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Degradation effects on structural safety of masonry walls

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Napoli, March 10, 2023

Felice Saviano

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Abstract

Assessing the vulnerability of buildings exposed to various climate conditions, which can severely influence durability and long-term performance, is a challenging topic in both research and engineering practice. Degradation affects all types of buildings across the world, differing in the timing and manifestation, for which specific rehabilitation measures are required. Most of the research activity in the last decades, was focused on seismic actions, even if analysis and rehabilitation against gravity loads represent a major challenge especially for historical buildings, mainly if degradation is the main reason for safety reduction.
In this framework, this thesis aims at the quantitative assessment of the effects of aging and material degradation on structural safety. In order to reproduce a geometric degradation of mortar joint, tests have been carried out by reducing mortar joint's width to simulate a typical form of aging in masonry, without an attempt to model the physical processes of material aging. Tests have concerned in a first phase both small scale masonry wallets of brick and tuff masonry then in a second phase full-scale unreinforced masonry (URM) walls with an opening were tested under different load schemes. Both in plane and out of plane loads were considered.In terms of in plane loading, a severe risk for existing buildings is represent by settlement at the base, on the other hand, out of plane load is significant to account for walls not being firmly connected to horizontal structures with uncounteracted horizontal forces. A further challenge has been the development of numerical analyses to simulate the capacity and behaviour of such walls against ageing effect with a calibration based on the experimental results from axial and diagonal-compression tests. Numerical models of wallets and full scale walls calibrated by using the experimental data confirmed the strength analytical envelopes, the failure mode and remarked the influence of the mechanical properties and their variations. In fact, refined numerical FEM models supported the analytical modelling approach, including a refinement of the spandrels failure criteria, modifying those devoted to piers.

Keywords: Ageing, Settlement, Out of plane load, Masonry, Numerical and analytical modelling, Experimental tests

Sintesi in lingua italiana

La valutazione della vulnerabilità degli edifici esposti a diverse condizioni climatiche, che possono influenzare severamente la durabilità e le prestazioni a lungo termine, è un tema impegnativo sia nella ricerca che nella pratica ingegneristica. Il degrado colpisce tutti i tipi di edifici in tutto il mondo, con tempi e manifestazioni diverse, per le quali sono necessarie misure di ristrutturazione specifiche. La maggior parte dell'attività di ricerca negli ultimi decenni è stata incentrata sulle azioni sismiche, anche se la progettazione e la messa in sicurezza per i carichi gravitazionali, rappresentano una sfida importante in modo particolare per gli edifici storici, soprattutto se il degrado è la ragione principale della riduzione della sicurezza.

In questo quadro, la tesi mira alla valutazione quantitativa degli effetti dell'invecchiamento naturale e del degrado dei materiali sulla sicurezza strutturale. Per riprodurre il degrado geometrico del giunto di malta, sono stati eseguiti test riducendo la larghezza del giunto di malta al fine di simulare una tipica forma di invecchiamento della muratura, senza tentare di modellare i processi fisici di invecchiamento del materiale. Le prove hanno riguardato in una prima fase pareti in muratura di mattoni e tufo in scala ridotta e in una seconda fase sono state testate sotto diversi schemi di carico pareti in scala reale in muratura non rinforzata (URM) con un'apertura. Sono stati considerati sia carichi nel piano che fuori paiano. Per l'azione nel piano, un grave rischio per gli edifici esistenti è rappresentato da un cedimento fondale, mentre il carico fuori piano è significativo per le pareti che non sono saldamente collegate alle strutture orizzontali, con forze orizzontali non contrastate. Un'ulteriore sfida è stata lo sviluppo di analisi numeriche per simulare la capacità e il comportamento di tali pareti in relazione all'effetto dell'invecchiamento, con una calibrazione basata sui risultati sperimentali delle prove di compressione assiale e diagonale. I modelli numerici dei pannelli e delle pareti in scala reale, calibrati utilizzando i dati sperimentali, hanno confermato gli inviluppi analitici di resistenza, le modalità di rottura e evidenziato l'influenza delle proprietà meccaniche e delle loro variazioni nei confronti del degrado. Infatti, i raffinati modelli numerici FEM hanno affiancato l'approccio analitico, che ha incluso un perfezionamento dei criteri di rottura dei pannelli di fascia, modificando quelli previsti per i pannelli di maschio.

Parole chiave: Invecchiamento, Cedimento, Carico fuori piano, Muratura Modellazione numerica e analitica, Test sperimentali.

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Chapter 1

Background of Masonry structures

1.1. Background and Framework

Masonry buildings are a significant part of the worldwide built heritage, including most of European cultural heritage buildings.

The structural assessment of historical masonry buildings is a complex task because of several motivations, such as a significant variability in geometric and mechanical properties of masonry that are rather difficult to be characterised, and nonlinear behaviour of structural systems under different loading conditions. The structural analysis contributes to conservation of historical buildings, including diagnosis, reliability assessment and design of intervention, oriented to grant an efficient and respectful conservation of monuments and historical buildings [1]. Non exhaustive or incorrect structural analysis can lead to ineffective interventions.

Through their life structures are exposed to varying climate conditions which can severely influence durability and long-term performance.

Masonry is widely a topic of interest for researchers, because the mechanical properties of masonry constituents and assemblages are highly variable both for intrinsic spatial characteristics [2], [3] (type of matrix, quality of units, presence of mortar joints) but also due to variations in the quality of workmanship, environmental conditions during construction and service life, which include high moisture, temperature cycles and the presence of salts. Changes caused by these factors affect the performance of the structures, so it is important to understand how degradation mechanism affects structural components to be taken into account to assess the vulnerability of such buildings.

Degradation affects all types of buildings across the world, differing in the timing and manifestation of anomalies, for which specific rehabilitation measures are required.

Also reinforced concrete (RC) buildings are affected by signs of degradation as well as hidden defects, even if constructed in recent times regardless of environmental zone, urban or industrial areas, where in the latter results a significant concentration of carbon dioxide, carbonation-corrosion prevails due to a significant concentration of carbon dioxide in the environmental pollution. Reinforcement corrosion may be induced by the penetration of chloride ions, producing the so called ‘‘pitting corrosion”, or by the carbonation process of concrete cover. On the other hand, chloride-induced corrosion is of utmost importance in structures exposed to marine environments.

The deterioration of concrete as well as the progressive corrosion of reinforcing bars may lead to significant changes in the safety coefficients. Erduran et al.[4] presented models intended at simulating the evolution (generally stepwise linear in time) of relevant geometric properties, such as effective concrete cover thickness and radius loss in steel rebars. As for the member-scale analysis, N-M interaction curves drawn for RC section in the various stages of their degradation configuration show that degradation leads to significant reduction in terms of section capacity subjected to normal stresses and concrete cover can delay the development of degradation, influenced by the environmental conditions which the element is exposed to.

Numerical investigation of the environmental effects on the seismic behaviour of RC structures was described in [5], where the progressive deterioration of RC structures over time implies the reduction of their load bearing capacity and, also the shift of the failure mechanism from the ductile to the brittle type.

For existing RC and masonry structures exposed to aggressive conditions, engineering interest has increased in the evaluation of their remaining safety and serviceability over time [6], [7].

The characteristics of the mortar are a key factor in controlling the height of rising damp and the amount of subsequent evaporation. For a brick wall, a high permeability mortar gives moisture content of 15 to 20 w_t% whereas a low permeability mortar gives only 1 to 3 w_t% as described in [8].

Foraboschi et al. demonstrated (in [9]) that moisture significantly reduces the compression strength of a brick; the greater the moisture content the lower compression strength, all other condition being equal, in particular salt concentration inside the brick. Moreover, the experimental results demonstrate that salts together with moisture significantly reduce brick compression strength, while salts without moisture increase brick compression strength. However, the crystallization of these salts can cause subflorescence and efflorescence inside the bricks, which eventually reduce the compression strength of the bricks and the masonry.

Analysis of mortar loss and spalling on structural safety for a masonry arch aqueduct is described in [10], where it is claimed that the influence of dispersed loss is less than those of concentrated loss. With reference to the location of degradation, mortar loss at the vault is most dangerous, followed by the arch shoulder, and then the arch foot part.

Masonry can be regarded as a very hard to be described building materials both for the mechanical properties and his behaviour. Heterogeneity composition of this material represents the first issue in the mechanical behaviour, which is usually based on the collaboration between mortar joints and block units, with the exception of the dry-jointed masonry structures which are also widely spread. Ultimately, masonry behaviour necessarily depends on the mechanical properties of the components and on the masonry bond (arrangement of the stones).

Most of the research activity on vulnerability and damage assessment of masonry buildings was focused on seismic actions, even if analysis and rehabilitation against gravity loads represents a major challenge especially for historical buildings, even before earthquakes.

Walls are fundamental structural elements in masonry buildings and can be understood mainly as a compressive element providing an appropriate support to vaults, domes and arches. When connected and correctly

constructed, walls represent the major structural element able to face in-plane actions from gravity load to wind and seismic events.
The investigation of the serviceability condition is a fundamental topic, in the case of masonry structures especially, and the serviceability limit states are worth to be studied with numerical analyses, e.g. crack control and differential movement.

The in-plane behaviour of masonry walls has been widely investigated from both the experimental and the theoretical points of view. Failure of wall regarding gravity load can be divided in :
-"in-plane" where the flexural controlled failure mode is characterised by flexural vertical cracks at pier, horizontal cracking at pier tops and bases, and a compression crushing at plastic hinge locations, typically in solid walls without openings , while the frequently noted shear controlled failure modes concerning the sliding along a mortar joint (step joint or bed joint) or diagonal cracking through bricks, in either spandrels or piers, typically in perforated walls, .e.g. when subjected to settlement of the foundation soil.
-"out-of-plane", mostly because flexural stresses produced by arch and vault thrusts.

Potential failure mechanisms in spandrel panels are almost equal to those of piers (with different level and orientation, with respect to bed joints, of axial load), as mentioned before, sliding shear, diagonal cracking, and flexural toe crushing [11], [12], but ageing development a rather different nonlinear response may produce, with a flexural to shear failure mode transition as the degradation level increased. Degradation, as a form of decay and physical-mechanical alteration of constituent materials, is also a potential cause of vulnerability that, in the event of a seismic event, but not limited to, can affect the response of the building.
In this contest appears that knowledge of ageing effects plays an important role for engineering development affecting both design stages (for the development of new types of strengthening systems and techniques) and the implementation of structural health monitoring

systems (to predict the residual lifetime of structures). A significant challenge is still open with respect to damage phenomena.

The present thesis is framed within the activities of the research project DETECT-AGING "Degradation Effects on sTructural safEty of Cultural heriTAGe constructions through simulation and health monitorING", funded by the Italian Ministry of Education, Universities and Research (MIUR). The project aims to develop a new analytical-instrumental approach aimed at the quantitative assessment of the effects of aging and material degradation on structural safety of cultural heritage (CH), with particular reference to masonry structures. Through the combined use of structural models and health monitoring (SHM), indications and operative tools will be provided for the identification and quantification of structural damage, for the management of built cultural heritage especially that are a significant part of the worldwide built.

Structural health monitoring, aimed at reducing epistemic and aleatory uncertainties in the assessment process, will be mainly supported by computationally efficient models, such as Equivalent Frame (EF) essentially limiting the use of refined 3D FEM.

This project also developed a sustainable management strategy for CH at the quantitative assessment of the effects of aging and material degradation on structural safety that aims to evaluate the ability to identify, locate and eventually quantify degradation-induced damage, through a joint processing of monitoring and structural simulations for pro-active risk prevention.

The Consortium is composed by four Research Unit (RU): RU1 (Naples), coordinated by Prof. Lignola and Prof. Parisi focuses on degradation effect modelling: from the material scale to the whole structure with experimental test on brick and tuff walls and full-scale unreinforced masonry (URM) wall with an opening tested under different loading conditions, in plane and out of plane, both new prototype and damaged and intrinsically degraded panels made of URM at the construction stage, i.e. with imperfections; RU2 (Genova) coordinated by Prof. Cattari deals with modelling at structural element scale (EF models), reliability of simplifications by comparison with results from nonlinear detailed FE models (accounting for aleatory and epistemic uncertainties); RU3 (Perugia) coordinated by Prof. Ubertini is working on development of new SHM systems for historic masonry structures aimed at revealing, localizing and possibly quantifying a structural damage caused by material degradation; RU4 (Bologna) coordinated by Prof. Buratti deals with estimation of effects of aleatory and epistemic uncertainties on the results of numerical simulations with experimental full-scale prototype building as testbed for the SHM and damage identification techniques.

DETECT-AGING is a three-year project, started on 1st of September of 2019 and is now ending with the publication of the final deliverables, after an extension due to Covid19 delays.

1.2. Motivation of research

It's really undeniable the expressive force conveyed by masonry construction, as an arch, a tower or a dome, which leads us to preserve as unquestionable heritage for the community

Masonry constructions are massive structures and their safety and stability are mainly provided by geometry and geometric proportions of the building. These concepts were clear to old workers, consolidated through successive experiences, trials and errors,

In a lot of seismic regions around the world the masonry buildings have not been designed to hold up the appropriate seismic load with structural walls of these buildings principally designed to resist only gravity loads [13]. Indeed, ancient historical buildings were constructed following the so-called "rule of thumb" (based on the experience from previous built structure) and they were not capacity designed such as today.

A lot of strengthening techniques has been implemented in the last decades to enhance the structural response of masonry constructions [14]–[17], which led to increased awareness of the importance of preserving historic buildings not only in scientific community but also being fully implemented in different country environmental policies.

Furthermore, these structures have been designed and built in periods with no regulations, specific methodologies and calculation tools, favouring a design approach based more on the intuition and experience (e.g. geometrical rules).
The design approaches, which guarantee stability and performance for the buildings, less frequently were applied to the ordinary buildings.
The use of numerical or analytical models is not simple, given the fragile architectural and structural context, especially for the use of the Performance-Based Assessment (PBA) which assumes a set of Performance Levels that a specific structure can exhibit against defined hazard levels.
The correct identification of mechanical parameters plays a crucial role for a good accuracy of modelling results. In last years, al lot of researchers have been dealing with experimental studies on both masonry walls and masonry walls strengthened with composites subjected to ageing due to environmental conditions during construction and service life, which include high moisture, temperature cycles and the presence of salts.
An initial numerical study was performed to evaluate the influence of the variability in mechanical properties of wall masonry and to quantify the effect of degradation at the wall scale through a statistics-based sensitivity analysis and subsequent regression analysis [18]. Numerical analysis results indicate how the degradation is not only the reason of a capacity loss in terms of stiffness and resistance, but it also affects the expected failure mode, changing from flexural failure to either a mixed or shear failure.

In order to reproduce a geometric degradation of mortar joint, tests have been carried out by reducing mortar joint’s width to simulate a typical form of aging in masonry, without an attempt to model the physical processes of material aging. The objective of this research was to quantify the performance of two masonry typologies: brick and tuff masonry.

-The former type was studied for evaluating aging effect from the level of material to the scale of component and so to define a simple tool to support the prediction of structural capacity, which can also be used for real-scale prototype building test, that will be carried out by UR4 in the research project.

-Tuff masonry was carried out to investigate in-plane and out-plane behaviour of unreinforced tuff masonry walls with door opening in the centre (URM) when subjected to gravity load with foundation movements or with transversal force.

Masonry behaviour necessarily depends on the mechanical properties of the components, being masonry a composite material, so in order to fully characterize masonry properties, a comprehensive testing program was set-up using destructive testing through uniaxial and diagonal compression test.

Briefly, the following tests, carried out at the Laboratory of department of Structures for Engineering and Architecture, University of Naples Federico II, have been conducted:

-four uniaxial and diagonal compression test on brick masonry, where for each load condition, half of test was on aged specimens

-four uniaxial and diagonal compression test on tuff masonry, where for each load condition, half of test was on aged specimens;

-two in-plane URM test subjected to gravity load and settlement of the pier, one test in intact and one test for the deteriorated configuration;

-two out-plane URM test, one test in intact and one test for the deteriorated configuration.

A challenging task in this field is represented by the ability to develop numerical analyses to simulate the capacity behaviour of such a structure against ageing effect in order to analyse the structural vulnerability and design effective solutions to protect them. Several modelling approaches exist in literature, each one of them trying to better simulate the very hard structural behaviour of a material like masonry.

It was of particular interest to investigate:

-Mechanical characterization of brick and tuff masonry under compression test with the aim of obtaining their complete behaviour, enabling the determination of the elastic modulus, strength and fracture properties.

-the effects of aging and material degradation on structural safety in terms of mechanical properties

-The in-plane strength and deformation capacity of perforated unreinforced masonry (URM)

- Review the test result using the DIANA Finite Elements program.

- The relationship between the analysis and the experiment.

The final goal of the present work is to provide useful information for the mechanics of existing stone masonry buildings, allowing the assessment of sophisticated nonlinear analysis models and the safety assessment of buildings.

As a future work, the experience gathered on the mechanics of the masonry walls under in- and out-plane loading can be of great advantage in the decision process related to the strengthening possibilities of ancient structures to face the seismic action not dealt with in this context.

1.3. Thesis outline

The thesis outline is here reported:

Chapter 2. The dissertation starts with a full description of the experimental program to investigate how aging and degradation impact the structural capacity of masonry walls, starting from the masonry assemblage small scale of brick and tuff masonry wallets to a full-scale unreinforced masonry (URM) wall with an opening. This chapter is dedicated to the description of the results obtained by experimental tests, with a fundamental comparison between the two configurations tested of intact and degraded masonry, used to simulate a geometric degradation.

Chapter 3. In this chapter the main experimental outcomes are discussed. with reference also to the theoretical considerations by performing an experimental-theoretical comparison. For the settlement load, building damage criteria based on critical displacement parameters are proposed.

Chapter 4. This Chapter is dedicated to the description of the results obtained by numerical evaluations using the FEM software DIANA FEA

10.4. The research outcomes have been also validated with the FEM simulations in terms of both global load vs displacement, and damage pattern.

Chapter 5. Conclusive remarks and further developments of the carried out work in this Chapter are described, focusing on the effect of degradation at the different scales considered in this project and on the different effects of degradation at different loading conditions of real scale masonry walls.

Chapter 2

Experimental Program: From the design to the main experimental outcomes

2.1. Abstract

The results of a research project carried out on masonry brick and tuff panels with degradation in masonry joints are presented. The experimental part of the project consists of laboratory tests, the prototypes made of both single and double leaf stone walls made of common bricks and other with tuff and natural hydraulic lime mortar, were performed respectively for uniaxial and diagonal compression test, with the arrangement of masonry units for single-leaf and double leaf walls reported in Figure 1. In addition, test on aged specimen, where the physical processes of material aging was not attempted but reproducing only a final state, have been carried out. In particular geometric degradation of mortar joint was performed by reducing their width to simulate a typical form of aging in masonry. Figure 1. also reported the dimensions of tuff unreinforced masonry wall (URM) with an opening tested under in-plane and out-plane loads.

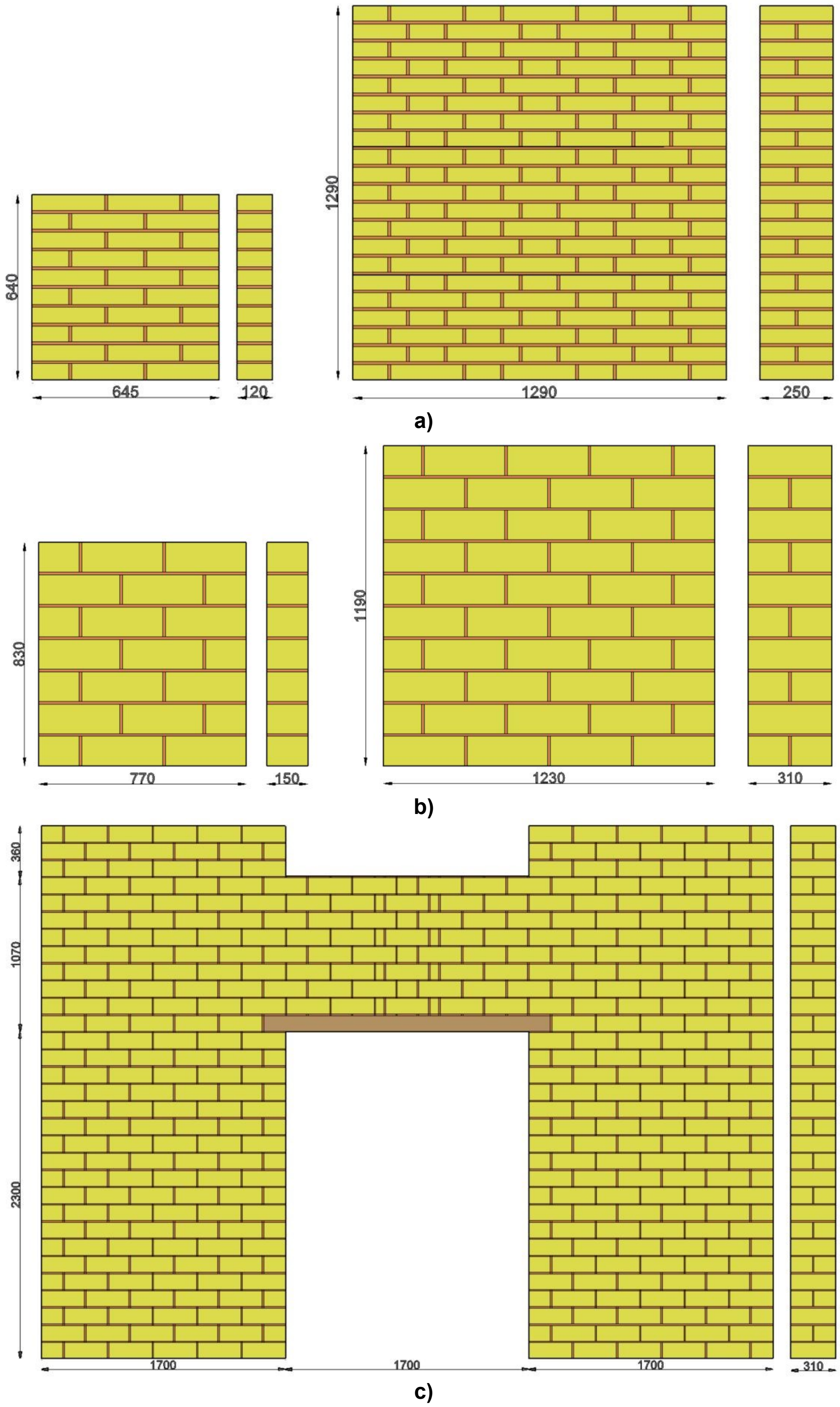


Figure 1. Dimensions of the specimens and masonry bond pattern for: a) brick masonry subjected to uniaxial and diagonal compression loads with single-leaf and double leaf respectively; b) tuff masonry subjected to uniaxial and diagonal compression loads with single-leaf and double leaf respectively; c) tuff URM tested under in-plane and out-plane loads.

2.2. Experimental program for bricks masonry

Within the framework of the DETECT-AGING research project, an experimental program was undertaken. The main aim was to investigate how aging and degradation influences the structural capacity of masonry walls, starting from the masonry assemblage scale where experimental tests focused on variations in Young's and shear moduli of masonry as well as its compressive and shear strengths. Accordingly, the experimental program included a set of characterization tests to assess the mechanical properties of masonry. Four masonry wallets were tested under simple uniaxial compression, whereas other four specimens were subjected to diagonal compression tests. The former set of specimens were made of single-leaf clay brick masonry (CBM), whereas specimens tested in diagonal compression consisted of double-leaf CBM. To simulate masonry in existing buildings, CBM was made of common clay bricks and natural hydraulic lime mortar. Half of each set of CBM wallets was fabricated with mortar joints being characterized by reduced area, in order to simulate potential effects of CBM degradation in the form of geometric joint alterations on each side of the specimen.

Diagonal compression tests allow the panel a free deformation, since its four sides are free from any kind of constraints so this situation may be assumed to be representative of masonry spandrels in which the vertical compression stress may be considered equal to zero and the effect of confinement is very limited. Although this type of test is not univocal as it has given rise to different interpretations in the literature, it is a useful tool for studying the behaviour and shear resistant capacity of masonry.

Conversely, this study of an experimental nature, aims to evaluate the effects of degradation at the smallest scale of masonry, with particular reference to monotonic actions attributable to static loads.

2.2.1. Description and mechanical properties of brick masonry materials

The selection of materials and construction techniques was driven by the aim of recreating conditions that are representative of historical masonry buildings. Clay brick masonry was fabricated in laboratory, according to a running bond pattern. Clay bricks were produced with soft mud technology and were characterized by a nominal size of 250x120x55 mm^3, showing an old-like geometry with rounded edges that allows the recreation of historical brickworks in several countries such as Italy.

The masonry joints were nominally 10-mm-thick and filled with a premixed hydraulic mortar composed by natural hydraulic lime (NHL) with 1:4 water/binder ratio by weight (i.e., 6.25 L of water per 25 kg of lime) and fine sand, resulting into a low-performance lime mortar. The mortar composition was designed in a way to reproduce the main features of old mortar types in historical masonry buildings.

The bricks had mean unit weight w = 15.40 kN/m^3, with mechanical properties determined by means of experimental results on prismatic samples 40x40x160 mm^3 according to UNI 8942-3 standard [19]. The mean flexural strength f_{fb}=7.38 (CoV = 9.30%), was obtained by means of three-point bending while the mean compressive strength f_{cb} =20.79 MPa (with coefficient of variation CoV = 19.09%) was determined on the halves of the specimens after bending tested under flexure. According to technical product declarations by the mortar manufacturer, the premixed hydraulic mortar was classified as M2.5 (corresponding to mean compressive strength of mortar f_{cm} = 2.52 MPa) according to Eurocode 6 [20] and Italian Building Code [21]. During the construction of each masonry wallet, mortar prisms (40x40x160mm^3 in size) were prepared and tested under three-point bending according to EN 1015-11 standard [22]. Using the same procedure for characterization of bricks, the two parts of each prismatic specimen after flexural rupture close to the mid cross section were individually tested under uniaxial compression.

Table 1 outlines the mean values and CoV for both compressive and flexural tensile strengths of mortar and bricks.
All specimens were cured for 28 days at standard levels of relative humidity and temperature.

Table 1. Mechanical properties of masonry constituents*.

Material	Statistic	f_c	f_f
Clay brick	Mean value [MPa]	20.79	7.38
	CoV	19.09%	9.30%
		(8)	(4)
NHL mortar	Mean value [MPa]	2.52	0.96
	CoV	27.32%	19.57%
		(12)	(6)

* f_c and f_f indicate compressive and flexural strengths of either material; bracketed figures denote the number of specimens for each experimental test.

2.2.2. Geometry and fabrication of specimens

The specimens tested under simple compression were characterized by a single-leaf masonry assemblage with overall size equal to 645x640x120 mm^3,in agreement with other experiments carried out in the past [23] and 10 masonry layers (Figure 2.a). By contrast, the specimens tested under diagonal compression were fabricated according to a double-leaf masonry pattern with overall size equal to 1290x1290x250 mm^3 in agreement with standard ASTM [24] and other studies[25], [26]. Regarding the masonry fabrication, the bricks were wetted in water before their installation in contact with the mortar. The specimens with artificial degradation (abbreviated as 'deteriorated specimens' hereinafter in contrast to 'intact specimens' with fully mortared joints) were made of partially filled mortar joints, as shown in Figure 2.b. In those specimens, the amount of mortared joint area can be deduced according to the ratio s/t between the full width of the mortared joint (*s*) and the total thickness of the wallet (*t*). The fabrication of deteriorated specimens was carefully controlled so that *s/t* was equal on average to 33% and 24% in specimens to be tested in simple and diagonal compression, respectively.

a)

b)

Figure 2. Pictures of specimens to be tested under (a) simple compression and (b) diagonal compression

A beam of high strength and stiffness, used for testing procedure, has been placed on the top of the specimen made perfectly flat by the application of a layer of mortar, to remove surface roughness and ensure a uniform distribution of the load and a smooth contact surface during the uniaxial compression test. For each of the two specimen configurations (i.e., intact and deteriorated), strain-sensing piezoresistive bricks denoted as 'smart bricks' in previous papers [27]–[29] were integrated in the specimens to assess their ability to monitor the stress/strain progress for structural health monitoring (SHM) applications. The specimens with smart bricks are labelled with final letter 'm'. Intact specimens included three smart bricks in both front and rear leaves of the masonry, whereas only the front leaf of deteriorated specimens was equipped with three smart bricks (Figure 3).

The novel sensors are made of fiber-reinforced clay-based material mixing fresh clay with stainless steel micro fibers to supply the intrinsic piezoresistivity of the clay matrix. So smart bricks provide variations in their electrical outputs when mechanically strained under compression loads. A detailed description of smart brick operating principle can be found in [27], [28], [30]. (Figure 4).

a)

b)

Figure 3. Smart bricks pattern for diagonal compression test: a) Intact; b) Deteriorated

a)

b)

Figure 4. Masonry bond pattern for diagonal compression test with smart bricks for configuration: a) intact; b) deteriorated

2.2.3. Experimental setups and testing procedures

2.2.3.1. Uniaxial compression for brick masonry

The experimental setup for simple compression tests consisted of a universal testing machine Italsigma: the machine consists of a rigid steel base, equipped with T-slots for mounting the test equipment and specimen restraints, four columns located at the vertices of a rectangle, fixed in the base and a movable beam, which slides along the four columns. An actuator is mounted on the beam, allowing both monotonic and cyclic loading displacement-controlled tests up to a maximum stroke of 75 mm and force control up to 3000 kN in compression and 2400 kN in tension.

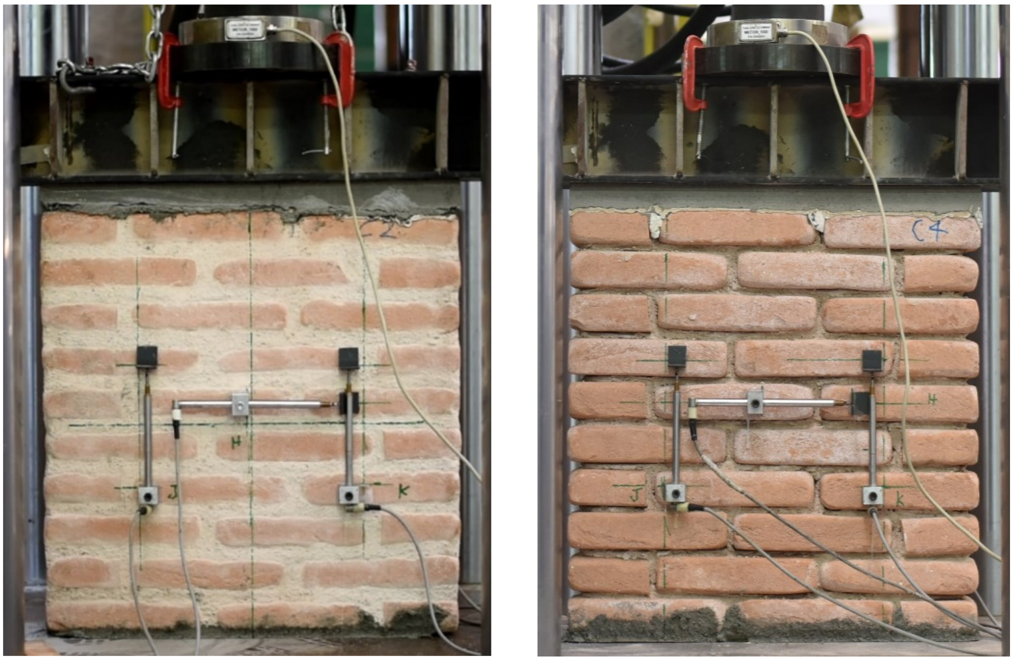
Each specimen was thus placed on the basement of the testing machine and equipped with a rigid steel I-beam on top, in order to allow an almost uniform distribution of pressures. (Figure 5)

Load was transferred to the specimen via spherical hinge, interposed between the load plate of the actuator and the upper beam of the panel keeping the resultant force centred on the wall section.

All specimens were tested under monotonically increasing displacement up to failure, assuming a displacement rate equal to 0.01 mm/s to ensure effective monitoring of cracks and to fully measure the nonlinear behaviour of masonry including post-peak strain softening.

The first couple of specimens with intact conditions was labelled as CB_A_1 and CB_A_2, whereas their deteriorated counterparts were labelled as CB_A_1_D and CB_A_2_D, using symbol D to indicate a deteriorated condition.

According to previous investigations, measurement devices were installed in the central region of both specimen sides so that measurements were not affected by local effects on top and at the bottom of the specimen. Deformations were measured by three inductive linear variable differential transformers (LVDTs) as follows: two LVDTs per side were parallel to the loading direction, and the other was orthogonal to the loading direction. All LVDTs were connected only to bricks, according to provisions by EN1052-1 standard [31].



a) b)

Figure 5. Experimental setups of specimens subjected to simple compression in configuration (a) intact and (b) deteriorated.

2.2.3.2. Diagonal compression for brick masonry

Diagonal compression tests were carried out to investigate the in-plane shear behaviour of different double-leaf specimens with the same type of masonry assemblage. Diagonal compression tests, indirect type test compared to shear-compression test, are preferred compared to the latter, because the former is simpler to realize with limited cost and duration for set-up procedure, but on the other hand their interpretation is more uncertain with different approaches available in literature to calculate mechanical parameters of masonry used in analytical models.

a)

b)

Figure 6. Experimental setups of specimens subjected to diagonal compression in configuration (a) intact and (b) deteriorated.

Four URM panels with global dimensions 1292x1290x250 mm^3 were tested, two intact labelled CB_D_1; CB_D_2_m and the other deteriorated specimens CB_D_1_D; CB_D_2_D_m, final letter 'm' stands for the specimens with smart bricks, following the same approach for uniaxial compression test with a ratio between the full width of the mortar strips and the total thickness equal to 24% on average (Figure 6).

Testing procedures involved rotation of the URM wall panel by 45° and once centred in the machine frame the specimen was instrumented, and then subjected to in-plane diagonal loading along one of the wall's diagonals.

Diagonal compression tests were carried out with displacement control up to failure, using the same universal testing machine described for simple compression tests (see Sect. 2.2.3.1) and the same displacement rate (i.e., 0.01 mm/s).

Load was applied on top corner of each specimen by means of two complex L-shaped elements (i.e., steel shoes), which derived from the assembly of steel plates with suitable thickness to avoid local crushing of masonry. Those loading shoes were thus installed on opposite corners of each specimen, along the diagonal line so that the eccentricity between loading direction and such diagonal line was minimized. It is noted that quick-setting anti-shrinkage mortar was filled locally between the steel shoes and the free surface of the specimen to ensure effective bond and transfer mechanism of local pressures.

Diagonal load was transferred to the specimen via spherical hinge, capable of absorbing any out-of-plane deformations of the panels during testing, placed between the actuator and the load cell.

The diagonal compression test was stopped when approximately 50% of peak force was reached on the post-peak softening branch of the force–displacement diagram.

On each side, relative vertical and horizontal displacements were measured by linear variable differential transformers (LVDTs) with gage length g = 400 mm, so as not to have localized effects in the centre, bearing in mind that ASTM E 519-07 does not provide standard gage lengths for LVDTs.

Smart bricks measures are not elaborated in this study as it is subject matter of UR3 “Department of Civil and Environmental Engineering, University of Perugia” involved in the DETECT-AGING research project.

2.2.4. Results of simple compression tests for brick masonry

2.2.5. Results of diagonal compression tests for brick masonry

2.2.6. Significant mechanical parameters of brick masonry

2.2.7. Comparison between experimental results

2.3. Description and mechanical properties of tuff masonry materials

Tuff masonry was fabricated in laboratory, according to a running bond pattern. Tuff was characterized by a nominal size of 300x150x110 mm^3, while masonry joints were nominally 10-mm-thick and filled with a premixed hydraulic mortar composed by natural hydraulic lime (NHL) with 1:5 water/binder ratio by weight (i.e., 5.25 L of water per 25 kg of lime) and fine sand, resulting into a low-performance lime mortar. The mortar composition was designed in a way to reproduce the main features of old mortar types in historical masonry buildings.

The stone had mechanical properties determined by means of experimental tests on six cubic tuff stones samples 75x75x75 mm^3 for compressive strength, according to [32]

The mean compressive strength f_{cb} = 4.30 MPa (with coefficient of variation CoV = 12.90%). The modulus of elasticity of the tuff stones was determined from tests on six prismatic specimens with dimensions 75X75X150 mm^3 and was equal to 2098 MPa (CoV=3.95%) [33]. Ten tuff specimens of dimensions 50x75x300 mm^3 were tested for flexural strength [34]. The mean flexural strength f_{fb} was equal to 0.85 (CoV = 3.34%). According to technical product declarations by the mortar manufacturer, the premixed hydraulic mortar was classified as M2.5 (corresponding to mean compressive strength of mortar f_{cm} = 2.5 MPa) according to Eurocode 6 [20] and Italian Building Code [21]. During the construction of each masonry wallet, mortar prisms (40x40x160mm^3 in size) were prepared and tested under three-point bending according to EN 1015-11 standard [22]. The two parts of each prismatic specimen after flexural failure close to the mid cross section were individually tested under uniaxial compression.

Table 2 outlines the mean values and CoV for both compressive and flexural tensile strengths of mortar and tuff.

All specimens were cured for 28 days at standard levels of relative humidity and temperature.

Table 2. Mechanical properties of masonry constituents*.

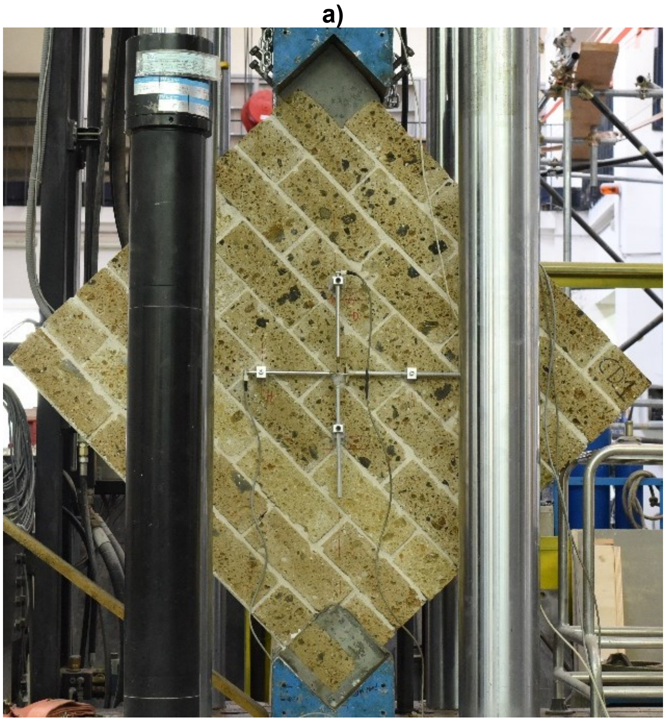
Material	Statistic	f_c	f_f
Tuff	Mean value [MPa]	4.30	0.85
	CoV	12.60%	3.34%
		(6)	(10)
NHL mortar	Mean value [MPa]	2.82	0.80
	CoV	10.27%	5.96%
		(12)	(6)

* f_c and f_f indicate compressive and flexural strengths of either material; bracketed figures denote the number of specimens for each experimental test.

2.3.1. Geometry and fabrication of specimens

The specimens tested under simple compression were characterized by a single-leaf masonry assemblage with overall size equal to 770x830x150 mm^3, while the another one double-leaf masonry assemblage with overall size equal to 770x830x310 mm^3, in agreement with other experiments carried out in the past [23] with 10 masonry layers (Figure 7.a). By contrast, the specimens tested under diagonal compression were fabricated according to a double-leaf masonry pattern with overall size equal to 1190x1230x310 mm^3 in agreement. with standard ASTM [24] and other studies[25], [26]. Regarding the masonry fabrication, the bricks were wetted with water before their installation in contact with the mortar. The specimens with artificial degradation (abbreviated as 'deteriorated specimens' hereinafter in contrast to 'intact specimens' with fully mortared joints) were made of partially filled mortar joints, as shown in Figure 7.b. In those specimens, the amount of mortared joint area can be deduced according to the ratio *s/t* between the full width of the mortared joint (*s*) and the total thickness of the wallet (*t*). The fabrication of deteriorated specimens was carefully controlled so that *s/t* was equal on average from 36% to 10% in specimens to be tested in simple compression and from 20% to 10% for the ones tested in diagonal compression.

a)



b)

Figure 7.Pictures of specimens to be tested under (a) simple compression and (b) diagonal compression

2.3.2. Experimental program for tuff masonry

Also for tuff masonry, as illustrated before for bricks (see Sect. 2.2), an experimental program was carried out. The comprehensive testing program was set-up using destructive testing through uniaxial and diagonal compression test. Experimental tests focused on variations in

Young’s and shear moduli of masonry as well as its compressive and shear strengths, to inspect how tuff masonry reacts to a change due to ageing influence.

The assessment of tuff masonry’s mechanical properties, through these set of characterization tests, has been vital to understand how degradation effects from the scale of material up to the scale of component have an effect on to the scale of structure

In the following paragraphs, in fact, they will also be shown tests on full-scale unreinforced structures in degraded conditions, where degradation does not always trig to an unsafe effect compared to intact conditions.

Four masonry wallets were tested under simple uniaxial compression, whereas other four specimens were subjected to diagonal compression tests. The former set of specimens were made of single-leaf tuff masonry (TM) in number of three and one test on double-leaf TM, whereas specimens tested in diagonal compression consisted only of double-leaf TM. To simulate masonry in existing buildings, TM was made of common yellow tuff stones from a quarry near Viterbo, Italy, and natural hydraulic lime mortar. Half of each set of TM wallets was fabricated with mortar joints being characterized by reduced area, in order to simulate potential effects of TM degradation in the form of geometric joint alterations on each side of the specimen.

2.3.3. Experimental setups and testing procedures

2.3.3.1. Uniaxial compression for tuff masonry

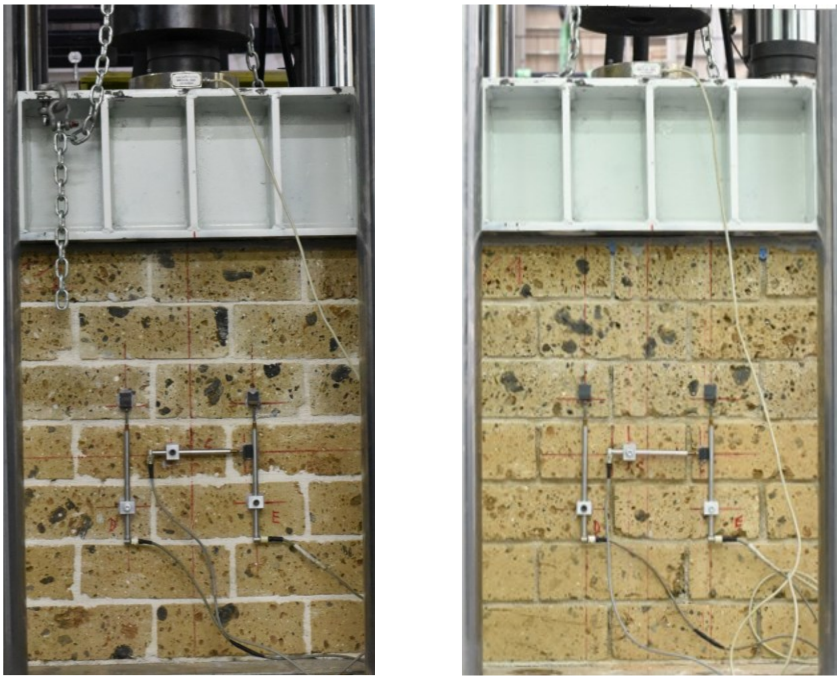
The experimental setup for simple compression tests consisted of a universal testing machine Italsigma, with the full characterization reported in Sect.2.2.3.1

Test required a rigid steel I-beam on top, to allow an almost uniform distribution of pressures. (Figure 8)

All specimens were tested under monotonically increasing displacement up to failure, assuming a displacement rate equal to 0.01 mm/s to ensure effective monitoring of cracks and to fully measure the nonlinear behaviour of masonry including post-peak strain softening.

The only specimen with intact condition was labelled as TM_A_1, TM_A_2_D for the single-leaf tuff masonry and TM-DL_A_D for the one double-leaf, using final symbol D to indicate a deteriorated condition.

Deformations were measured by three inductive linear variable differential transformers (LVDTs) as follows: two LVDTs per side were parallel to the loading direction, and the other was orthogonal to the loading direction. All LVDTs were connected only to tuff, according to provisions by EN1052-1 standard [31].



a) b)

Figure 8.Experimental setups of specimens subjected to simple compression in configuration (a) intact and (b) deteriorated.

2.3.3.2. Diagonal compression for tuff masonry

Diagonal compression tests were carried out to investigate the in-plane shear behaviour of different double-leaf specimens with the same type of tuff masonry assemblage.

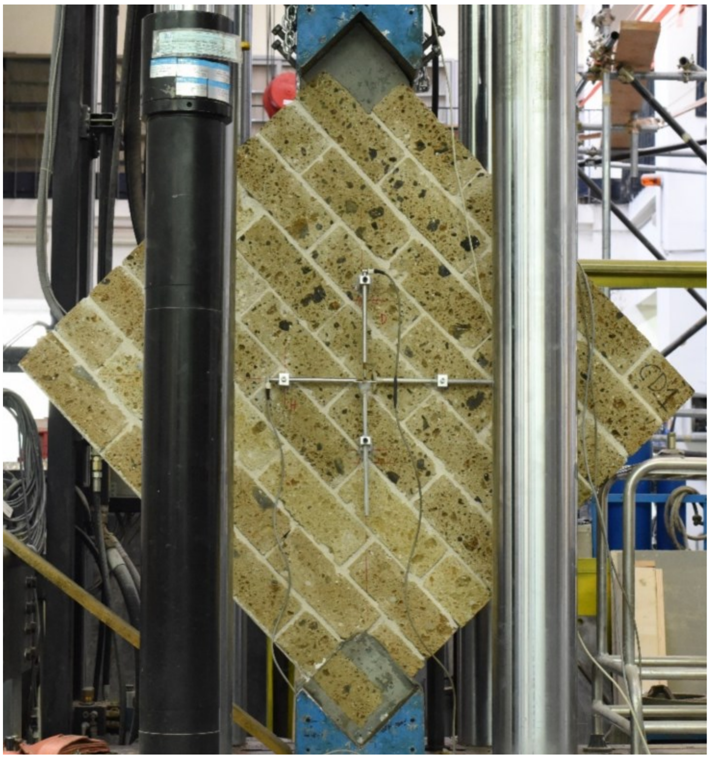
The two intact specimens with intact condition were labelled TM_D_1; TM_D_2 and the other deteriorated specimens TM_D_1_D; TM_D_2_D following the same approach for uniaxial compression test with a ratio between the full width of the mortar strips and the total thickness from 20% to 10% on average (Figure 9).

Testing procedures involved rotation of the URM wall panel by 45° and once centred in the machine frame the specimen was instrumented, and then subjected to in-plane diagonal loading along one of the wall's diagonals.

Diagonal compression tests were carried out with displacement control up to failure, using the same universal testing machine described for simple compression tests (see Sect. 2.3.3.1) and the same displacement rate (i.e., 0.01 mm/s). Load test procedure was the same as that used for bricks masonry test. (see Sect. 2.2.3.2)

The diagonal compression test was stopped when approximately a 50% of peak force drop was reached on the post-peak softening branch of the force–displacement diagram.

On each side, relative vertical and horizontal displacements were measured by linear variable differential transformers (LVDTs) with gage length g = 400 mm, not to have localized effects in the centre, bearing in mind that ASTM E 519-07 does not provide standard gage lengths for LVDTs.



a)

b)

Figure 9. Experimental setups of specimens subjected to diagonal compression in configuration (a) intact and (b) deteriorated.

2.3.4. Results of simple compression tests for tuff masonry

2.3.5. Results of diagonal compression tests for tuff masonry

2.3.6. Significant mechanical parameters of tuff masonry

2.3.7. Comparison between experimental results

2.4 Settlement testing of unreinforced masonry

This part of the thesis presents the results of a laboratory test carried out on a full-scale unreinforced masonry wall (URM) with an opening subjected to a differential settlement. Specific attention was paid to aging effect, so two configurations have been adopted, intact and deteriorated such as previous described simple and diagonal compression test. The main objective of this study is to make available accurate and reliable experimental data to be used as validation of numerical results.

It was observed that masonry structures subjected to foundation movements usually develop typical failure patterns when they are affected by ground movements at the base, depending on the portion of the structure involved in the movements, the type of differential settlement pattern. Figure 10 shows a series of typical damage patterns for specific masonry types, such as façades, corners, connection, arches and vaults [35].

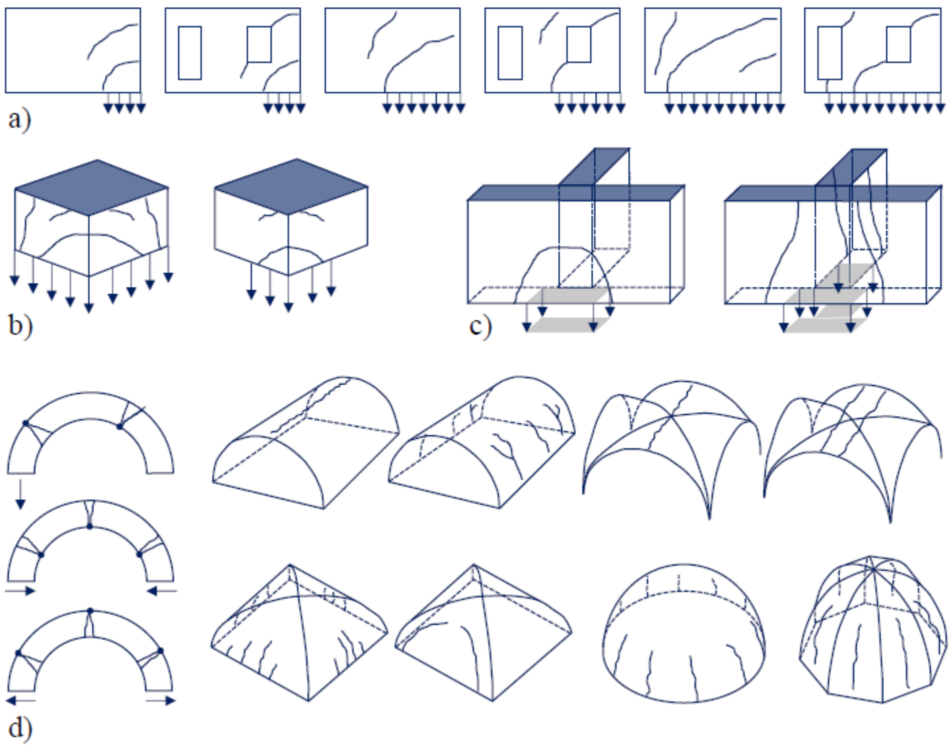


Figure 10. Damage patterns for masonry structures subjected to settlements: (a) Façade with and without openings; (b) buildings corner connections; (c) T-connections; (d) arches, vaults and domes.

Korff [36] noted that buildings with load bearing walls are more vulnerable to damage than buildings with frame structure. For the same vertical displacement, frame structures can accommodate differential displacements by deformation of the beams, whereas load bearing walls need to bend, which leads to cracking more easily. This situation led to a 20/25% lower tolerable relative rotation and settlement for load bearing walls.

Buildings under specific loading condition can move, crack, deform, tilt with damage depending on their construction type, stiffness, openings and joint [36].

Possible causes of building deformation are self-weight, temperature changes, moisture content changes or settlements. Settlements can be seen as subsequent to environmental changes. Environmental conditions that can cause settlement are due to soil characteristics, changes in groundwater level or mining activities, causing vibration and deep subsidence, changes in neighbouring buildings, vibration due to traffic and construction of new roads or structures [37].

These deformations lead too strain which in turn may cause important damage to the structure with possible tilt. Tilt phenomena are characterized by a rigid body motion of building portion under settlement load. Building deformation due to differences in settlement over the extent of a building may cause several types of damage.

The most likely deformation modes are the hogging and sagging mode (see Figure 11).

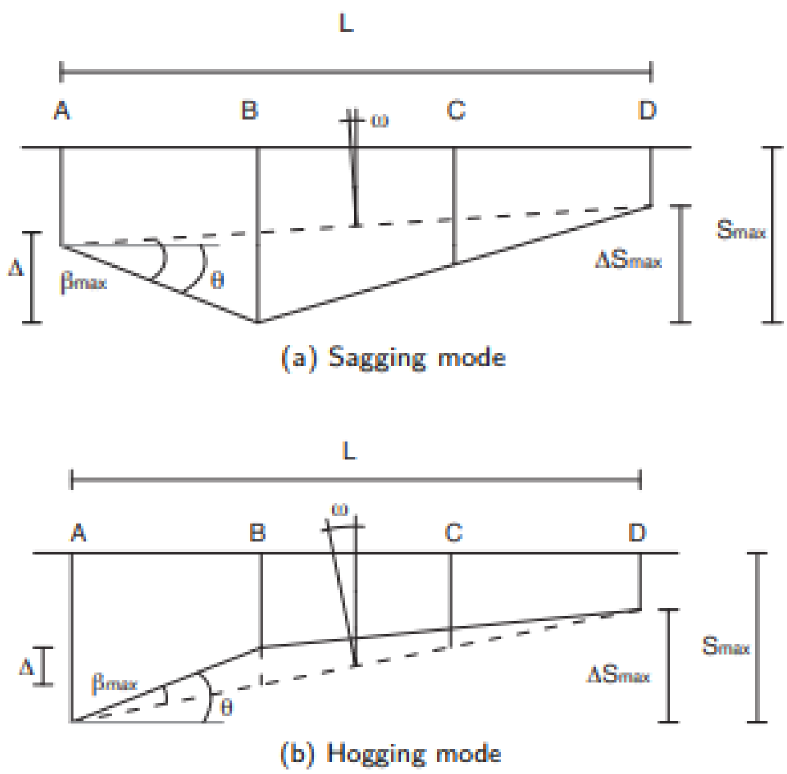


Figure 11. Deformation mode due to settlement

The former is characterized by sides of the building with greater slump than the average, while in the latter mode, greater slump is at the centre of the building.

Building deformation can be specified in more detail into several modes, such as shear and bending deformation as well as elongations and shortening (Figure 12).

Generally, a combination of deformation modes occurs simultaneously. When settlement affects the building, tensile strains occur due to bending deformation and diagonal strains due to shear deformation, generally both at the same time.

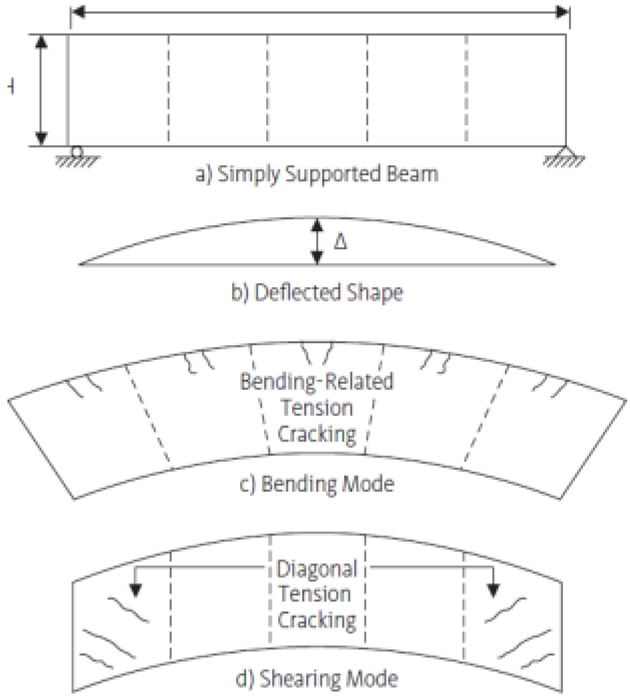


Figure 12. Overview of deformations in buildings and related damage. Boscardin & Cording [38]

2.4.1 As-Built Specimen Geometry

The tuff units used for URM had the same dimensions of those employed for the tested tuff wallets previously described, such as the mortar joints with a thickness of 10 mm.

According to technical product declarations by the mortar manufacturer, the premixed hydraulic mortar was classified as M2.5 (corresponding to mean compressive strength of mortar f_{cm} = 2.5 MPa). Mechanical properties of the constituent mortar system materials were first determined through laboratory tests. During the construction of each URM, mortar prisms (40x40x160mm^3 in size) were prepared and tested under three-point bending according to EN 1015-11 standard [22]. The two parts of each prismatic specimen after flexural failure close to the mid cross section were individually tested under uniaxial compression.

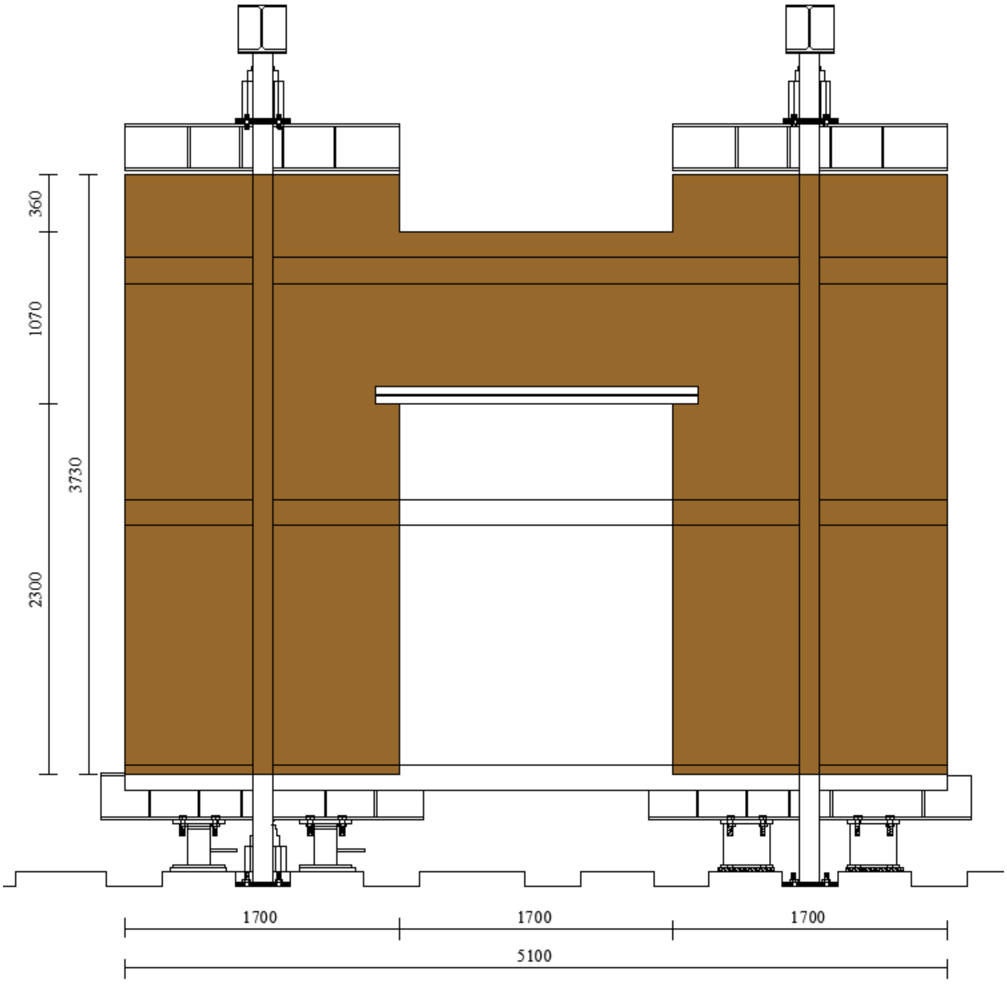


Figure 13. Dimensions of tested URM (in mm)

The wall was globally 5.10 m long, 3.73 m high, and 0.31 m thick, composed by two piers connected by a spandrel panel. Both piers and spandrel panel had a length of 1.70 m, whereas the height of the latter was equal to 1.07 m including the wooden lintel, that has a bond length of 150 mm at both sides of the spandrel (Figure 13). URM can be seen as a representative part of a building type structure, so the presence of the other overlying storyes, is assumed through the transferred load from three masonry layers constructed over the spandrel. The brickwork is arranged in a stretchers bond pattern with all stones laid as stretchers and half-bats at the beginning or at the end of alternate courses .

The fabrication of deteriorated URM was controlled so that *s/t* was equal on average to 20%, such as for wallets tested in diagonal compression.

A joint study on masonry behaviour in degraded conditions was carried out with UR3 Perugia, within the framework of the DETECT-AGING research project. In the SHM framework, the damage modelling strategy within the finite element method FEM plays an important role in the implementation of automatic damage detection algorithms, allowing the development of simplified macro-element models from FEM [18].

The challenge in the DETECT-AGING framework, is to correctly identify when damage detected through SHM measurements is caused by, for example, structural deterioration; and with structural models, to develop numerical analyses to analyse the structural vulnerability for the quantification of structural damage. A configuration of accelerometers was used on the URM deteriorated specimen with eleven devices useful to assess the decay of frequency and modal form. Results of the SHM measurements are not elaborated in this thesis as it is the subject matter of UR3 "Department of Civil and Environmental Engineering, University of Perugia" activity.

2.4.2 Test Setup and Instrumentation

2.4.3 Damage Patterns and analysis of the Experimental Force-Displacement Curves

2.5 Out-of-plane testing of unreinforced masonry wall

This part of the thesis presents the results of a laboratory test carried out on a full-scale unreinforced masonry wall (URM) with an opening subjected to a progressive damage induced by increasing out-of-plane loading conditions. As previously described for other tests, two configurations have been adopted, *i.e.,* intact and deteriorated to pay attention on aging effect. The main objective of this study is to improve the understanding of failure mechanisms occurring when URM walls are subjected to horizontal forces by analysing and discussing failure modes and their out-of-plane capacity and make available accurate and reliable experimental data to be used as validation of numerical models.

Existing URM buildings tend to be more vulnerable than new buildings, not only because they have been designed to little or no seismic loading requirements, but also because the façade may separate from transverse walls and overturn or fail by bending, not being firmly connected to horizontal structures [39].

The vulnerability of masonry walls under out-of-plane loads is one of the main causes of earthquake induced damage, but not only. In general, horizontal forces generated from roofs, arches, and vaults not counteracted by appropriate structural elements can lead to out-of-plane mechanisms similar to the effects of seismic actions. Therefore, flexural collapse may occur in slender masonry panels and/or panels restrained far apart from orthogonal walls.

The strength assessment of existing URM structures is important due to the large number of buildings designed without due consideration to wind and earthquake loading.

For URM walls subjected to out-of-plane loading, several key factors, must be considered: support conditions, masonry material, random variability of masonry; and the cause of out-of-plane loading.

According to the support condition, if the upper and lower edges of the wall are restrained between rigid supports, such as walls built inside a reinforced concrete frame, then significant in-plane arching can develop resulting in increased load capacity. (Figure 14.i). A wall fixed only on vertical sides and with reduced restraint along its base will undergo one-way horizontal bending (Figure 14.ii). For all other factors being equal, these walls generally show greater capacities than vertically spanning walls. For walls with at least two adjacent supported sides, two-way bending will occur (Figure 14.iii), further increasing the capacity.

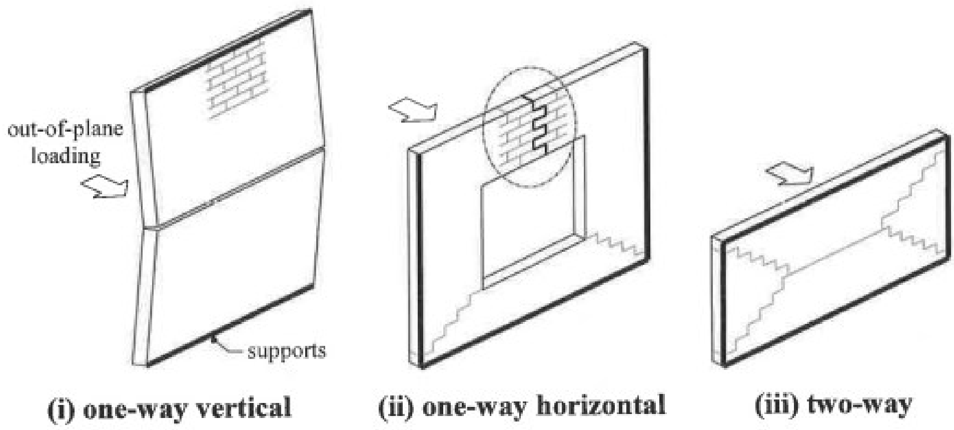


Figure 14. Out of plane bending mechanism [40]

Masonry is a composite material consisting of units and mortar, it is markedly non-homogeneous and anisotropic, showing distinct directional properties due to the planes of weakness created by the mortar joints so this influences also the different bending mechanisms. In addition, the factors affecting variability include inherent variation in materials, variation in manufacturing processes, unit and mortar properties (surface conditions, porosity, moisture content and suction rate).

For the cause of out-of-plane loading, for seismic loading, out-of-plane bending arises as a result of the inertia forces caused by the transverse horizontal component of the ground motion [41].

For multi-storey buildings, the inertial forces are higher for upper storeys, that are the weak elements in the seismic load path of URM for the inadequate out-of-plane bending strength, because of a combination of higher out-of-plane loading and a lower level of axial loading, which produces stabilising moments and acts to strengthen the walls [42].

However, it is not excessively conservative to assume that the out-of-plane load, which may be directly related to ground acceleration, is uniform over the storey heigh.

Walls subjected to out-of-plane loading are known as “flexural walls” because the flexure is the predominant action. The out-of-plane behaviour is considerably more complex than in-plane behaviour of walls, because in the former the tensile strength in horizontal flexure can be several times greater than the strength in vertical flexure [43].

This difference can occur because the vertical flexure depends basically on the tensile bond strength of the unit mortar interface of the bed joints, whereas the horizontal flexure depends on the friction resistance of the bed joints and on the tensile bond strength at vertical joint interfaces.

In unreinforced masonry walls supported on four sides, the vertical bending moment at mid-height of the wall induces tensile stresses perpendicular to the bed joints. When these stresses are higher than the tensile strength, a horizontal crack initiates and the behaviour of the cracked wall depends upon the orthogonal flexural strength of the masonry. The crack propagates along the bed joints and the mechanism is immediately formed (Figure 14.iii). On the contrary, when the horizontal flexural strength is greater than its vertical strength, a crack propagates along the bed joints under constant load and a stable state is reached with two sub-panels, each simply supported along three sides and free along the cracked bed joint, with a final diagonal crack.

In the experimental carried out activity, URM simulates perimeter building walls where the progressive release of steel tying, or the punctual load of arches, pushes URM to an out-of-plane load, resulting in bending mechanism. Progressive release of steel tying can be seen also as a degradation effect of previous (historical) retrofit interventions.

2.5.1 As Built Specimen Geometry

2.5.2 Damage Patterns and analysis of the Experimental Force-Displacement

2.5.3 Damage Patterns and analysis of the Experimental Force-Displacement

Chapter 3

Experimental-Theoretical Comparison

3.1. Abstract

Ancient masonry buildings are often characterized by high seismic vulnerability, due to low tensile strength. Particularly for the spandrel panel, tensile strength could have a key role for the assessment of buildings. In this background, the numerical analyses provide important information about the structural behaviour of such elements. However, the use of refined numerical FEM models can be always adopted as a support of an analytical modelling approach. Spandrel behaviour, part of URM substructures, was studied for the different load and degradation conditions. Spandrels are usually modelled as piers, but rotated by 90°, and boundary conditions are very different from those of piers, so transposing the experimental results of piers to the spandrels without failure criteria modifications can be inconsistent.

In this background, an analytical modelling approach for capacity assessment is presented.

For the settlement load, building damage criteria based on critical displacement parameters, namely deflection ratio, horizontal strain, and twist, are proposed.

3.2. Settlement test

3.2.1. Theoretical model

3.3. Theoretical model for out of plane testing

As pointed out by Liu et al [44], in Figure 15 the increase of the axial load increases the out-of-plane strength but also reduces the ductility.

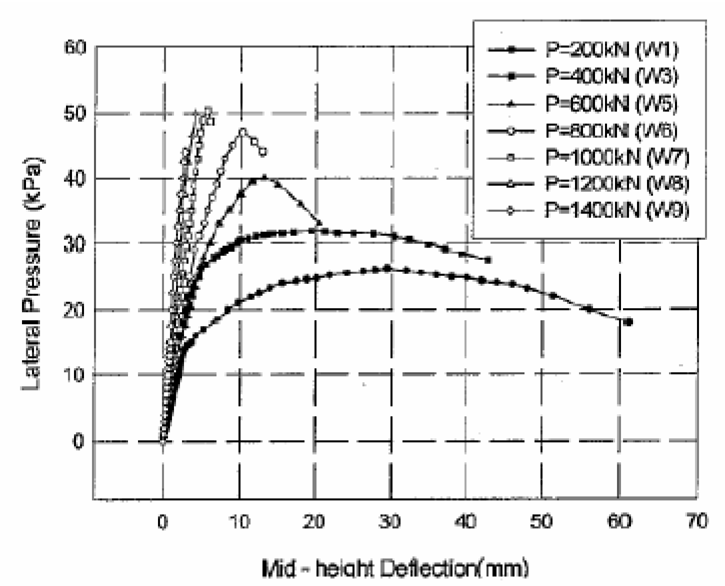


Figure 15. Mid-height deflection vs. lateral pressure measured in reinforced masonry walls (Liu et al [44]**).**

Brittle behaviour exhibited by the degraded URM is compatible with the last remark, with a drop in load capacity after peak load was reached. For the intact URM, peak load is recorded for a considerable displacement, but this is attributable to the splitting phenomenon, which partially interrupted the overturning mechanism. Deteriorated wall had a proportionally higher axial load ratio, since its vertical capacity is lower.

As in shear walls, where the behaviour is governed by in plane mechanisms as illustrated before, flexural strength of masonry is a central property in the behaviour of walls under out-of-plane loading.

Vertical axial load has implications in the evaluation of the energy absorbed in the bed joints:

Four kinds of joint failure mechanisms, namely bending and torsional failure of bed and head joints, majorly contribute to the force capacity of wall, along a diagonal crack line, as happened in the intact test (Figure 16,Figure 17) :

1) the flexural tensile strength of the head joints ;

2) the torsional capacity of the bed joints;

3) the torsional capacity of the head joints;

4) the flexural tensile strength of the head joints ;

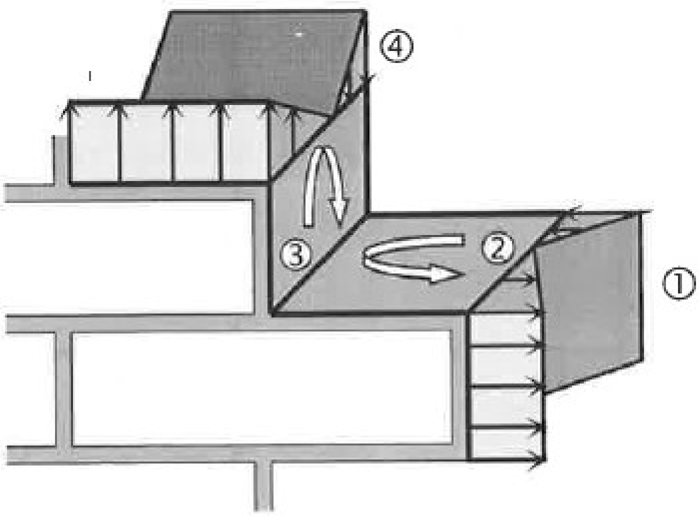


Figure 16. Failure mechanisms contributing to flexural strength.[40]

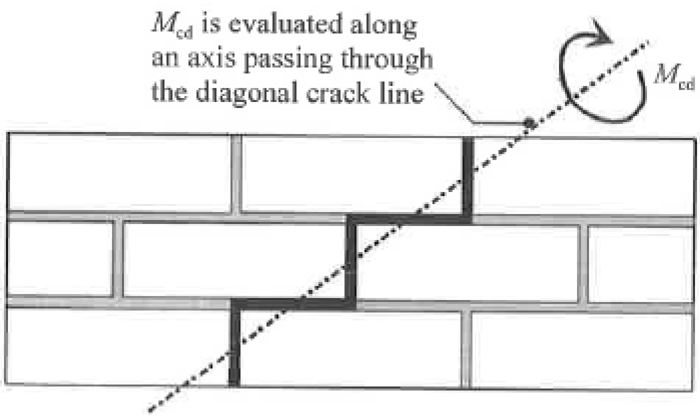


Figure 17. Bending moment along an axis passing through a diagonal crack line[40]**.**

Lang-Zi Chang [45] explained that fracture energy dissipated by all joint failure mechanisms increases as the pre-compression increases.

Intact URM showed a diagonal stepped crack affecting the loaded pier and passing through the whole spandrel thickness due to a clear overturning mechanism. The achievement of flexural tensile strength yields to URM failure. Due to the lack of experimental data on the masonry's flexural strength, for the spandrel it is increased by 1.2 the previously introduced pure tensile strength (see equation 14)

Chapter 4

Finite Elements Nonlinear Modelling of Masonry Structures

4.1. Abstract

A relatively simple numerical model, suitably calibrated, is used to analyse the results of the experimental investigation, leading to a validation of the model itself.

The work includes the calibration of numerical microscopic/detailed models considering the masonry units and the mortar joints separately and characterized by different constitutive laws.

Hereafter, as presented in the experimental part, first numerical analyses on bricks and then on tuff masonry are illustrated. The finite element method (FEM) was used to simulate the mechanical behaviour of the walls tested under uniaxial, diagonal compression test and for URM subjected to in and out plane. The experiments were simulated using the FEM software DIANA FEA 10.4

4.2. Numerical modelling for diagonal compression test

4.3. Masonry modelling, boundary conditions

4.4. Comparison of numerical-experimental brick test

4.5. Comparison of numerical-experimental tuff test

4.6. Numerical modelling for settlement test

4.7. Numerical modelling for out plane test

Chapter 5

Conclusions

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