LEARNING FROM CRACKS. EVALUATION OF THE MASONRY BEHAVIOUR FOR THE STRUCTURAL IMPROVEMENT OF THE ORATORIO DELL’ANNUNZIATA IN FERRARA

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Keywords: crack pattern, in-plane and out-of-plane collapse mechanisms, macro-elements.

Abstract. The architectural heritage conservation frequently faces problems of balancing the structural safety behaviour and operating requirements of cultural expression with preservation goals. On the one hand, stability, structural safety and easy maintenance of structures are required; on the other hand, design of assembling systems, materials and construction techniques demand authenticity respect enforcement. To sum up, the aim in architectural heritage conservation is twofold: firstly, to preserve and to strength historic structures with compatible materials and technologies, and secondly, to take a critical aware approach to conservation based on the comprehension of previous techniques, working methods and processes. These are -if one has sufficient insight and experience to read them- documents from which may gather knowledge of many aspects of the technical culture that produced them.

The paper aims to present the qualitative approach in the structural analysis of masonry traditional buildings through the critical evaluation of instability mechanisms that describe the damage scenarios of historic buildings in seismic areas. Thus, as observing in transparency the static operation of each single element in relation to the masonry box behaviour, it will be showed how the term improvement is preferred to adaptation, as it denotes the ability to respond either to the ordinary stresses or to the pathological strains greater than the initial one. This approach is achieved by means of diagnostic practice and homeopathic design, analysing the building by fractures and construction techniques similar to and compatible with those principles, materials and techniques that provided the building design and its construction ab initio.

Finally, the paper will introduce some examples that illustrate the challenges faced by the strengthening design of masonry in a historical building of Ferrara, such as the Oratorio dell’Annunziata, after the seismic sequence of May 2012. A review of the wide literature on conservation problems of masonry structures will be presented, as well.
1 FOREWORD

It is universally acknowledged that Galileo founded the current building science, but it is
the Cartesian method, in particular, that fostered to overcome the complexity of the problem
through its discretization into individual questions of an easier solution. It is precisely this at-
titude to divide the difficulty, to disassemble it into simple steps to find elementary but irrefu-
table solutions, that will be referenced in the seismic behaviour analysis of the case study,
characterized by significant margins of uncertainty that depend not only on the knowledge
level definition of the materials mechanical properties but, above all, on the particular ar-
range ment and composition of resistant structures. In fact, a wide literature on the subject has
demonstrated that, in historic masonry buildings the collapse is established by the lack of con-
straints or assembly defects or by the presence of discontinuities that are not always visible,
rather than the ultimate strength of masonry. It was therefore decided, following the methodo-
logical framework defined by the Guidelines for the assessment and reduction of the seismic
risk of Cultural Heritage [1], to focus on the approach based on local collapse mechanisms, by
performing a thorough cataloguing of fractures in order to associate significant damage and
structural organization to the resistant elements structural behaviour.

2 INTRODUCTION

The research was developed with the intent to specify the path of cognition and judgement
of seismic vulnerability, converging towards the project of improving interventions. That
meant a logical process of intuitive/deductive type which required a capacity of comprehe-
sion and synthesis not only for the construction process that, over the centuries, have been
stratified on the building, but also for the natural disasters that left traces of themselves in
fractures, deformations and alterations in the alignments of the construction.

Thus, steps toward the interpretation of the structure damages are set out. After a notice of
the principal historical events of the monumental compound, the diffused cracked framework
of the Oratorio is described, explaining the on-going phenomena.

2.1 The Oratorio dell’Annunziata in Ferrara and the processes of historical sedimenta-
tion

Located in an area of Ferrara so plentiful in artistic evidences of architectural importance
(fig. 1), which have in the church of Santa Maria in Vado and the palazzo Schifanoia examples
of greater importance, the Oratorio dell’Annunziata is closely linked to the fortunes of the
Confraternita della Buona Morte that has governed its administration since the foundation.
The brotherhood started accomplishing tasks autonomously taken, and then also formally de-
egated by the city government and the ducal court.

In fact, it is possible to recognize in the stratification of the figurative episodes in the Orato-
torio the growing role of the brotherhood in the society, not only for its miserable support role
to the dying and sentenced to death, but also for the funeral service, so that it become the only
institution authorized to undress corpses of garments and anything owned. Due to the link
with the Confraternita, it is possible to support a venue for the hospitale at least by the four-
teenth century, as the association was constituted on 5 August 1366 [2]; at that period, should
exist nothing but a small shelter for the dying, while the structures of comfort for those sen-
tenced to death were located near the places of execution.

With the increasing privileges and donations, including the legacies of the Marquis Nicco-
lò III in 1441, the brotherhood established within the city walls a worship place, choosing to
build an oratory, a small place of worship formed on a built area, in semi-public character,
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 reserved to the use of the community and guests of the hospitale, and accessible to visitors place; while the underlying level, taking advantage of an identical covered surface, assumed the role of first asylum and shelter for those poor and indigent that only later would have been accepted into the romitorio. For this reason, the lower level was organized in different spaces; while the upper level was a single chamber, as now days. Thus, it is concluded that since the beginning of the Fifteenth century the oratory had reached the current dimension, but there are only few information about the figurative apparatus inside; the surveys carried out on the walls showed the presence of a plaster even more ancient than that of the Resurrezione, dated between the second decade and the fourth of the Fourteenth century. Consequently, it has to be a late medieval plaster, partly frescoed and in part simply lime washed, laid inside on walls that, to the south, had five round-arched openings and three to the north. As the development in height is similar to the current dimension, these masonries were ended with eaves frame of “type A”, according to the Righini classification, still visible on the northern front, and were characterized by a lime wash surface treatment. This chromatic season was replaced by a new figurative plan, to which belongs the Resurrection previously mentioned, spatially complemented by the construction of the lacunar wooden ceiling in 1495. The appearance of the chamber was rapidly transforming, due to the changing needs of the Brotherhood, which, in this period, seemed to prefer the pompous apparatuses in religious services, progressively more extended to visitors than the restrained simplicity of the late medieval structure. The pictorial decoration of the oratory walls dates to the second half of the Sixteenth century, 1547 to be precise, documenting the devotion of the confraternity to the Holy Cross festivity, established May 3, 1510, on the occasion of the arrival in Ferrara of the Cross relic. The current configuration is the consequence of the demolition of the timber floor (rebuilt in 1960 with reinforced concrete after the Second World War damages) that the Brotherhood decided to remove on July 20, 1612 in order to better serve the liturgical exercise of Quarantore; the squaring and the perspective architectures are instead ascribed to the intervention by Francesco Scala in 1693.
According to the examination of the confraternity accounting records, on July 20, 1612 the efforts started from the bottom to the top toward the renovation of the oratory in a single hall. By the resolution, laying down the signatures (among others) of conte Camillo Estense Tassoni, governor of the confraternity and the commissioner Flaminio Zipponari, Giovan Battista Aleotti was in charge of the project, concluded by 24 December of the same year. It is interesting to record how much calzina (i.e. hydrated lime) used for the construction was purchased on several occasions in Zocca, Bondeno and Bologna. Among the workmen employed is Josafat murattore (simple operator as a bricklayer involved in masonry construction) and Ippolito Bonso tagliapedra (a skilled worker engaged in sorting, cutting and carving bricks, called pedracotta).

The activities performed include the construction of the new façade and the adjustment of the side on the main road via Maestra, also known as via della Buona Morte (currently via Borgo di sotto), by using about 12200 bricks. As the floor demolition decreased the structural behaviour, the two outer masonry walls were consolidated. The new architectural conformation of the façade, consisting of one single story of pilasters and niches, turning on the corner between the viazzola (the little street that only after a century and a half, as the consequence of the demolition of a small building, will give rise to the churchyard) and the main road helps to improve the structural behaviour of the compound. Along the side on the main road, the portal is still present as it can be seen in the Ferrara view of Andrea Bolzoni (fig. 1) that only in the eighteenth century will be closed also to solve the problem caused by the excessive number of openings on the southern front. In order to increase the cross-section of the base wall, it is provided the doubling size of the masonry thickness that, once compensated the shrinkage of mortar bed joints, is placed in tension with the above masonry by a double row of wedge-shaped bricks (fig. 3). Then to better distribute the tensions between the new parts and the existing ones, for the ⅔ of the wall thickness, a stringcourse of Istria stone is interposed along the whole length of the front side.

After a little more than a century, the building was to arouse concern since, in 1727, the confraternity instructs Giuseppe Tommaso Bonfaldini to assess the cost of the required work, for which it was engaged Vincenzo Santini, whose entourage actively worked in this period at Ferrara. Once again, the work will mainly involve the masonry lower parts where a new frame in the form of a pedestal will be leaned against the base wall, thus extending the high podium of the lateral side. The single story of Tuscan pilasters, so defined, is balanced by closing the first rise of niches and blinds and outlining cushion ashlars that refer to a solution previously adopted for the façade of St Domenico’s church in Ferrara, a Vincenzo Santini’s project.

The structure did not experience significant changes until the twentieth century when, after the tragic bombings that affected Ferrara, on the September 2, 1944 the oratory was damaged by the explosion of an airplane bomb. As the photographic repertoire shows (fig. 2), here for brevity only two images more relevant to the present study are reported, the damages were such as to settle the demolition of part of the façade, and then rebuilt. On this occasion, it was decided to split up the oratorio in two parts again by building a reinforced concrete floor and, unfortunately, an hollow-core concrete roof over queen-post timber trusses.

2.2 The construction techniques of the resistant framework

Since few years ago, the architectural post-medieval heritage of Ferrara was concerned by a systematic investigation that, in line with the approach of the elevations stratigraphic analysis [3], aims to formulate an organic range of traditional building components as to explain the relevant chronological keys. Due to the archaeometric mensio-chronology approach, the complexity of the historical constructive practice is investigated to identify those chronological keys of dimensional or morphological kind (e.g. wall patterns, corner/border framings,
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lintels, arches, vaults, timber floors and roofs, windows, doors, pavements) useful and practical both in the analysis and preservation of the historic built heritage. On account of their irreproducibility, these material issues are investigated as individual identities, in the perspective of the impossibility to simplify the complexity of both the phenomena and the historic constructive processes, examining each building as the set of significant matters [4].

Figure 2: Damages suffered after the bomb blasting on September 2, 1944. (on the left) The external view of the oratory façade with the safety intervention carried out before the partial demolition and reconstruction. (on the right) The internal northwestern view toward the entrance of the oratory shows the severe damages that revealed the underlying ancient structures; at the middle of the wall elevation, it is possible to identify the perimetric timber tie corresponding to the current height of the reinforced concrete floor.

The epistemology of construction stratifications does not arrange the building to a simple timetable, but contributes to a cultural qualification of the historic built heritage. This means that the gear of information provided by the study managed by the proper tools of architects (the field survey, the study of direct and indirect sources, the comprehension of the sedimentation processes of the construction phases, the identification of figurative expressions linked to a particular historical culture) has a self-hermeneutic value that contributes to the representation of the phenomenological complexity of actuality.

Hence, it is crucial the recognition of specific characters of the oratory masonry walls and documents of material and constructive culture they expressed. This study requires a change of scale of the annotations [5], which moves from macroscopic component of architectural configuration to that of the construction detail of a masonry. For once, it is not intended as a simple structure or support, but as an expressive surface itself, attested by the forms of brick finishing, the specific rules of laying the bricks and the arrangement of the mortar joint.

An archaeometric mensio-chronology approach for the study of bricks used in the past in Ferrara accuses margins of uncertainty higher than elsewhere, as the consequence of a dimensional heterogeneity, in part, due to systematic reuse of construction materials over time.
On the basis of the stratigraphic observations carried out and the information acquired, it is assumed the timeline of the main stages of construction and transformation, correlating to distinct masonry specimen detected. In particular, the southern front and the western one lend themselves better to this type of research. On the southern elevation, the load-bearing structure is composed by multiple leaf masonry (0.80 m cross-section), particularly slender (13.50 m high) and heavily loaded on the top by the concrete roof slabs. It is possible to distinguish a first stratigraphic unit due to the end of the thirteenth century when the city was still mainly made by wood, and the bricks appear largely reused. It is well known that the widespread presence of broken elements (with fringed sides) and a significant size variability points out the reuse of the material.

More accurate is the production of the podium masonry under the stringcourse; the bricks are red, uniformly cooked and geometrically attuned (range: 23-26 cm × 9-12 × 4-6). They are arranged in Flemish cross bond style by alternately laying headers and stretchers along the courses while the mortar joints (consisting of fine sand and lime) do not exceed 1.5 cm. In the binder, it is also possible detect unslaked lime particles. The sample placed over the first stratigraphic unit, due to the half of the fifteenth century, shows more fired bricks, in red and brown colour, a characteristic that suggests how the operating kilns were not yet fully improved (range: 27-29 cm × 13-14 × 6-7). Due to the irregular texture, the mortar joints height, which exceeds 2 cm, and the presence of plaster fragments, it is possible to consider that this masonry was not meant to remain visible. On the western elevation, by a preliminary critical analysis it has been verified the lack of disturbance phenomena such as re-used bricks and therefore, except for the rebuilt portion, the sample shows bricks (range: 24-26 cm × 12 × 5-6) well fired and laid onto thin and well worked mortar joint, almost suggesting a facing brick texture.

3 CRACK PATTERN OBSERVATION

The analysis of a diffused crack pattern in historic masonry building particularly references to the seismic consequences as to appraise the resistant structural frames by mass and shape, in order to describe the elementary fractures, presenting the behaviour of masonry walls and the consequent cracked framework constituted by failures of various nature [6]. The masonry performance failure is referable to stress distribution within load-bearing structures so as to trigger creep deformations in a non-homogeneous material and geometrically non-uniform
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3.1 Masonry failure investigation

Close attention was paid to analyse the mechanics of structures with regard to seismic actions [8], defining: the behaviour of the reinforced concrete floor and the mixed wood-concrete non-cooperating roof structure (hollow-core concrete roof on queen-post roof trusses); the effectiveness of connection between vertical structures; the forces distribution and the main collapse mechanisms, dealing with the behaviour of the building in aggregate within the surrounding urban block, as well. Instead, it was decided to postpone to a later evaluation stage the assessment of the soil influence on the seismic forces effects.

The identification of the static scheme in a structure evolved through centuries was of crucial importance, bearing in mind that the strength of materials decreases over time as a result of natural use, inconstancy of the loads and environmental conditions [9]. This characteristic, together with the degradation inevitably caused through centuries, made these structures particularly vulnerable to ground deformation and seismic actions. Briefly, every masonry monument is a unique building, that is characterized by a specific path due to subtractions, substitutions, additions that succeeded one another over the centuries and its study can not be separated from a careful analysis of the main historical events experienced by the construction, in terms of both natural disasters and changes to the resistant structure brought by human intervention.

The above considerations realise that the analysis of such buildings requires a specific approach [10]. The comprehension of the current status of maintenance is, therefore, an important step because, among other things, it is preliminary to the assessment of vulnerability regarding seismic actions.

3.2 Cracks indexing and semiotic of damages

The Oratorio shows a definite crack pattern, with fractures of different significance primarily affecting the southwestern corner, the southeastern corner and the eastern wall with the reopening of an old fracture in correspondence of the fresco of the Resurrection. The crack pattern survey was developed according to the following steps: 1) measurement performed in situ within the geometric survey of the building; 2) photographic documentation functional to the cracks examination, both to the texture and degradation level of masonry; 3) wide-ranging classification in which the fractures are reported into the geometric survey to facilitate an overall comprehension; 4) cracks indexing, which allowed to catalogue each fracture hierarchically identified in relation to the primary disruptive action or subsequently activated by its effect [11].

This filing, therefore, represents the synthesis of whole crack pattern survey and allows focusing on the phenomenon, both locally and globally defined. In every representation the crack pattern is described in all its significant aspects, thereby reporting an adequate graphical reproduction that provides qualitative aspects of the phenomenon, too.

In order to provide clues to the damage causes, the analysis of strains started with the crack pattern following the explosion in September 2, 1944 (fig. 4), identifying this episode as a non-secondary impact to what subsequently happened with the seismic sequence in May 2012. The interpretation of external signs of strains, having a specific way of occurrence, can be defined as the semiotics of damages. For diagnostic purposes, it is, therefore, important to understand size, location, class of strains and, if possible, their evolution over time by tracking historical charts of deformation. Hence, any elongated narrow opening is respectively
classified as a fissure, cleavage, separation, break, split, or fracture extending from the brick surface into the masonry unit, resulting from imposed loads, which induce excessive stress of
Figure 5: (on the top) Western elevation, the crack pattern after the earthquake shock, drawing scale 1:100. (on the bottom) Plan details showing the crack pattern at ground floor (left) and at the first floor (right), drawings scale 1:200.
Figure 6: (on the top) Eastern cross-section, the crack pattern after the earthquake shock, drawing scale 1:100. (on the bottom) Eastern plan detail showing the crack pattern at the first floor, drawings scale 1:100.
strength in compression, tension, or shear. Principally in structural frames, it is clear, as the cracks between bricks and mortar bed joints are the consequence of strains imposed by flexure (fig 5) or shear (figs. 6-8). Non-secondary factors are referable to the fatigue effect due to cyclic actions imposed by the wood expansion of the roof trusses along the perimeter ledge, the vibration of the concrete roof slabs hammering on the top of the slender masonry frame and, at last, the differentiated expansion of bricks as consequence of moisture effect; while the dead loads play a secondary role in the propagation of the crack pattern.

The tensile strength was evidently exceeded for the above-mentioned factors, in general, without affecting the behaviour of the whole structural frame. Tensile fractures established solutions of the continuity in the masonry leafs, leaving each split part with its mechanical characteristics, still allowing the state of equilibrium. The achievement of the values of tensile failure in one or more sectors does not cause the collapse of the bearing element, but produces a change in the resistant mechanism, arranging the undamaged areas to further collaboration; this aspect is strictly connected with the residual strength of brick masonry. Therefore, even if the phenomenon is extended but the cracks extent remains contained, then the trend can be regarded as circumscribed, although in evolution. Thus, a stable equilibrium is still possible, if the movements of the different parts, resulting from the separation of the whole frame, are efficiently thwarted.

Instead, highly alarming is the strain rate achieved by the splays of the first wall opening in
the southern elevation, the one closer to the western façade. The crack pattern is characterized by progressive development of vertical and sub-vertical cracks, corresponding to a severe structural damage that produced discontinuity of masonry in its thickness. It appears with great evidence that, as the volumetric deformation already took place through fracturing and vertically cutting the bricks, the compressive failure is approaching. Hence, it was of pivotal importance the safety intervention consisted in propping up the wall opening with timber shores.

4 VULNERABILITY ASSESSMENT AND COLLAPS MECHANISMS

At the present state of knowledge, the global analysis and a non-destructive diagnosis campaign are pending. As the consequence of an accurate fractures analysis, also regarded in terms of their evolution, taking into account the several interventions that occurred over time, the activated collapse mechanisms were theorized to justify the crack pattern, according to the appraisal of the specific vulnerability of the building compound [12]. The option of predicting the likelihood of damages is related to the knowledge of all the possible mechanisms of pro-
gressive failure and collapse, to be obtained by means of empirical observation and on-site damage assessment [13]. Hence, the phenomenological study of the building state of preservation supports the identification of macro-elements or, in other words, those structural components that, considering the presence of mutual bond and restraints, demonstrate an almost independent behaviour inside a mechanical ensemble, which acts as a kinematic-chain model [14]. The ultimate capacity of the mechanical model depends on the stability of its macro-elements rather than on the material stress exceeding. Essentially, it is supposed that the superposition of four main collapse mechanisms produced the crack pattern, as in the following.

A rectangular plan characterizes the building with high and slender walls, and a significant difference in the thickness cross-section between the masonry facing via Borgo di Sotto (0,80 m at the escarpment base instead of 0,46 m at the upper story) and the one on the cloister side consisting of 0,38 m. A hollow-core reinforced concrete floor, built in 1950, divides the interiors.

The upper level is accessible by two staircases made of reinforced concrete as well as the cover slabs above the wooden queen-post trusses. The use of reinforced concrete frames added more vulnerability to the building, such as the displacement of the stiffness center compared to those of the masses that, subjected to seismic horizontal action, could activate...
torsional mechanisms, fortunately not recorded on the occasion of the May 2012 earthquake.

In comparison to the rear pitched roof, the main façade pediment stands about 160cm, and, as the consequence of the lack of appropriate mechanical continuity, it is free to oscillate; hence, it is possible to trigger an out-of-plane overturning mechanism through the establishment of a horizontal cylindrical hinge at the entablature. As a consequence of both the construction of the hollow-core reinforced concrete roof and the removal of the last queen-post truss, which remains on site with the only chain that supports the wooden lacunar ceiling, the roof slabs rest widely on the masonry wall of the pediment with the likelihood of locally triggering hammering phenomena. Moreover, the central pinnacle appears simply rested on the masonry wall of the pediment, and it is characterized by head joints unsafely aligned vertically; the only connection is made with five headers rows and, consequently, the risk of overturning toward the courtyard or onto the slopes behind, according to the dominant direction of disruptive action, is seriously high. On the eastern front, the wooden joists of the roof in the
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contiguous building (in the cross section of figure 6 these are represented with a dotted line) triggered punching phenomena, as the seismic stress acted at right angles to the façade, favored by the lack of isolation joints that would have allowed the two parts to move or settle differentially and independently. On the northern front, the two large fractures converging toward the center, the bowing and buckling of the wall yield results useful to identify how the out-of-plane overturning mechanism of the wall is triggered not only by the presence of the in-cast concrete ring beam, but also by the spreading of the wall, without any transverse restraints. In fact, contrary to what it could be expected, the bolted end-plates present at the level of the perimeter ledge do not match any orthogonal stiffeners. Finally, on this front the presence of the bell tower has evidently triggered a crack pattern by hammering.

Figure 13: (on the left) On the northern façade, the hammering action of the bell tower. (on the center) The five stories of the bell tower are outlined in their buckling shape. (on the right) The bell tower may collapse onto the slopes of the pitched roof behind due to the out-of-plane overturning mechanism.

5 CONCLUSIONS

The methodology here presented is well established, as it tends to understand the seismic behaviour of masonry structures and guide the damage assessment through the comparison of the crack pattern with the main failure mechanism reported in literature. It consists on a multi-level approach intended to acquire any information on the construction techniques, on the physical and mechanical properties of the masonry specimens, on the crack pattern activated by previous seismic actions and on the strengthening interventions occurred during centuries.

Thus, the application of the methodology pointed out four activated failure mechanisms in the oratory bearing framework, which appears strictly related to the processes of historical sedimentation, to the typical masonry characteristic in Emilia-Romagna (i.e. slender multiple leaf brick wall) and to the retrofitting intervention arranged to make the oratory as safe as a new building designed according to an old seismic code.

In this phase, the attention concentrated to the macro-elements contributed to a more appropriate, even if qualitative, assessment of the vulnerabilities to pay attention to [15]: the in-plane shear and the out-of-plane flexural failures are identified as the main collapse mechanisms that needs to be go into. Then, without entering into details, and being aware that the phenomenon needs to be studied besides the simplification used at this stage of the research, it seems to be clear that the hollow-core reinforced concrete roof is the worst likelihood way of damage. Consequently, the only efficient approach to counteract such an apparently secondary aspect is to remove the roof slabs. Finally, what seems to be useful to the strengthening improvement of the bearing framework in order to avoid the future evolution of local failures into more severe damages is the ringing of the openings in the southern façade and connection of the roof covering to the perimeter ledge with metals shelf angles upon the head of the walls.
6 ACKNOWLEDGEMENTS

The author gratefully acknowledges all those who have offered their support to the study; in particular, for their valuable contribution in considerations and research ideas, prof. Marco Stefani and arch. Andrea Alberti. Special thanks go to ing. Andrea Giannantoni for his special assistance that was of great spur to the paper and, finally, the author is also grateful to the Referees whose critical remarks helped to advance the paper arrangement.

The subjects herein described were summarized in few presentation slides on the occasion of the 9th International Conference on Structural Analysis of Historical Constructions - SAHC 2014 - held in Mexico City from 14 to 17 October 2014.

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