Extended summary

Experimental analysis and modelling of historical masonries

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Abstract. The preservation and the conservation of historical masonries are also based on an appropriate knowledge of their constructive techniques and their mechanical behaviour. Starting from these general considerations, a specific technological-constructive methodology of some Romanesque masonries of a church was studied by a multidisciplinary approach. The first step of the research was the analysis of the constructive techniques. In a second phase the analyses of the chemical, physical and mechanical properties of the original materials (tile and brick fragments, mortars) were carried out by laboratory tests. In a third phase, wall specimens were built with the same materials and constructive technique of the investigated masonries. The results of the compression tests on the reproduced wall specimens allowed to assess the influence of the technology and the constructive technique on the entire mechanical behaviour of the investigated masonries and, in general, to increment the current knowledge on the historical masonries. Finally, the Non-Smooth Contact Dynamics (NSCD) method was applied to investigate the dynamical behaviour of the considered structures. Parametric analyses were carried out considering a real earthquake accelerogram applied to the supporting base of the three-dimensional church.

Keywords. Historical masonry, experimental characterization, mechanical properties, NSCD method, dynamical analysis.

1 Problem statement and objectives

In the cultural heritage historical masonries represent an important part to protect and to preserve. The preservation and the conservation of historical masonries are also based on an appropriate knowledge of their constructive techniques and their mechanical behaviour. In the past the lack of knowledge about the influence of the constructive techniques of the masonries on their mechanical behaviour had often caused wrong and out of context repairs and in some cases the increment of the structural vulnerabilities. The choice of the parameters that influence the mechanical behaviour cannot be delegate only to the technical literature, that often describe only the most common types of masonry and it does not take into account the influence of the local constructive technology on the mechanical performances of the investigated masonries.

In this context, a relevant problem in the conservation of the Medieval masonries is the lack of an appropriate knowledge of the so-called "poor techniques", that have received less attention than, for example, other constructive techniques based on the use of the stone, in all its forms. The archaeological investigations show a frequent use, in the Middle Age, of constructive techniques that are characterized by the use of tile and brick fragments to build masonries, that contradicts the idea that the use of these techniques was confined in few cases.

The historical masonries often present peculiar constructive techniques and, also for this reason, their study preferably requires a multidisciplinary approach as shown in literature [1–3]. This approach consists in a historical study on the different constructive phases of the investigated masonries; then it proceeds with the chemical, physical and mechanical characterization of the materials and the constructive techniques. The study of the history of the investigated structures is finalized to understand the sequence of the constructive phases and the evolution of the used constructive techniques, and to identify the possible traumatic events, like earthquakes, which may have altered the structural integrity of the building. In some cases the occurrence of earthquakes has not been accompanied by the use of different constructive techniques to improve the structural performances of the historical masonries [4]. Furthermore, the correct choice of the method for the structural analysis allows a description of the mechanical behaviour as close as possible to that of the real masonries [5]; this is true especially for the historical masonry that is often characterized by local constructive techniques. The re-production of wall specimens, with constructive technology and technique similar to those of the original structures, and their mechanical characterization are useful to understand the influence of the constructive technology on the mechanical behaviour of the investigated masonries. Thus, the mechanical characterization of wall specimens similar to the investigated masonries is useful to understand their entire mechanical behaviour and to evaluate the effectiveness of the repair techniques, as shown in literature [6–8].

Starting from these general considerations, a specific technological-constructive methodology of some Romanesque masonries of S. Maria in Portuno's Church (Italy) was studied by a multidisciplinary approach carried out by engineers of the Department of Civil and Building Engineering, and Architecture (DICEA) of Polytechnic University of Marche (UNIVPM), researchers of the Department of Material and Environmental Engineering (DIMA) of University of Modena and Reggio Emilia (UNIMORE), and archaeologists of University of Bologna (UNIBO).

The investigated masonries are an example of use of tile and brick fragments to build walls in the High Middle Age (10^{th}-11^{th} centuries A.D.), as shown in [9]. The High Middle

Age was characterized by periods of economic and political instability alternating with periods of relative quiet. Certainly in this period there was a cultural impoverishment of the building art of the masonries. To build new masonries, both for civil and religious purpose, pre-existing structures were exploited [9]. This allowed to employ the ancient masonries as foundation, as those below the ground floor upon which the medieval constructions were built, and as “borrow quarries” for construction materials.

The analysis of the structural behaviour of the historical masonries requires models that allow to describe the real behaviour of the investigated structures [3].

The historical masonries are characterized by a discontinuous structure both for the different mechanical performances of the materials and for the presence of peculiar wall layout influenced by the local building manners. They can be considered as discontinuous systems in the case of monuments made of blocks not bounded by mortar and in the case of masonries with poor mortar. Masonries during the collapse is a discontinuous union of approximately rigid blocks and their dynamical behaviour depends on the blocks geometry and texture. Thus, the historical buildings may be considered as multi-body systems, made of rigid or deformable bodies, and subjected to different phase motions: sticking, slipping, impact and free-fly [10].

During motions with multi-contacts, impacted are expected and their produce velocity discontinuities and make impossible to define the acceleration as the usual second time derivative of the configuration parameter. The considered structural field was that of the non-smooth dynamics, using the Non-Smooth Contact Dynamics method (NSCD) that allows to analyse the evolution of a multi-body system made of rigid blocks subjected to friction and impacts under dynamical loadings [11].

The multi-disciplinary research on the investigated masonries of S. Maria in Portuno’s Church was carried out by two research levels.

The first one concerning the analysis of the constructive technique and the experimental analyses of the investigated masonries to reach the following aims:

1. to investigate the chronological evolution of the constructive techniques;
2. to chemical, physical and mechanical characterization of the investigated masonries to obtain useful data for the future repairs;
3. to investigate the influence of the constructive technique of the considered masonries on their mechanical behaviour;
4. to increment, in general, the current knowledge of the historical masonries.

The second one concerning the use of numerical methods of structural analysis to reach the following aims:

1. the description of the dynamical behaviour of the archaeological masonries with complex geometries;
2. to investigate the reliability of an approach based on the macro-elements of the church in the study of its dynamical behaviour;
3. to assess the sensitivity of the dynamical behaviour of the investigated masonries to the changes of contact parameters, masonry connections and block sizes;
4. to investigate the hypotheses of past earthquakes that may have been interested the considered masonries.

2 Research planning and activities

2.1 Experimental analyses

The Medieval masonries of S. Maria in Portuno's Church were investigated by a multi-disciplinary approach. The in-situ investigations started from an analysis of the technology and constructive techniques both at foundation and elevation level by visual inspections. These preliminary investigations allowed to guide the sampling of the in-situ materials to execute chemical and physical analyses. The sampling procedure allowed to take fragments of bricks, tiles and mortars according to Italian Standard [13].

The procedure used for mortars characterization was developed according to Italian Normal standards [13–15]. The determination of the particle size distribution was performed by sieve analysis according to Italian Standard [16] on samples. Moreover on this binder fraction (grain size < 0.063 mm) several analyses were performed. The mineralogical analysis was performed by X-ray diffraction (XRD). Finally, to confirm the binder nature, thermogravimetric (TG) and differential thermal analyses (DTA) were recorded at 20°C/min up to 1000°C in flowing air.

The procedure used for bricks and tiles characterization was developed according to Italian Standard [15] both on fragments used in the Romanesque masonries and on samples coming from the pre-existing local Roman walls. The true density (ρ_t) of the fired samples was determined using a gas displacement pycnometer instrument while the total porosity was calculated. XRD and thermal analyses were performed on the matrix in order to obtain information on the mineralogical composition and firing temperature of the bricks.

Data of the physical-chemical analyses executed on mortar samples were used in order to reproduce the composition of the mortar; the considered samples were those of the elevations of the Romanesque masonries [17–18]. The mixture was obtained considering the average percentages, by weight, of each constituent (Table 1): gravel (2 mm < d < 12 mm), sand (0.063mm < d < 2 mm) and hydraulic lime (d < 0.063 mm). This proportion derived from the granulometric analyses carried out on the mortar samples. The reproduced mortar from the engineering point of view was classified as concrete and so cubic specimens of size (15×15×15) cm^3 were carried out in order to characterize their mechanical behaviour according to European Standard [19].

Table 1. Mortar mixture proportions relative to an unitary volume (1 m^3).

Mixture proportions [Kg/m^3]			
Gravel	Sand	Hydraulic lime	Water
744	909	89	156

Compression tests were carried out, with a resultant load rate equal to 0.30 N/(mm^2s), according to Italian Standard [20] to determine the mechanical properties of the original tile and brick fragments.

The reproduced mortar and the original tile and brick fragments were used to build wall specimens with the same technology and constructive technique of the investigated Romanesque masonries. The knowledge of the constructive technology and technique allowed to carry out wall specimens similar to the investigated masonries to execute compression tests to assess their mechanical behaviour. The brick and tile fragments were taken from S. Maria in Portuno's site with the approval of the archaeological Superintendence. Monotonic and cyclic compression tests were carried out on wall specimens and for the cyclic test four loading steps were performed, at ¼, ½ and ¾ of the maximum value of the compression force obtained after the monotonic compression tests and the last loading step until the rupture of the wall specimen.

2.2 Modelling of the investigated masonries

Starting from a geometrical model that represents the structural configuration of the Medieval church with a nave and two aisle, analyses of the dynamical behaviour of the church were carried out. The structural analysis of the masonries with complex geometries requires that they are modelled as a system constituted by an appropriate number of rigid (or deformable) blocks in order to reach both reliable numerical results and acceptable CPU time consuming. In literature [21–22] approaches based on the use of simplified geometrical models were used. Contrarily to the approaches shown in literature, the model of the whole church was maintained and it was divided in different macro-elements (the façade of the church, the longitudinal wall of the nave).

Each macro-element was modelled with small rigid blocks, while the other walls were described by big rigid blocks. The choice to use rigid blocks came from two main considerations. The first one [23] was the low operating compression stress in comparison with the average compression strength of the investigated masonries (see section 3.1). The second one came from the observed failure mode of the tested wall specimens; in fact, the internal core of each wall specimen mainly supported the applied vertical compression until rupture and the failure mode of the investigated masonry was different from that of the common three-leaf walls with an internal core made of concrete and with external leaf made of stones or bricks (see section 3.1). Since the joints between blocks of the investigated masonries are constituted by poor mortar, their strength and cohesion were neglected. Thus the contact between blocks was modelled by considering only the dry friction law.

The first 10 s of a seismic input were considered and the time-histories of the velocities were applied to the supporting element in the three directions. In this way, the masonry model was based on a supporting element that acts as a shaking table with vibrations in three directions. For each considered macro-element the dynamical behaviour under seismic loads was investigated by parametrical analyses in order to understand the influence of the block size, of the masonry connections between perpendicular walls and of the contact law parameters.

3 Analysis and discussion of main results

3.1 Experimental characterization of the masonries

In the last period of the Roman Age and in the Middle Age masons usually employed brick and tile fragments taking from pre-existing masonries to build three-leaf walls, roughly shaping them in triangular or trapezoidal forms with blunt edges. The investigated masonries of S. Maria in Portuno's Church may be considered a good example of this building manner. The sizes of the tile and brick fragments of these Romanesque masonries are consistent with those of the Roman tiles and bricks found under the Medieval level of the church. These results seem to suggest the re-use of the ceramic fragments starting from pre-existing structures, as shown in [9]. The masonry lay-out is made by two types of horizontal layer, piled one after the other (Figure 1): the first one (type 1) is made by brick and tile fragments so as to achieve a sort of U-shaped formwork to be filled by the second layer. Tile fragments, in fact, were placed with the raised edges towards the outside and this could also permit to have a regular external leaf. The second one (type 2), confined within the external raised edges of the tiles, fills the internal U-gap and it is always made by tile and brick fragments but it has not tile fragments with raised edges.

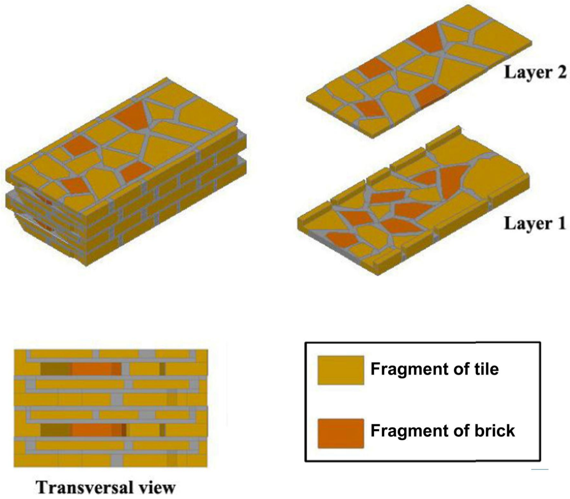

Figure 1. Scheme of the typical constructive technique of the Romanesque masonries.

Generally, as already evaluated by visual observation, all the mortar samples showed aggregates of more than 2 mm in diameter ranging from 40 to 60 wt% while the percentage of binder (< 63 μm) results very low (10 wt%). The grain size distribution of the fine aggregate (from 2 mm to 63 μm) was very variable and differs in each sampling area, but the percentage in the overall weight emerges to be ranging in an average from 40 to 50 wt%. The obtained results allowed to define that the binder used in this site was lime with small amount of clay impurities that gave a slightly hydraulic nature to the mortar. The mortar specimens had a low compression strength due to both the coarse dimensional distribution and the low lime's content.

Concerning the analyses carried out on brick and tile fragments, these tests were useful to characterize both the inert and the matrix; the chemical and physical properties of the Romanesque ceramic samples are consistent with those coming from the pre-existing local Roman structures. The experimental results indicated that all the analyzed brick and tile fragments were mostly fired at around 900° C. The obtained values of the porosity (around 40%) are quite similar and they indicate a general uniformity in both fragment composition and thermal treatment. The average mechanical properties of the tile specimens and of the brick specimens, tested according to Italian Standard [20], were very similar and the compression strength of these types of ceramic specimens was equal to 22.1 MPa and 23.0 MPa, respectively. Even their average elastic modulus did not differ so much and they were equal to 679 MPa and to 809 MPa, respectively.

The monotonic compression tests allowed to assess the mechanical properties of the wall specimens. The first cracks appeared around an average normal stress equal to 0.8 MPa. The average compression strength was equal to 1.62 MPa and the average elastic modulus was equal to 180 MPa (Figure 2). From archaeological hypotheses the ancient lateral aisle of the church was reasonably made up of one level (roof), while the principal nave was made up of two levels (roof of the lateral nave and its own roof). Thus, the expected operating compression stress at the base of the structure, from a load analysis, can be assumed of about 0.1 or 0.2 MPa, respectively. In this way, an average first-cracking stress equal to 0.8 MPa seems to be quite safe. Considering the Italian technical standards [24] the average compression strength of the tested walls is consistent with those shown for irregular stone masonries (1.00 - 1.80 MPa) and for masonries made by tuff blocks (1.40 - 2.40 MPa). On the other hand, the average value of the elastic modulus of the reproduced walls is lower than those of the previous types of masonries, that have an average Young's modulus equal to 870 and 1080 MPa, respectively. This low average value of the elastic modulus can be surely related to the constructive technology and technique.

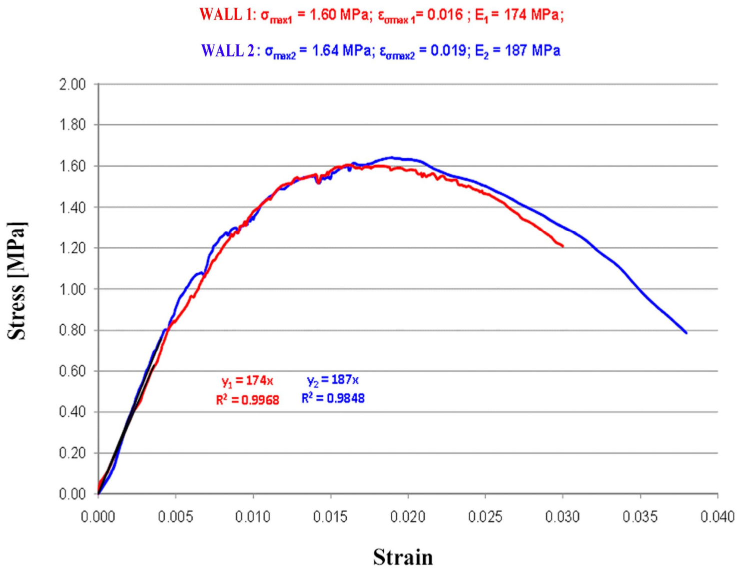

Figure 2. The stress-strain curves of the monotonic compression tests.

The cyclic compression test showed a compression strength equal to 1.87 MPa and the values of the elastic modulus for the four loading step were equal to 165 MPa, 394 MPa, 382 MPa and 324 MPa, respectively. The increment of the elastic modulus, caused by the first loading step, can be related to the compaction of the wall specimen. The first cracks were formed at an average value of normal stress equal to 0.8 MPa and they were placed near the raised edges of the tile fragments close to the external surface of the walls. By increasing the compression load, these initial cracks caused the detachments of the external raised edges of the tile fragments (Figure 3). The raised edge of a tile fragments may be considered as a cantilever subjected to a lateral thrust in the transversal plane of the wall (Figure 3), that is exerted by the mortar. Thus, these parts tend to be separated from the inner part (Figure 3). After the detachment of the tile's edges, the internal core of each wall specimen (Figure 3), mainly supports the applied vertical compression until failure. The failure mode of the tested wall specimens was different from that of the common three-leaf masonries made by an internal core of concrete and external leaf made by stones or bricks. The rupture of the three-leaf walls is generally due to the separation and expulsion of the external parts due to the vertical load (out of plane mechanism).

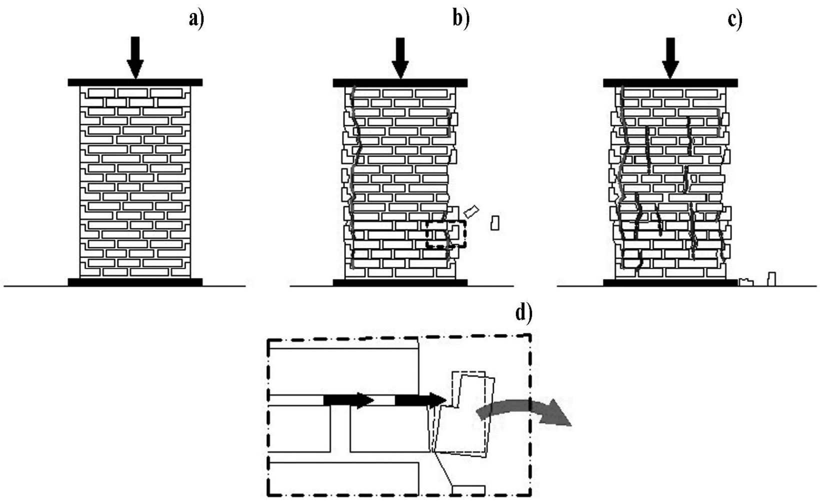

Figure 3. The failure mode of a tested wall specimen: a) the initial configuration; b) the cracking and the detachment of the external raised edges of the tile fragments; c) finally, the inner part supports the compression load until the rupture; d) the lateral thrust of the mortar causes the cracking of the raised edges of the external tile fragments.

3.2 Dynamical behaviour

For the investigated macro-elements of the church model, the decrement of the friction coefficient caused an increment both for the in plane and for the out of plane displacements of the blocks. The absence of effective masonry connections caused the increment of the out of plane displacements of the blocks and a decrement of the in plane displacements in comparison with the models characterised by effective masonry connections. The last result seems to be due to the influence of the inertia of the walls perpendicular to each considered macro-element. The influence of the masonry connections was important for the models with high friction coefficient. The masonry connections influenced also the failure mechanisms of the investigated macro-elements that were characterised by “bending”-like mechanism for the models with effective masonry connections and by “rigid translation”-like mechanism in the other cases. The use of macro-elements made of big rigid blocks allowed to understand the qualitative dynamical behaviour of the considered macro-element, but for a deep study on the failure modes of the masonries the use of models made of small rigid blocks is preferable. The use of geometrical models made of big blocks caused displacements higher than those obtained for the models made of small blocks.

4 Conclusions

The Romanesque masonries of S. Maria in Portuno’s Church made up of tile and brick fragments were the object of a multidisciplinary research. The masonry construction technique did not require expert masons and it allowed to reduce building cost and time by re-using ceramic fragments coming from local Roman structures and by employing a mortar with a low binder content. Besides, the considered constructive technique allowed to obtain regular masonry sides, by putting the raised edges of tile fragments toward the outside of the wall. In this way, these masonries at a first glance look like an ordinary masonry made by full bricks, and this can misguide engineers or architects. Furthermore, the compression strength (1.62 MPa) of the investigated masonry type seems to be more comparable to that of some historical masonries, such as rubble stone masonry and tuff blocks masonry, rather than full brick masonries, but having a bit smaller stiffness (Young's modulus) than the previous two. The investigated constructive technique influences the failure mode of the considered masonries, that is characterised by a first detachment of the external raised edges of tile fragments, and by a second phase in which the internal core of the wall mainly supported the applied compression load.

The reliability of an approach based on the macro-elements in the study of the dynamical behaviour of the church was investigated. The obtained numerical results allowed to assess the influence of the contact parameters, masonry connections and block sizes on the dynamic response under seismic loadings.

Starting from these results, future developments will deal with the following topics: (i) the modelling of this particular masonry using results from mechanical characterisation; (ii) the assessment of the safety of the church and its seismic risk, providing compatible retrofitting interventions and selecting compatible materials for its conservation and restoration.

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