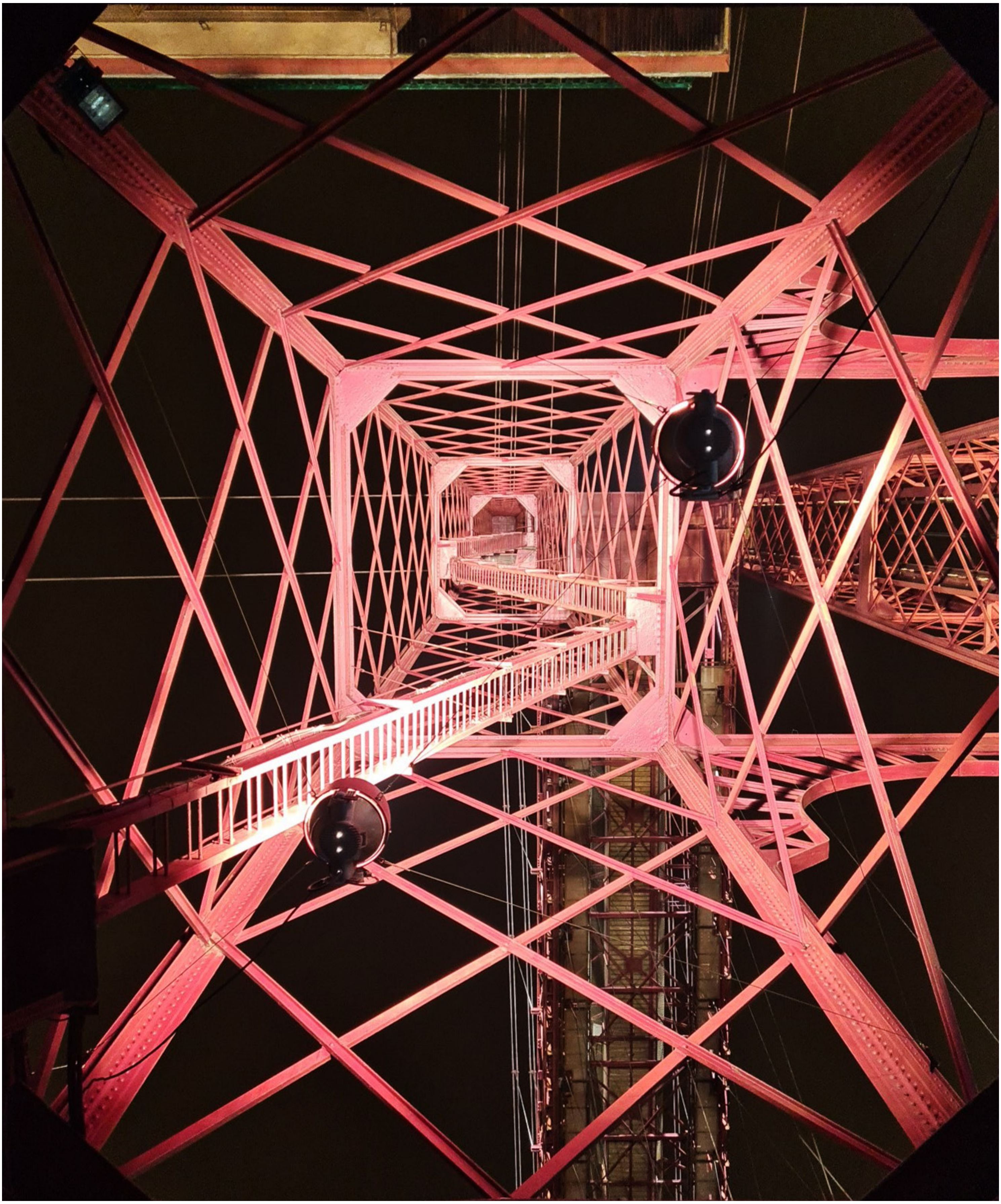

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BRICK MASONRY STAIRCASES OF THE EARLY 20TH CENTURY: HISTORICAL RESEARCH, CONDITION ASSESSMENT AND DIAGNOSTIC INVESTIGATION OF A "TRANSITION" CONSTRUCTION TYPE

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Abstract

Staircases play a key role in the rehabilitation and retrofitting of historic public buildings in terms of respecting building regulations for fire protection, accessibility and seismic resistance. Assessing their construction materials and techniques, as well as their current condition and residual performances, are paramount in order to employ effective, compatible and low-intrusive conservation measures. In particular, staircases dating back to the early 20th century call for a comprehensive understanding of technical and technological solutions. This is because they were conceived in a "transition" phase from traditional masonry structures to modern systems based on the employment of metal elements. Thus, they show a variety of hybrid solutions, often depending on the local practice and the specific application. Consequently, historical research from technical handbooks of the time should help define the purposes and boundaries of the diagnostic investigation of characteristics and pathologies. Additionally, both documentary records and on-site/laboratory tests should support the identification of potential local failures, which are generally omitted in global analytic simulations. In the light of the above-mentioned issues, the paper provides an overview of the historical evolution of masonry staircases of the early 20th century, with a specific focus on brick structures in central-southern Italy. Based on the most documented systems and the most recurring pathologies, this research outlines a methodological framework for on-site and laboratory diagnostic investigation, aimed at the identification of construction materials and techniques, detection of decay patterns and characterisation of mechanical performance. The proposed framework is applied to a case study, the monumental staircase of a school building, and some insights into the operational procedures are also addressed.

Keywords

Historical handbooks, Masonry staircases, Mixed structures, Building pathology, On-site diagnostics.

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1. INTRODUCTION

Staircases play a key role in the rehabilitation and retrofitting of historic public buildings in terms of respecting building regulations on fire protection, accessibility and seismic resistance. To this end, the well-established pipeline of anamnesis, diagnosis, therapy and controls should move from the correlation of direct observation to historical research, structural analysis, experiments and tests [1] so that the accurate assessment of construction materials and techniques, as well as of current conditions and residual performance, might address effective, compatible and low-intrusive conservation measures.

The review of the state-of-the-art points out that most studies on masonry staircases, mainly located in the Mediterranean area and based on the Roman building tradition, are focused on the evaluation of their structural stability and earthquake response [2–5]. However, the analytical models are necessarily based on simplified typological schemes. Thus, although essential for understanding the overall behaviour of a system, they should be integrated with detailed qualification of technical-technological characteristics and state of conservation in order to identify local vulnerabilities and failures that are generally omitted in global system simulations. Consequently, documentation as a holistic approach to the collection and interpretation of data related to history, geometry, construction, pathology and performance is usually the most fundamental and crucial process that can affect and facilitate any required procedures to preserve and safely operate heritage buildings [6].

The above-mentioned issues are particularly relevant whenever the technical solutions belong to a relatively short period and/or to the local construction practice because they might be less documented in terms of scientific research and practical case studies. In this sense, brick staircases dating back to the early 20th century are representative. In fact, they were conceived across a “transition” phase from traditional masonry structures to modern systems with metal elements, which were initially employed as local reinforcement and afterwards as structural members completed with non-structural brick blocks. Thus, they show a variety of hybrid systems, often depending on the specific site and requiring comprehensive technical and technological understanding, based on the above-mentioned integration of documentary records, direct surveys and experimental measurements toward phenomenological and analytical modelling.

According to the recalled research lines, the paper provides a description of the historical evolution of brick masonry staircases between the 19th and 20th centuries in central-southern Italy, based on technical handbooks and inventories on the most common construction techniques. Thus, a methodological framework is proposed for on-site and laboratory diagnostic investigation, aimed at the identification of construction materials and techniques as well as detection of decay patterns and characterisation of mechanical performance. The framework is discussed and validated in a case study, the monumental staircase of a school building, where some insights into operational procedures are also addressed.

2. RESEARCH BACKGROUND

2.1. HISTORIC OUTLINE

The employment of bricks between the 19th and 20th centuries for building masonry staircases is widely documented in several geographical areas, in general in Europe [7, 8] and in particular in central-southern Italy [9–12], where the Roman founded construction practice inspired the building tradition until pre-modern times and then radically evolved as a result of the nascent and revolutionary technology of reinforced concrete. According to a well-established classification, the staircases in historic buildings might belong to two main types: the former has a central structure, either linear (walls) or punctual (pillars, columns) with elements that «cooperate with the perimeter walls as further creating a second support for the steps or for the elements on which they rest»; the latter is supported only by the border cage, and it is preferred in order «to take advantage of the lighting from above» and «give the staircase a light, pleasant appearance» [13]. With a specific focus on central-southern Italy, the second type was mainly used with the development of a peculiar sub-type, known as the “Roman” staircase. In general, these are stairs with landings on barrel or cross vaults and flights on a barrel, lame barrel, low barrel or cross vault, cantilevered on the longitudinal walls with mutual contrast of the flights. The intermediate landings are typically built as half-pavilion intersections of the inclined vaults of the flights. Alternatively, the flights might be supported by rampant vaults whose generator line is perpendicular to the slope. In this case, their intersection with the landing is more complex, from both the geometrical and constructional point of view, due to the relevant thrusts of the rampant, which often require the construction of transverse connecting arches. Finally, further variants concern «systems of rampant vaults that have the lower shutter on the side of the previous rampant vault and the upper shutter on the opposite wall and so on» or stairs «with self-supporting steps so that it is not necessary to prepare an underlying structure to lay on» [13].

The construction materials used mainly depended, in central-southern Italy as elsewhere, on the geographical area with prevailing solutions in both natural [11, 12] and artificial [9, 10] stone. In the case of brickwork, the blocks are generally arranged in two or three courses with stretchers along the longitudinal section of the flights. The steps are typically made of marble or travertine and rest on a filling of mortar and stone aggregates. Furthermore, as regards the planimetric layout, in most cases, there are two parallel flights or, alternatively, three flights, two on the long side and one on the short side opposite the floor landing. However, there is no lack of more complex solutions, such as polygonal, oval, curved or, in the case of monumental stairs, pincer flights, to amplify the perspective effect [14]. The above-mentioned general features were predominant until the end of the 19th century, whereas from the beginning of the 20th century, similar construction solutions began to be integrated with metal elements. At an early stage, the metal elements were used as a support/reinforcement of the primary masonry structure, and they were often hidden in order to «show convenient decoration [...] in harmony with the other parts where the stairs are located» [15]. These are generally U or double T-shaped metal profiles, arranged longitudinally on the free side of the flight, connected to the surrounding walls by transverse iron tie rods and to the landings by transverse iron beams (Fig. 1). Latterly, in analogy with the evolution of slabs and balconies, the metal elements were used as bearing joists [14, 16], either parallel or perpendicular to the flight slope, and completed by light hollow brick tiles, both flat and curved (Fig. 2). In this case, if the iron joists are parallel to the flight slope, they are placed on both sides of the flight, at the interface with the perimeter wall and the stairwell to withstand the thrust of the brick

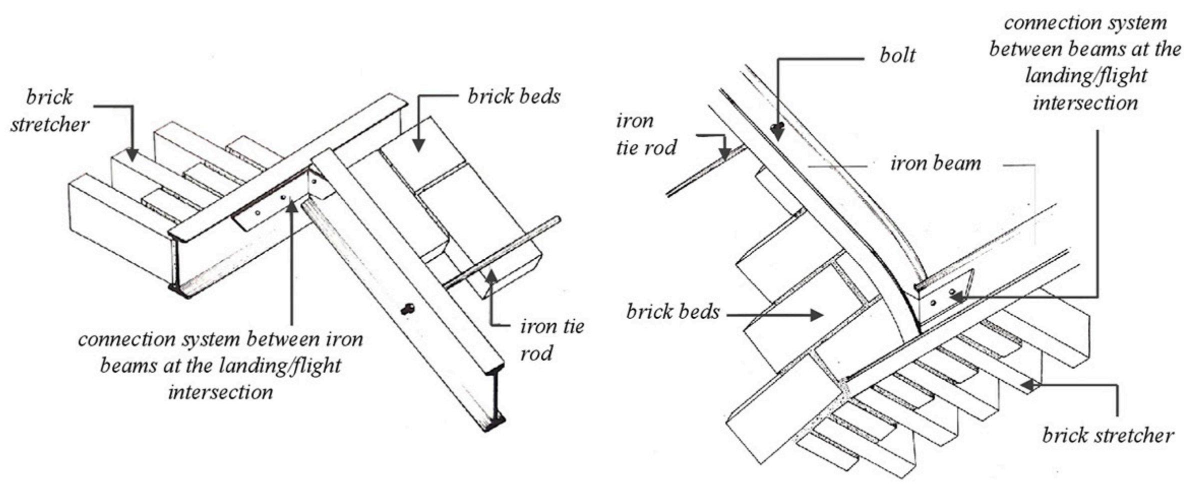

Fig. 1. *Details of brick masonry staircases with support/reinforcement metallic elements [9].*

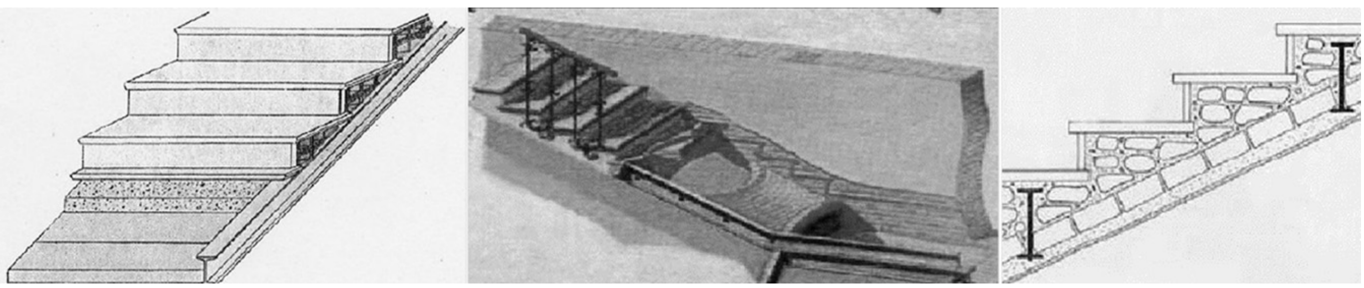

Fig. 2. *Examples of mixed brick/iron staircases: from the left, iron beams parallel to the flight and flat brick blocks [16]; iron beams parallel to the flight and vaulted brick blocks [16]; iron beams perpendicular to the flight [14].*

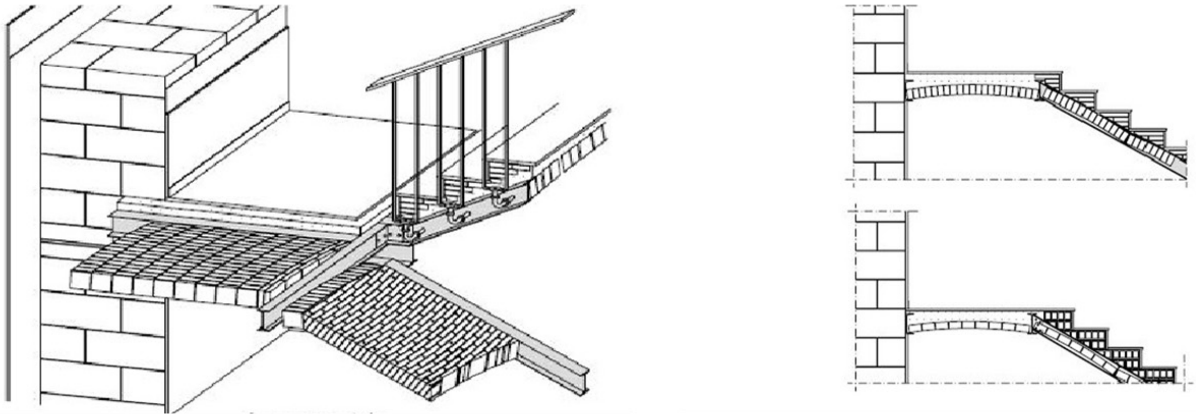

Fig. 3. *Axonometric schemes of mixed-structure stairs: from the left, profiles parallel to the flight and vaulted brick blocks; profiles perpendicular to the ramp and vaulted brick blocks set on headers (top) and stretchers (bottom). (Drawing by the Authors).*

curved tiles and/or accommodate the flat brick tiles at the endings of the slab span (Fig. 3). However, suppose the iron joists are perpendicular to the flight slope. In that case, they are cantilevered from the perimeter wall, spaced about one meter apart and connected to each other and to the edge beams of the landings by means of round iron ties [17].

The technical construction solutions may, in some cases, appear similar in the two phases, especially in the presence of wall structures with lowered vaults and large spans. However, the load transfer from the flights to the landings, from the flights to the walls and from the landings to the underlying structures are substantially different and thus require a critical understanding of the technical choices. Moreover, the structures that can be found in such a transition period might be affected by the specific local practices and contingent needs, in particular, «in Rome and in central and southern Italy» where «special vaulted structures are frequent in terms of shape and orientation of the materials» [14].

2.2. PATHOLOGY AND DECAY PATTERNS

Brick masonry staircases primarily show decay and pathologies of the brick itself, which might be considered a porous stone, with alteration mechanisms caused by the hydrophobic behaviour of the blocks [13]. Thus, for taxonomic classification, references should be made to well-established codes, such as the Italian standard UNI 11182 *Cultural heritage. Natural and artificial stone. Description of the alteration - Terminology and definition*, as well as to international guidelines *ICOMOS-ISCS. Illustrated glossary on stone deterioration patterns*. Aside from manufacturing defects, the most recurrent phenomena may concern erosion and disintegration due to the crystallisation of salts, especially at the interface with the mortar, as well as freezing, biological colonisation and efflorescence; the latter is less frequent for indoor components unless exposed to aggressive atmospheric agents due to disuse and abandonment. The aforementioned signs of deterioration also extend to the joints and coatings, with possible pulverisation of the mortar and deformation/detachment of the plaster (Fig. 4 left).

Furthermore, specific problems can be found due to the employment of iron beams, tie rods and bolting in early 20th century constructions. In such cases, problems might occur related both to the deterioration of the metal elements and to the physical-mechanical incompatibility between iron and brick. For instance, oxidation phenomena caused by the absence of protection and/or unfavourable conditions of temperature and relative humidity are recurrent (Fig. 4 middle), with the consequent danger of corrosion and reduction of resistant sections. Moreover, the aforementioned oxidation phenomena are generally associated with the swelling and/or cracking of the layer of plaster at the interface between profiles/bars and bricks (Fig. 4 right) due to the increase in volume and the onset of tensions from the corroded metal products on bricks and mortar. Interface cracks can also be caused by the physical-mechanical incompatibility of the different contiguous materials due to their different thermal, hygrometric and deformation behaviour.

Fig. 4. *Examples of decay patterns and pathologies.*

3. METHODS AND TOOLS

It is widely known that the diagnostic investigation of historical buildings should rely on the preliminary qualification of the specific case study, through bibliographic-archivist research on the original configuration and following modifications and a direct survey of characteristics and decay patterns. Such a qualification is paramount to guiding the choice of the most suitable on-site and laboratory techniques based on the investigation objectives and the surrounding conditions [18–22]. Nevertheless, in the light of the historical framework outlined in section 2 and on the basis of the experience developed by the authors through academic research and technology transfer [23–26], a general framework (Fig. 5) was outlined that relates several well-established diagnostic tests with the technical and conservative peculiarities of brick masonry staircases of the early 20th century.

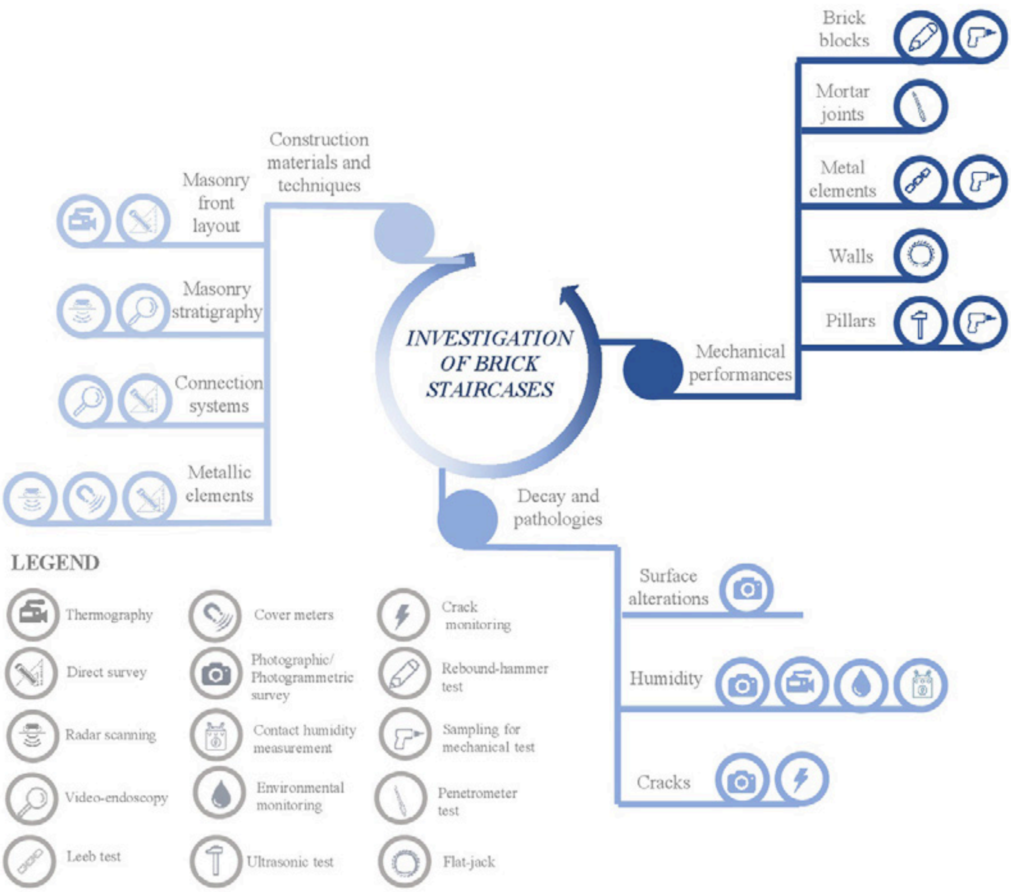

Fig. 5. *General diagnostic framework.*

In detail, three main investigation areas are highlighted:

- identification of construction materials and techniques, as related to flights, landings and perimeter walls, in order to classify the masonry front layout and stratigraphy, connection systems between contiguous flights and between flights and landings, as well as possible metal elements;
- detection of anomalies, as related to decay and pathologies, in order to map cracks, humidity patterns and surface alterations, also in terms of their evolution over time;
- characterisation of mechanical performances, as related to materials and components, with the double purpose of addressing reliable analytical modelling and identifying local vulnerabilities/inconsistencies.

A number of non-destructive (NDTs) and destructive (DTs) techniques are proposed below for each investigation area, and relative targets, based on the principle that NDTs should enable the preliminary, extensive and qualitative assessment and, thus, support the selection of representative elements whereas DTs can provide local and quantitative measurements as validation.

Concerning the identification of construction materials and techniques:

- the front layout of the masonry might be conveniently surveyed using thermography when it is covered by a finishing layer since the underlying support should show a different response in the infrared spectrum from the brick blocks and mortar joints. However, it is not unlikely that the surface thermal distribution could be fairly homogenous if the indoor temperature is stable and the thermal exchanges between contiguous materials as well as between the materials and the environment are low. In this case, active thermography could be useful. In any case, the thermographic acquisition should be subsequently supported by a direct survey to observe representative areas and local anomalies after the removal of the finishing layer;
- the masonry stratigraphy is generally successfully assessed by radar scanning, which detects inner material discontinuities based on the transmission of electromagnetic waves that are scattered back at the interface between media with different dielectric properties. To this end, some operational recommendations might be useful. Both longitudinal and transversal profiles should be acquired on the extrados for the flights that are under investigation. For the longitudinal profiles, the installation of temporary inclined supports (e.g., rigid plastic or wooden boards) should facilitate the antenna sliding. Moreover, for the transversal profiles, whenever surrounding metallic elements are close to the antenna (e.g., stairwell railings), they should be protected by insulating solutions in order to prevent any interference in the signal reflection. The direct validation of the radar scanning results is subsequently achievable with video-endoscopy inspection through significant cross-sections;
- the connection systems between contiguous flights and between flights and landings are difficult to qualify through indirect non-destructive tests due to their limited extent and morphological complexity. Consequently, they might greatly benefit from direct micro-drilling, video-endoscopy inspection and visual survey after the removal of the finishing layer;
- the metal elements, eventually installed within the flights and the landings, could be investigated by radar scanning, given the different behaviour of masonry and steel in the propagation/reflection of the electromagnetic waves. The above-mentioned operational recommendations also apply to the flights. Alternatively, a preliminary cover meter test could localise any metal element within 8-10 cm of the surface using much lighter portable equipment. However, the subsequent direct examination should be considered after the removal of covering layers in order to survey the typology and size of the elements.

Concerning the detection of decay and pathologies:

- the systematic photographic acquisition should be used to map and analyse cracks, humidity patterns and surface alterations. In particular, beyond conventional photography, 360° panoramic spherical images can support the overall documentation and decay annotation using photo-editing tools. Moreover, when the surfaces are not covered by a finishing layer, photogrammetric processing tools can be used to reconstruct a 3D model and extract 2D othoplanes by taking high resolution close range pictures with suitable overlapping percentages;
- humidity patterns can be further investigated by thermography, following the potentialities and limitations previously discussed for the identification of the masonry front layouts. However, in this case, the possible presence of active imbibition should be detectable due to the moisture evaporation that lowers the local temperature. For direct confirmation, measurements of the moisture content of the materials should be taken by the weight method, as well as a campaign of local environmental monitoring;
- cracks can be further investigated in terms of their progression over time using manual, mechanical or electronic devices. The monitoring activity, which includes the compensation for seasonal oscillations by temperature measurements, should be extended to a period of at least 12 months.

Concerning the characterisation of mechanical performances:

- the compressive strength of brick blocks can be preliminarily assessed for an extensive number of points by the rebound-hammer test, which measures the surface hardness opposed by the material to the impact of a spring-loaded mass. Therefore, at a limited number of points, borehole samples can be extracted to carry out laboratory compression testing;
- by means of the penetrometer test can be used on-site to measure the compressive strength of the mortar joints, based on the measurement of the penetration depth of a steel needle inserted into the joint by means of a striking mass. This measurement, although indirect, is effective and feasible, whereas the extraction of samples might result in specimens of inadequate size to carry out laboratory compression testing;
- the tensile strength of metallic bars and beams can be measured in analogy to the method referred to for brick blocks through preliminary extended qualification on a significant number of elements by the Leeb test for measuring the surface hardness and subsequent extraction of samples to carry out the tensile test;
- the characteristics of resistance and deformability of the masonry walls and pillars supporting the flights and the landings can be measured by several methods, including flat jacks, borehole sampling and sonic/ultrasonic tests. However, it should be noted that these aspects are beyond the specific construction type under investigation and fall within the broader case of the characterisation of the masonry structures.

4. CASE STUDY

In order to validate the general framework, as presented in §3, the main experimental results achieved on the monumental staircase of the school building “G. Carducci” in Cerignola (FG), South Italy, are discussed below. The design and construction of the staircase, as of the entire building dating back to the early 20th century, are not documented by specific archivist and bibliographic records. For this reason, the diagnostic investigation plan required for the fire safety assessment of the building system was mainly based on the preliminary direct survey.

4.1. DIRECT SURVEY

The monumental staircase under study (Fig. 6) develops on two floor levels. It is arranged according to a “pincer” scheme: for each floor, from the central starting flight (span 2.1 m), free on both sides, one arrives at the first intermediate landing, from which two transversal symmetrical flights (span 1.6 m) develop, each one connected,

Fig. 6. *Equirectangular 360° panoramas of the ground floor starting flight (left) and second floor landings (right).*

through a further landing, to a flight (span 2.1 m) parallel to and opposite the starting one. The landings are built on a system of three rib vaults set on corner pillars on the first floor and on a recently built reinforced concrete slab on the second floor.

From a typological point of view (Fig. 7), the flights are "gooseneck" rampant vaults, the curved intrados line of which continues seamlessly onto the next intermediate landing. The intrados also has a vault profile which is greatly lowered in the transversal direction. The construction technique is based on the use of brick blocks, somewhat visible due to the presence of a thin lime plaster. They show heterogeneous colours, from yellow ochre to light red, and are arranged with the header or the stretcher along with the line of the flight in two or three rows (average thickness of 12 cm). In some cases, the blocks have been replaced with more recent analogues. The material and construction of the structure are char-

Fig. 7. *Construction details: transversal flight from the ground to the first floor (top left); flights ending on the second floor (top right); flights showing metal edge beams (bottom left) and connecting tie rods (bottom right).*

acterised by the presence of some visible metal elements, including a longitudinal edge beam on the free ending of one of the two flights leading to the first floor, as well as two beams on both free endings of the central flight starting from the first-floor landing. Moreover, the latter two beams are connected by transverse tie rods, visible on the intrados. The state of conservation was found to be generally good, except for the detachment and deterioration of the thin coating plaster and some infiltration humidity stains on the second floor, which probably developed before the original roof was repaired by a metal one.

4.2. ON-SITE AND LABORATORY INVESTIGATION

The investigation campaign on the monumental staircase was planned and applied, starting from the general diagnostic framework presented in Figure 5, then adapted to both the specific targets and conditions. In detail, it mainly focused on the identification of construction materials and techniques. In fact, the key goal was to understand whether the staircase was originally conceived as a mixed iron-brick structure with beams and tie rods systematically used as main resistant elements and possibly hidden, or whether, on the other hand, it was a load-bearing masonry structure with local metal reinforcements. Nonetheless, the diagnostic investigation took into account the temporal and economic resources that could be allocated in order to plan further tests for the detection of decay and pathologies as well as the characterisation of the mechanical performances. Thus, focusing here on the flights and landings for the sake of brevity, the on-site and laboratory activities involved several diagnostic techniques, as described below.

Concerning the identification of construction materials and techniques, radar scanning and direct survey techniques were employed. Radar scanning was used for both the assessment of the masonry stratigraphy and the detection of metallic elements. The equipment consisted of a 16-bit single-channel IDS DAD FastWave system and IDS TRHF 2000 MHz antenna. For the flights, two longitudinal profiles, at a distance of about 30 cm from the endings, were acquired by means of wooden boards to allow the continuous and easy sliding of the probe. Moreover, a series of transversal profiles, spaced about 90 cm apart, were acquired directly on the step treads. For the landings, grids of longitudinal and transverse profiles spaced 50 cm apart were recorded using transparent plastic sheets on which a metric reference had previously been drawn as a guide. Furthermore, the presence of metal elements and the configuration of the connection systems were checked when NDTs indicated representative areas by a direct survey after the removal of external brick elements and/or by micro-perforations into the elements.

Decay and pathologies were detected using a virtual tour of 360° panoramic spherical images developed from the acquisition of equirectangular pictures (Fig. 6) with a Samsung Gear 360 camera, which uses two fisheye lenses with 15-megapixel sensors on both sides of the device to simultaneously capture two 180° views which are then recomposed into a 360° image. Thus, all the panoramic photos, previously edited with Adobe Photoshop® for mapping the decay textures, were later integrated into the virtual tour using Easypano Tourweaver® software and enriched by conventional navigation switches. Moreover, a FLIR T430sc thermocamera was used for thermography to assess the potential presence of active humidity phenomena, eventually related to the detachment or deterioration of the thin coating plaster and the infiltration humidity stains at the roof level.

Concerning the mechanical characterisation of materials and components, the diagnostic campaign involved: sampling brick blocks by performing axial compression laboratory tests on three representative specimens of different colours; penetrometer tests using RSM - DRC equipment on mortar joints from eight different construction components to estimate the on-site compressive strength; and, Leeb tests with a DMQ - QH2 steel microdurometer, run on eight representative points from each of the main metal elements to estimate the on-site tensile strength.

4.3. DISCUSSION OF RESULTS

The identification of construction materials was carried out using techniques such as radar scanning for the assessment of the masonry stratigraphy, and the detection of metal elements of the flights enabled the identification of the inner configuration through the cross-section. Specifically, two continuous reflection planes were generally visible, one at the interface between the steps and underlying filling materials and the other at the interface between the filling materials and underlying masonry support. In no case were there any echo signals due to the presence of metal elements, except in situations already visible from a direct survey. On the other hand, in some cases, areas of high reflection could be found due to possible repairs/replacements of elements carried out after the original construction. In contrast, radar scanning of the landings (Fig. 8 left) revealed the presence of several metallic elements. In fact, as expected, in the recently built slab on the second floor, small and regularly spaced reflection hyperbolas were detected that are typical of the metal bars in reinforced concrete structures and are arranged in both directions of the component. Moreover, similar echoes were identified on the extrados of the vaults that support the first-floor landing. However, in this second case, the distance between the hyperbolas (about 50 cm) and the wider amplitude of the reflected signals led to the hypothesis that the inclusions were due to metal beams running in the longitudinal direction of the landing.

Temporary scaffolding was then erected to reach the investigation areas in order to validate all the above-mentioned results by direct observations and inspections. In particular, when radar scanning ruled out the presence of metal elements, the removal of some outer brick blocks and micro-perforation through the cross-section confirmed the preliminary assumptions. Similarly, when the radar detected relevant signal reflections, samples revealed iron bars and beams in geometrical and construction surveys. For instance, in the case of the connection between the first-floor landing and the arriving flight, the beam visible on the flight edge (Fig. 7 bottom left) was qualified as “INP” type (height equal to 14.5 cm), with transversal stiffening by metal rods (approximately 2 cm in diameter). Said beam is supported on the lower flange of another perpendicular “INP” beam (height equal to 22 cm) that is at the landing edge and corresponds to the first hyperbola of the transversal radar profiles of the

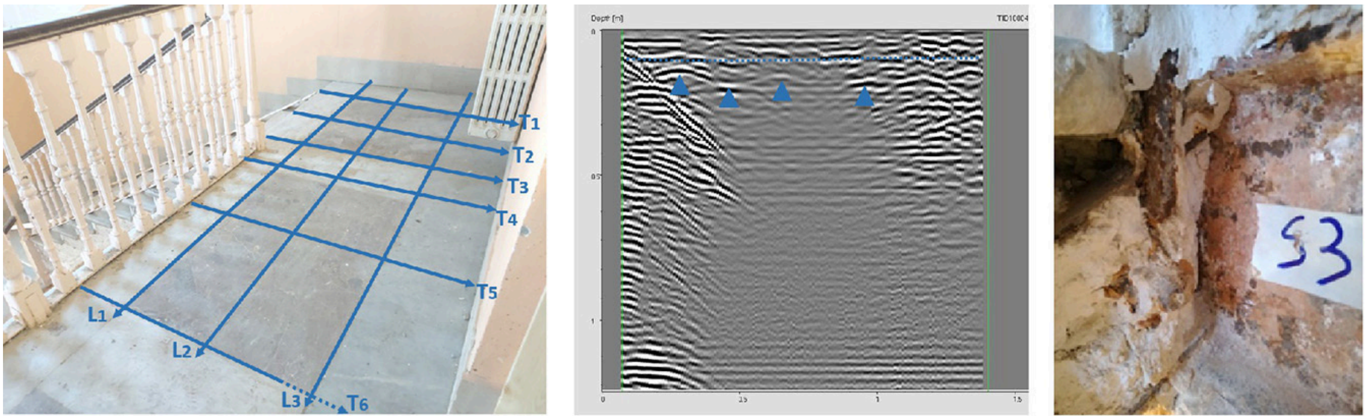

Fig. 8. *From the left: radar scanning grid of the first-floor landing; transversal profile T6 showing reflection hyperbola due to iron beams in the longitudinal direction; direct survey showing the connection between two iron beams at the flight/landing interface.*

landing (Fig. 8 middle). The outcome of the diagnostic investigation for the identification of construction materials and techniques, integrating the above-mentioned radar scanning tests and direct essays, resulted in thematic 2D and 3D drawings, documenting the layout of each flight and landing (Fig. 9).

Furthermore, concerning the detection of decay and pathologies, the virtual tour (Fig. 10) displaying the decay textures enabled rapid and comprehensive documentation of current conditions, remote inspection and analysis of the visible surface alterations and localisation of the areas investigated by diagnostic tests through

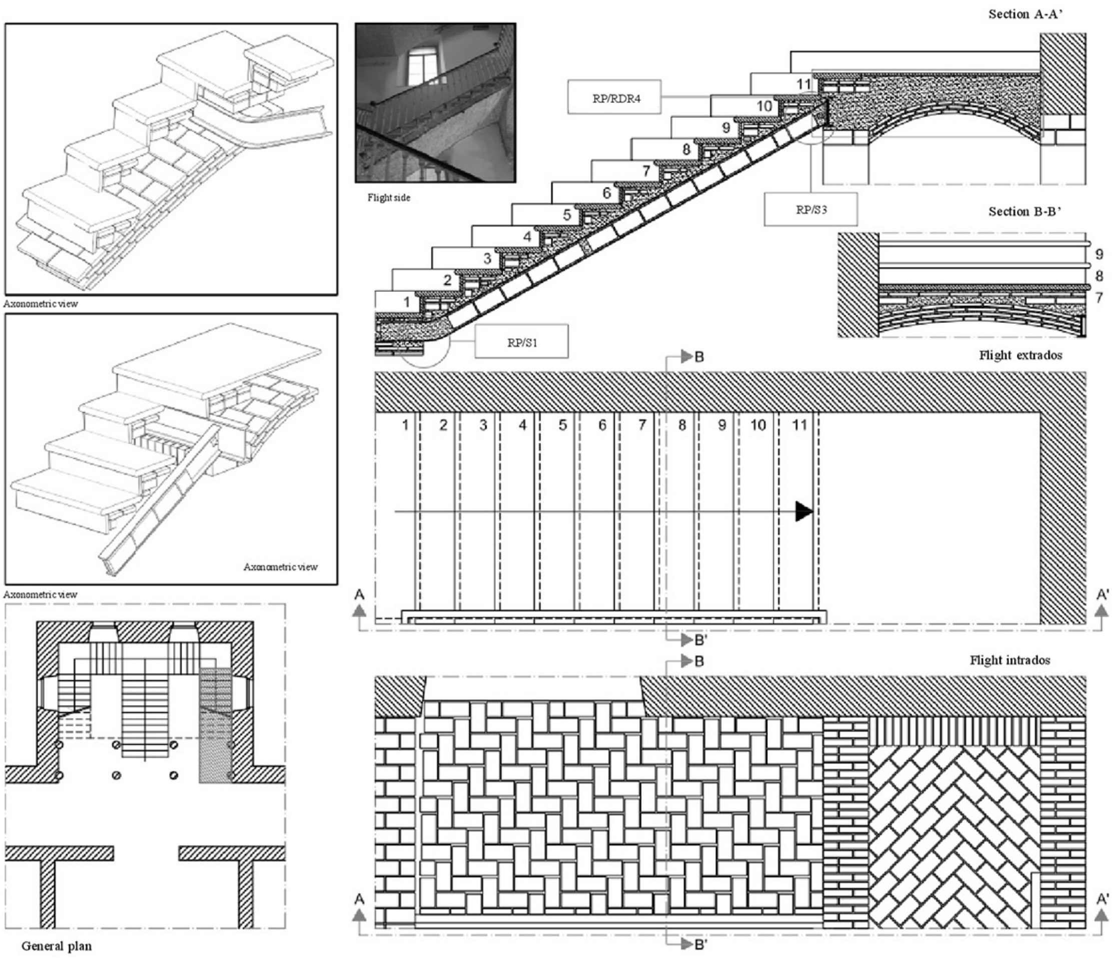

Fig. 9. *Example of datasheet with morpho-typological and material-constructional identification of a flight.*

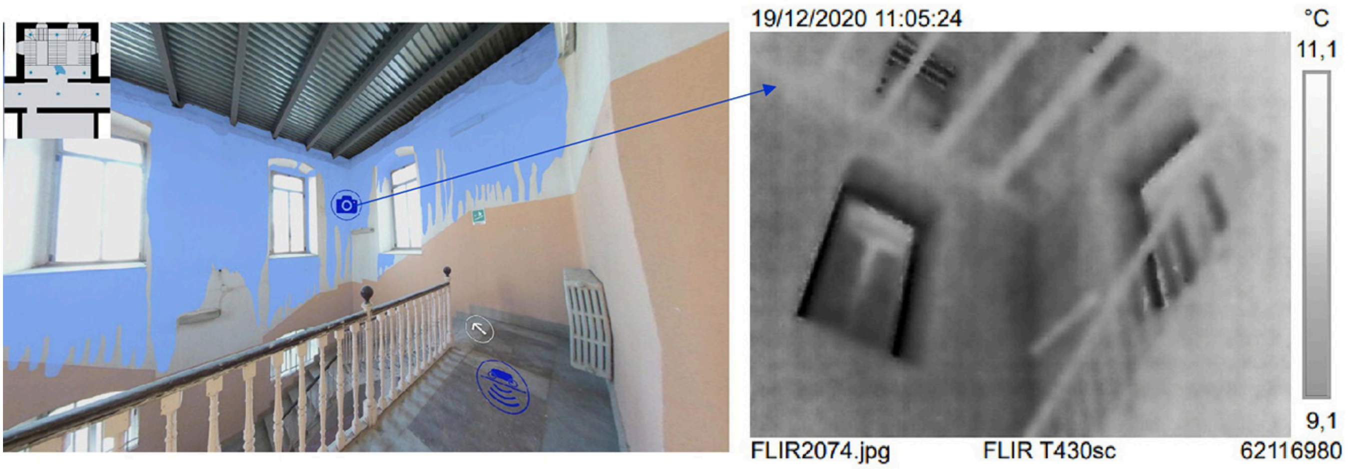

Fig. 10. *From the left: virtual tour displaying the decay maps and localising the diagnostic report; thermographic survey showing no active infiltration phenomena.*

hotspots to external links. The thermographic survey of the surfaces showing infiltration humidity stains on the second floor ruled out the occurrence of active phenomena since only localised variations in temperature due to constructional thermal bridges were found.

Finally, the results of the mechanical characterisation of materials might be summarised as follows. The axial compression tests on brick blocks (IIa2) showed fairly consistent values for different types/colours (C1 = 17.79MPa; C2 = 19.55MPa; C3 = 23.79MPa) that perform in a very comparable way. Similarly, the Leeb tests estimated quite regular tensile strengths for different elements and points under investigation, with average values of approximately 400MPa, proving that the elements are likely to belong to the same construction phase. On the contrary, the penetrometer tests on the mortar joints provided very heterogeneous results (PM1 = 1.3MPa; PM2 = 1.9MPa; PM3 $\leq$ 0.4MPa; PM4 = 1.15MPa; PM5 = 2.5MPa; PM6 = 1.5MPa; PM7 = 1.5MPa; PM8 = 2.4MPa), proving that possible replacements have taken place over time.

The overall assessment of the achieved results support the identification of some critical issues affecting the monumental staircase under investigation, both at the local and global levels. Firstly, from the direct geometry survey, it can be seen that the flights are generally quite slender, considering their thickness/length ratio. Moreover, they show non-homogenous stiffness, taking into account that they host a limited number of metal elements – only the visible ones, considering that no hidden beams, bars or ties were detected as internal inclusions by radar scanning. Thus, it is likely that the monumental staircase was originally conceived as a masonry brick structure and only reinforced after its construction with some sub-systems.

The variable material-constructional configuration is proved by further aspects. The construction survey found that the blocks had been replaced with more recent analogues in some areas. The radar scanning detected the presence of areas of high reflection due to possible repairs/replacements of elements carried out after the original construction, as well as the presence of metal beams as a reinforcement system at the extrados of the first-floor vaults. The penetrometer tests on the mortar joints provided quite heterogeneous results in terms of estimated resistance and thus proof of possible replacement interventions that have taken place over time. Finally, the recently built reinforced concrete slab on the second floor features another local anomaly: the radar scanning ruled out the presence of metal elements, such as edge beams and tie rods running along with the adjacent flights. Thus, the connection between flights and landings and the relative load transfer is left constructively unsolved.

All the above-mentioned issues should be carefully considered in the restoration measures involving local interventions, beyond the overall strengthening strategy, as addressed by analytical simulations.

5. CONCLUSIONS

The development of a diagnostic campaign for brick masonry staircases of the early 20th century should rely on a well-established methodological framework, based on historical technical handbooks, in order to target NDTs and DTs in the general investigation purposes and conditions toward reliable identification of construction materials and techniques, detection of decay and pathologies, and characterisation of mechanical performances. Nevertheless, the above-mentioned framework should be applied to a specific case study by operational procedures and practices that are strictly related to the outcome of archive/bibliographic research and direct survey on the one hand and on the available time and resources on the other.

Consequently, the diagnostic results can provide effective and comprehensive information supporting the retrofitting/maintenance activities, as well as contribute the knowledge of the characteristics of a certain construction type, albeit locally from contingent practices and needs. Finally, for technical applications in which a variety of solutions are linked to the historical transition from a traditional to a “modern” construction phase, the experimental measures make it possible to assess the current behaviour, state of conservation and residual performances, as well as increasing the available database on representative case studies, in terms of construction details, technical solutions, decay patterns and mechanical parameters of materials and components.

Authors contribution

Conceptualization of the research, F.F.; conceptualization of the paper, M.D.; methodology, F.F., M.D.; historical research, F.F., M.D.; experiments, M.D.; validation, F.F., M.D.; writing, M.D.; supervision, F.F.

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