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Artículos

In-situ Empirical Characterization of Constructive Typologies and Vulnerability Factors of Historical Nuclei, as a Prerequisite for the Construction of Suitable Experimental and Numerical Models - Case of the Dellys Kasbah*

Caracterización empírica *in situ* de las tipologías constructivas y los factores de vulnerabilidad de los núcleos históricos, como requisito previo a la construcción de modelos experimentales y numéricos adecuados - Caso de la Kasbah de Dellys

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Abstract:

This article aims to characterize empirically the constructive typologies of the Kasbah of Dellys, Algeria and the damage associated with them following the 2003 earthquake.

Visual recognition is essential as a prerequisite for the definition of experimental programs and simulation tools based on the typological characteristics of these discrete structures.

From the corollary of the data collected, there are categories of vulnerabilities involving building scales ranging from masonry apparatus to built aggregates and structural components. To this end, an adapted theoretical experimental protocol is outlined, combining several methods and levels of urbanfabric, structures and material investigations in accordance with the heritage character and the progress of research on weak masonry structures.

Keywords: stone maçonnerie, building process, built aggregate, visual diagnosis, discrete structures.

Resumen:

Este artículo pretende caracterizar empíricamente las tipologías constructivas de la Kasbah de Dellys, Argelia y los daños asociados a las mismas tras el terremoto de 2003.

El reconocimiento visual es esencial como requisito previo para la definición de programas experimentales y herramientas de simulación basados en las características tipológicas de estas estructuras discretas.

A partir del corolario de los datos recogidos, existen categorías de vulnerabilidad que implican escalas de construcción que van desde los aparatos de mampostería hasta los agregados construidos y los componentes estructurales. Para ello, se esboza un protocolo experimental teórico adaptado, que combina varios métodos y niveles de investigación de tejidos urbanos, estructuras y materiales, de acuerdo con el carácter patrimonial y el progreso de la investigación sobre las estructuras débiles de mampostería.

Palabras clave: Maçonnerie de piedra, proceso constructivo, agregado construido, diagnóstico visual, estructuras discretas.

Introduction

The masonry confinementwhich transforms drastically the original features of the building, derogates fromthe Unesco's conservation spirit, which tries through ICOMOS/ISCARSAH to maintain threatened heritage assets under the most unfavorable natural conditions. The characterization of materials and structural systems, assumes a historical dimension in regard of Mediterranean seismic culturesrediscovery requiring a cognitive approach to the technological characteristics of the existing building.

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At the Dellys Kasbah, during work onplaces of worship affected by the earthquake, reinforced concrete containment elements were used, opposing rigidity to the flexibility of the original materials. In this regard, the post-seismic experience feedback from 2016, in Norcia and Amatrice, in Aquila and Lazio, Italy, invalidated many similar investigation methods and reinforcement techniques.

The study of a corpus of 120 out of 200 houses in the Dellys Kasbah in homogeneous areas has made it possible to identify the architectural features and construction techniques (Bougdal, 2006). Recurring weaknesses in constructive and transformative practices had been identified, calling for more *in-situ* recognition. In addition, the safeguard plan reveals shortcomings in method, content, characterization of materials and structural behavior, particularly with regard to seismic action. This raises the question of research on unreinforced masonry (URM) building, which has long been excluded from approaches to discrete anisotropic media (Sauve et al., 2013).

As a result, visual characterization is required as a prerequisite for deepening the knowledge of the mechanical and behavioral properties of these reputedly discrete structures, with the aim of building appropriate analytical and numerical models. This delicate exercise involves the *in-situ* exploration of the geometries of materials and structures taking into account the stratification of the building, the typological architectural characteristics and construction techniques as well as pathologies and disorders linked to the environment and static and dynamic loads. The results achieved will provide a basisfor discussion on possible experiments at different levels of construction (urban fabric, built aggregate, materials and their assemblies). Experimentation can be conducted by correlating in situ characterisation with URM masonry research data, which uses increasingly accurate discrete models.

To decide on more appropriate rehabilitation and reinforcement solutions, laboratory tests and numerical modelling are used to better understand the failure mechanisms of structural elements in limit state. The characterization of the vulnerability factors of the traditional constructive typologies of the Kasbah goes through two stages:

1. The restitution of architectural and constructive typological characteristics as well as transformations and evolutions related to historical stratification,
2. The visual characterization of constructive typologies's vulnerability factors through the pathologies and structural disorders of the various components (materials, walls, floors, roofs), and those relating to their connective relations. Vulnerabilities due to the evolutionary and transformative process will also be identified, both at the scale of the built unit and the aggregate.

The body of knowledge and the data from these two steps will allow the approach of characterisation's methodissues of traditional constructions and those of their vulnerabilities in two stapes. The first is to discuss the results of *in-situ* characterisation of constructive typologies and vulnerability factors, including seismic dynamics in light of current discrete structure research data. Second, consideration will be given to the relevance of a more refined theoretical characterization protocol as well as the structural performance of the constructive typologies representative of the study case.

The draft protocol based on the empirical characterization of materials, structures and a first interpretation of vulnerability factors will include:

- An assessment of global seismic vulnerability by the Risk-EU method,
- In situ characterization of stress and elasticity module by the Flat Jack technique,
- An assessment of disorders of the discreet NSCD method,
- A classical program characterizing typical variants of masonry and its constituents.

Architectural and constructive typologies - From primary forms to hybrid transformations

The Dellys Kasbah is one of the rare historic coastal centers of ancient foundation in the Kabyle reference area of Djurdjura. It is located on the eastern slope of a tapering cape, the coastal end of a ridge (figure 1). The buildings are staggered on a barred spur site, with an average slope of 25 %, reaching 45 % upstream. The identification of architectural and constructive typologies was a prerequisite for the diagnosis of the building. The critical survey, which is the first step, highlights all the consistency, the evolution by successive additions from isolated building to complex structures and volumes, making the identification of vulnerabilities more difficult, and therefore the knowledge of the structural evolution essential (Binda et al., 2005).

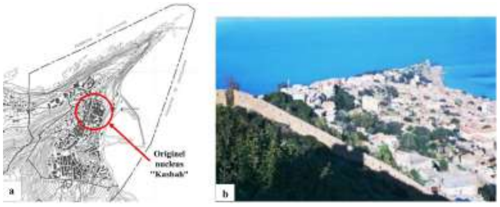

FIGURE 1.
Views of the historical urban area of the town of Dellys
Note: (a) Situation of the Kasbah in the safeguard perimeter. Source: Ministry of Culture.
(b) View of the historic center inscribed in the 19th century rampart. Source: own work

The two-storey houses that characterize the establishment crystallize in homogeneous aggregates. The introverted organization around a central courtyard *Haouch*, gives rise to an arrangement of opposing or angular buildings, according to the proportions and the stage of construction of the plot (Bougdal, 2006). The distributive mode remains at a proto-urban typological stage, with the location of the staircase in the courtyard. External galleries *Shin* or *Setwan* can be added to the structures, depending on whether they are located on the ground or upstairs. The primary body houses in its lower part the chicaneaccess system *Skiffa*, as well as the stable *Daynin*; the floor being reserved for a room *Ghorfa* or two, depending on the length of the building. The subsequent bodies, at the *Haouch* level, contain rooms *Biout*, without any specific specialization, while the upstairs rooms *Ghrof* constitute the sleeping area (figure 2).

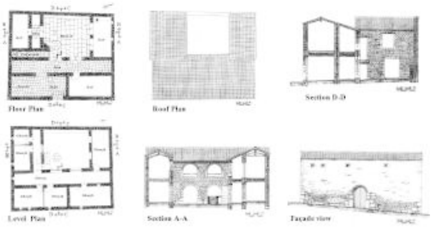

FIGURE 2.
Typological variant of house with courtyard
Source: Bougdal, 2006

Recurrent original constructive typologies and their evolutions

The sandstone walls, with a pseudo-isodomumapparatus, 50 to 70 cm thick, are formed by two walls of sandstone 8 to 10 cm thick, naturally squared and bedded, enclosingsmall pebblesand clay (Quelhas et al., 2014). A second variant, not widespread and of lesser quality, is characterized by rolling pebbles, of which only the visible side is squared (figure 3). These Mediterranean typologies, also present in Italy, are associated with earth mortar. According to their specialization, the walls are of three categories: longitudinal-wallssupporting the major partof the floors and roofsloads; gable-walls and shear-walls, independent of the floors, serving as supports for the ridge-purlins.

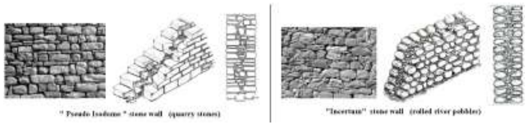

FIGURE 3.
Typological variety of walls
Source: own work

Stacked floors result in a thickness of about 50 cm. The variant is a primary hurdle of oleaster, formed of a sinuous main frame from 2.00 to 3.00 meters, the branches of which are preserved to gain in reach. This, also found in Lefkara (Cyprus), serves as a support for a bed of stones laid out as an overlap, in which is superimposed a layer of earth of about 20 cm and a finishing paving (figure 4).

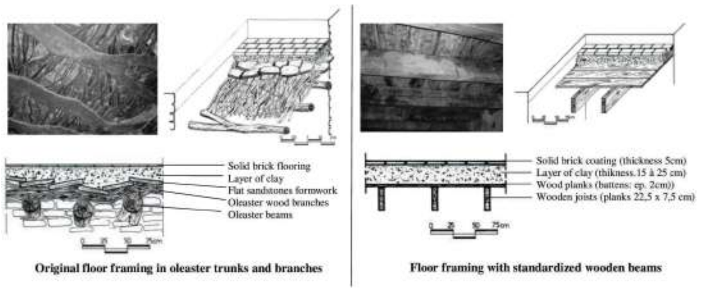

FIGURE 4.
Typological variety of floors
Source: Bougdal, 2006

The roof consists of two main elements; the ridge purlin *Quontas*, resting on the gable walls and the splits, and a curved oleaster trunk *Errafda* anchored in the longitudinal walls, preventing the binding of the ridge, also identified in Sardinian construction. The covering meanwhile includes a reed trellis, then an earth mortar on which the canal tile rests. The hurdle loads relate to the ridge purlin and the longitudinal walls through rafters (figure 5).

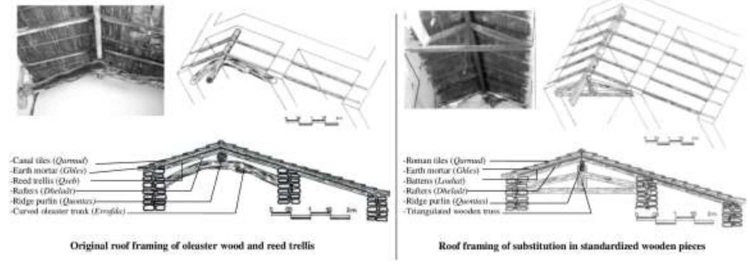

FIGURE 5.
Variants of roofs
Source: Bougdal, 2006

Spatial organizational transformations and structural hybridity

The phenomenon of overcrowding took place in the subdivision of spaces by separating partitions openings larger entrances (figure 6 d), closed *Shin* and *Setwan*, adjoining staircases, water rooms (figure 6 e and f).

The renewal rate for the entire corpus is estimated at 95 %. The transformation process has brought about the cohabitation of materials and structures from different periods. If the typology of the walls has remained unchanged, the original floor framing have been replaced by standardized wooden pieces (figure 4), vaults, concrete blocks associated with steel sections, reinforced concrete (figure 6 a, b, c). Regarding the roofs, triangulated wooden truss and the batten replaced the *Errafda* and the reed trellis (figure 6).

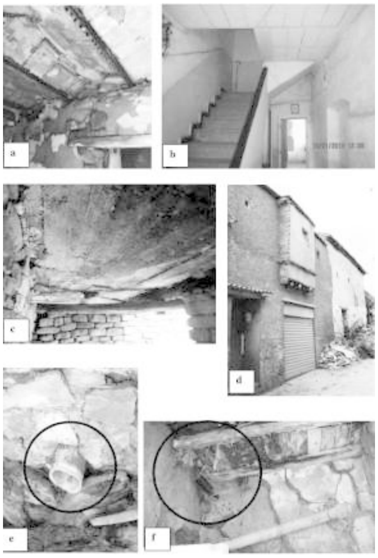

FIGURE 6.
Inadequate maintenance work
Note: (a) Brick vaults and metal profiles; (b) hollow floor and concrete staircase; (c) Concrete floor; (d) Large bay windows; (e) and (f) Waste water pipe incorporated into an original floor.
Source: own work

This characterization made it possible to develop the plan of constructive typologies by dividing the 120 houses of the corpus into six variants according to the synchronic and the diachronic evolution of the structural components (floors and roofs), the wall structures not having undergone notable change (figure 7a). This breakdown is as follows:

1. Original: containing the original structural characters,
2. Original + Colonial: Houses retaining original structural characters, and having introduced colonial characters,
3. Colonial: Structural character houses strictly colonial,
4. Original + Colonial + Postcolonial: Houses combining pre-colonial, colonial andpostcolonial structural characters,
5. Postcolonial: House comprising the postcolonial structural typology.
6. Colonial + Postcolonial: Houses combining colonial and postcolonial structural characters.

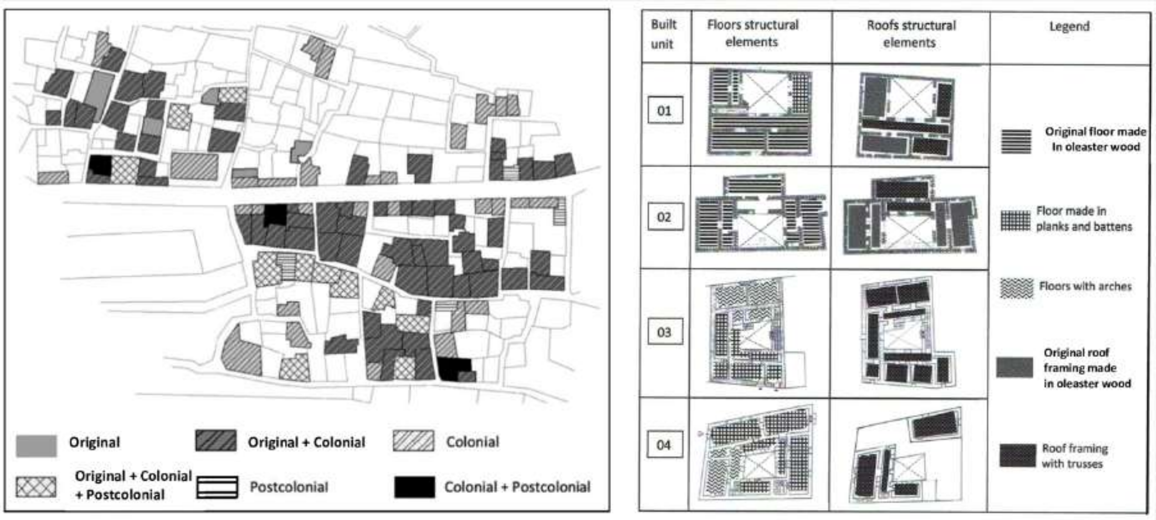

FIGURE 7

Structural stratification and concomitance

Note: (a) Stratification of the built corpus (120 houses) on the scale of the fabric of the Kasbah; (b) Example of structural concomitanceof built units.

Source: own work

Construction process and structural arrangement of the built units

The recurrent mode of construction for the entire urban fabric is the body built in a *box*, only one or two walls are added to form other bodies. The rest of the enclosure being ensured by the joint ownership of the pre-existing bodies and the terraced houses. This device generates structural discontinuities, since the heads of the walls are not connected with the previous bodies. When a later-erected body is higher, the missing rows of rubble and the crawling gables are laid in the adjoining cell, as shown in figure 8.

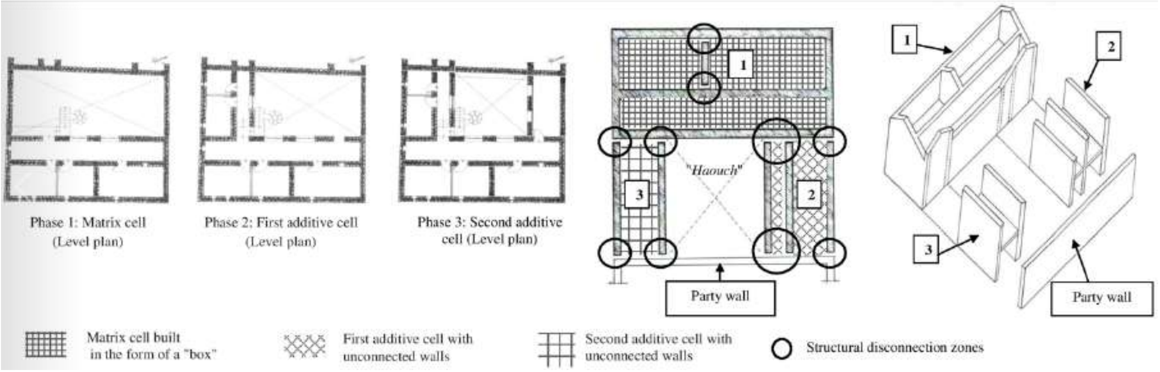

FIGURE 8.

The process of building the built unit

Source: own work

Seemingly autonomous, the houses reveal after probing, common wall structures and thus a close relation of agglutination (Ferreira et al., 2012). This form of economic growth, spreading as a tacit rule, to the entire historical nucleus, the easement of support establishing itself on the neighboring property, character generalizing to all the peripheral walls of the heart block houses (figure 9).

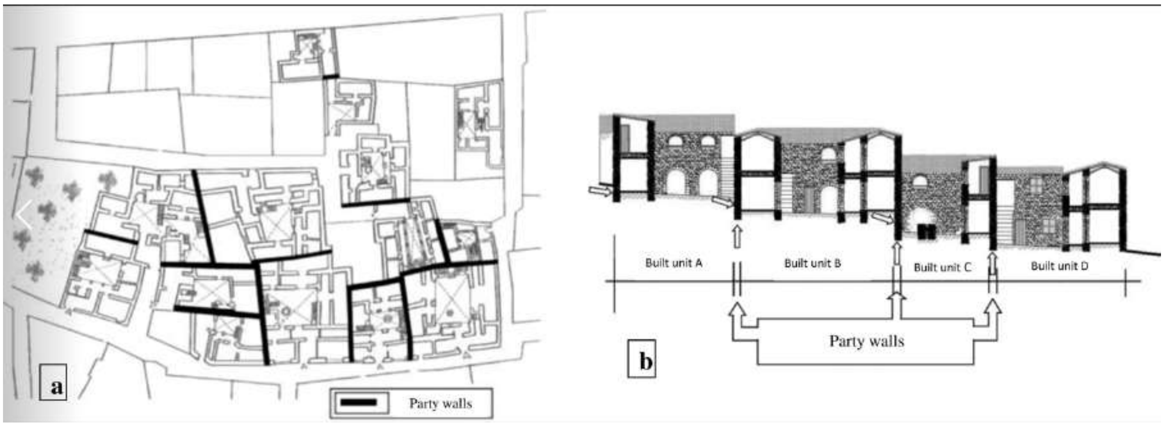

FIGURE 9

Structural joint ownership of the aggregate

Note: (a) Plan of a built aggregate; (b) Profile of a built aggregate.

Source: own work

Vulnerability factors: construction devices not very resistant to dynamic loads

The vulnerability factors of the constructive typologies identified following the Boumerdes earthquake of May 2003, presented in this chapter, are summarized as follows (table 1).

TABLE 1.

Vulnerability factors

Due to materials and implementation	**Due To Original Structuraldevices**	**Due to the transformations and evolutions of the building**
• Weakness of the apparatus of rubble. • Weakness of the mortar of brickwork.	• Low wall thickness. • Weakness of the gable tips. • Structural discontinuity of the peripheral walls of the bodiesof frames. • Length of the longitudinal walls and structural independence of shear walls. - Structural vulnerability of the complex aggregate. - Weak connections between floors and walls. • Heterogeneous transmission of floor loads. - Originals on the walls. • Deficiency of roof rigidity.	• Pathologies caused by floor substitution. • Opening of staircase hoppersin the frames. • Disorders caused by adding large bays windows and water points.

Source: own work

Vulnerabilities of materials and their implementation

Vulnerability of stone devices

The typological variants of walls lack of transverse connections (bond-stone and throughband) (figure 10a). Similar typologies leading to first order collapse mechanisms are reported in studies on Italian historic centers (Giuffré, 1993). As for the rolled stone walls (figure 10b) given the inclination of the stones, they present a problem of overall cohesion.

Under theeffect of loads and moisture, large and heterogeneous interstices filled with mortar submit the rubble components to shifts and settlements.

The out-of-plane bending results in overhangs, puffs, buckles, punctures. The «pseudo-isodomum» apparatus requires in some places, rows of finer stones and intermediate rubble to catch up with the level of laying. This results in discontinuities in the horizontal joints (figure 10c) which, under the horizontal seismic action, do not promote the friction movements necessary to dissipate the energy in hysterical form by the plastic deformation of the joints. Fiorentino asserts that for poorly matched and weakly paved walls, even metal tie rods are insufficient to cope with overcoming out-of-plane mechanisms, due to an inefficient transfer of forces to the masonry. The loading of the only internal wall, causesthe settling of the joints and the internal deformation of the walls. It was also found that the vertical crossing of the joints was not respected. Rubble stones often laid on a base stack underline continuous or insufficiently offset joints (figure 10d). On the other hand, their unequal size gives rise to a quality of the facing and an internal organization which does not comply with the rule (Sauve et al., 2013).

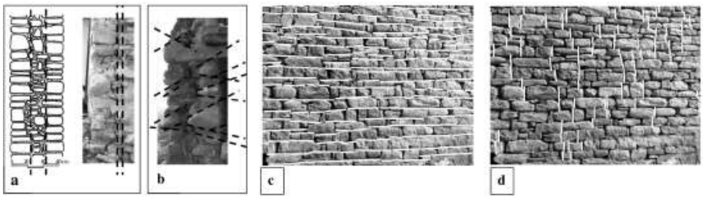

FIGURE 10.
Masonry equipment modes
Note: (a) Walls of stratified rubble; (b) Wall of rolled rubble with inclined faces;
(c) Discontinuity of horizontal joints; (d) Stack of plate effect of the device.
Source: own work

Low resistance of the mortar

The frequent presence in the mortar of straw strands, bones, pottery debris and other sea shells, attests to the little attention given to its selection. The earth is used in the pure state, except in rare cases where a heterogeneous and lumpy lean lime has been detected. If the mortar is generally fluent, able to support significant deformations, its resistance to meteoric and capillary water remains low (Bougdal, 2006). Therefore, long before the earthquake the degradation process has given rise to numerous collapses, due to leaching of the mortar (figure 11). This same weakness is reported on similar mortars in Accumoli and Amatrice (central Italy) during 2016 earthquake. Breakage onthe horizontal and vertical joints is wide spread at the Dellys Kasbah. The resistance in these cases is related on the one hand to the tensile strength by bending in the vertical direction of the joint and on the other hand to the torsional strength and to the friction in the horizontal direction of the joint (Bisoffi-Sauve, 2016).

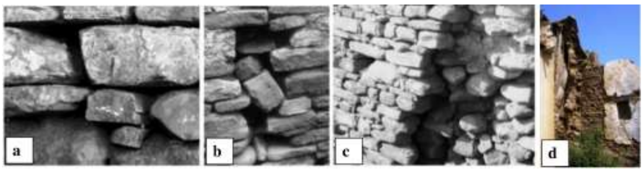

FIGURE 11.
Default collapse mode of joining
Note: (a) hollowing out of the joints; (b) disorganization of the rubble; (c) collapse of the outer wall; (d) suitability for deformation of the rubble-mortar assembly.
Source: own work

Vulnerability of the original structural devices

Wall thickness and slenderness

If for this type of wall the tolerated free height of 2.80 m complies with the general rule, the use of cut stone is required for any additional level. As for the slenderness ratio, for a wall to bee well made, the height/thickness ratio must not exceed the index value of 8 (Zacek, 1996). Given the values recorded 800/60 = 13 or 600/60 = 10, the typology of the walls of the Kasbah remains below the standard requiring 75 to 80 cm of thickness, allowing work in shear in the plane.

Vulnerability of gable wall spikes

The breakage of the gablewall spikes (figure 12) is often due to jointing. Thus, when the ridge purlin of a subsequent body presses on the wall of an older body with different foundations and levels, theresult is a differential work of the two structures, and a weakness to horizontal and torsional seismic stresses at the location connections. Other actions such as dimensional fluctuations of wood and hammering of ridge purlins contributed to this during seismic events

FIGURE 12.
Damage to the gable-walls
Source: own work

Vulnerability of bodies with discontinuous peripheral walls

Under the seismic action, the additive cells deprived of orthogonal links do not behave like a *box*, condition for a good resumption of the horizontal seismic actions. The extent of the disorders noted at the re-entrant angles, following a high concentration of torsional stresses, confirms the vulnerability of such a constructive arrangement (figures 13 a and b). The shear weakness is even greater when these walls are pierced with large openings, without strong frames. This is the case of the galleries overlooking the *Haouch*.

Length of the longitudinal wallsand dissociation of the shear-walls

The main buildings sometimes approaching fifteen meters in length deprived of an orthogonal connection with the partitions, give rise on the one hand to disorders linked to vertical loads and horizontal thrusts which accentuate the deformation of the longitunal walls. On the other hand, those linked to seismic, torsional and horizontal actions, causing out-of-plane bending, lead to the separation of the longitunal wallsfrom the floors, roofs and shear walls. The consequences being the appearance of cracks or the collapse of walls sections (figure 13 c).

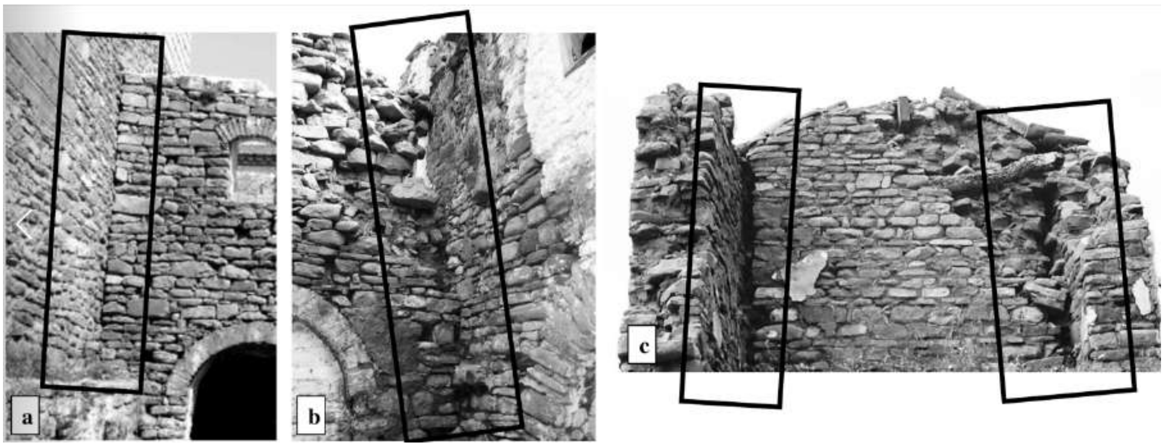

FIGURE 13.
Disorders of wall discontinuities
Note: (a) and (b) Damage from torsional forces in interior corners; (c) separation of the gutters and splitting.
Source: own work

Structural vulnerability of the complex aggregate

At the aggregate scale, the joint nature of the walls and the chain linkage of the built units gives rise to considerable seismic failure mechanisms sometimes extending to entire blocks of houses. The built units, are the result of an unconscious addition of cells having generated irregular geometric shapes, are far from meeting the traditional *earthquake.resistant* demand.

Other factors such asthe orography, the plot morphology, the interweaving of built units, the wall discontinuities, the fact that a majority of structurally connected bodies are independently founded, contribute to this (Ferreira et al., 2012). Indeed, given the steep slopes of the land, the postponement of roof loads on contiguous bodies with independent ground bases, generates differential settlement, giving rise to disorders in the connection zones (figure 9).

During the earthquake, the structural rigidities induced mainly by the transformations of the floors affected, particularely by hammering effect, not only the buildings subject to redesign but also those adjoining

(Valluzzi, 2007). The effects caused by this structural associations at the scale of the built unit (figure 9), deserve to be considered in the context of diagnosis extended to macroelements, of the whole built aggregate.

Weak wall / floor connections

The connective weakness between walls and floor frames is illustrated in the mid-wall supports, to a depth of barely 10 cm, preventing the distribution of loads throughout the thickness of the wall (figure 14). On the other hand, this causes the joists to separate from their supports, due to the stacking of floor components, which by lack of overall solidarity, tends to bend. Note the non-existence of traditional reinforcements such as steel or wood anchoring rods, to deal with wall gaps.

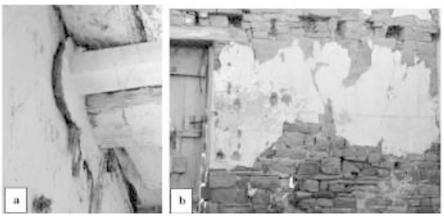

FIGURE 14.
Weaknesses of joist embedding
Note: (a)Joistsout of their supports;(b) Inconsistency of cavities.
Source: own work

Heterogeneous loads in the walls of the original floors

The original floor variant, with sometimes pronounced sinuosities, results in a heterogeneous distribution of the soil layer over the floor area (figure 15). This leads to inequal distribution of loads in the load-bearing walls, determining segments differently stressed and giving rise to varying settling of mortar joints and foundations (figure 9). The failure mode, resulting in vertical or inclined cracks, could be localized at the interface of rocky and plastic foundations, reacting differently to seismic actions.

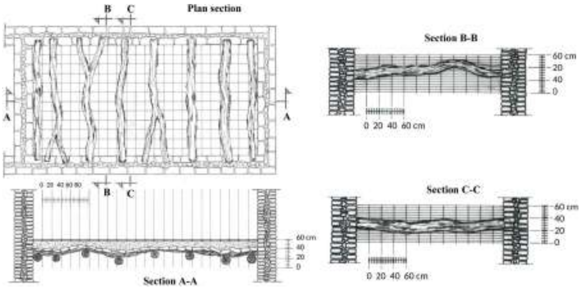

FIGURE 15.
Heterogeneity of loads in the original floors and walls
Source: own work

Roof stiffness deficiency

Roof timber frames tend to deform under the action of dimensional fluctuations and slope loads. Seismic effects on the roof are favored by the independence of the components (trusses, purlins, rafters and battens), simply stacked and not linked, able to withstand tensile/compressive forces. These disorderly movements mismatched the load-bearing elements and the covering and poured out the support of the ridge purlin *Djaiza*, which was not braced. In the direction of the gutters, the oscillatory movement of the purlin causes the rafters to slide out of plane and therefore the wall edges to dislocate. In the other direction, the same ridge purlin hammers the gables, disrupting the masonry and often causing collapses. Traditional tenon and mortise truss assemblies have shown their ineffectiveness in this case. As for the rafters they are connected by nailing to the ridge purlin and simply anchored in the masonry at the head of the wall without peripheral chaining.

Structural vulnerabilities to builttransformations and evolution

Pathologies caused by floor substitution

The introduction of new elements with all the structural reorganizations that this entails, openings, renewal of floors, addition of partitions, modify the usual behavior of structures. The frequent substitution of the original floors bystandardized wooden floors if it has the advantage of the uniformity of the soil thickness and the distribution of loads in the walls; it has nevertheless the disadvantage of modifying their usual path and distribution. This is also true for other substitutes, vaults, cement blocks or reinforced concrete slabs (figure 6), which, given their excessive mass and rigidity, undermine the walls, right down to the foundations. The frequent cross cracks observed at the supports of theI-beams illustrate the structural inadequacy. The same disorder was widely noted in Pescara-del-Tronto and Vezzano (central Italy) during the 2016 earthquake (Masi et al., 2016).

Opening of stair hoppers in built bodies

The stair hoppers incorporated into the main buildings further weakened the structure, as they constitute a break in the connection of the horizontal structure with the walls. The consequences are a greater aptitude of traditional floor frameto disorganization and deformation under seismic loads, thereby causing the out-of-plane displacement of the facade walls, the removal of joist from their supports and the separation between walls and floors. In extreme cases, the collapse of the latter is to be deplored.

Disorders caused by the addition of large bays and water points

The drilling of large openings lacking solid frames generates an increase in the deformation capacity and weakens the resistance of load-bearing walls with a geometic and consistency deemed low. This results in failure mechanisms in the form of lateral seismic loads, deforming the walls in a parallelogram. Shear breaks acan be read in diagonal cracks, originating at the angles of openings and progressing through the joints to other openings or wall edges. Combined with the floors and roofs off-plan behavior, the rupture phenomenon has often evolved into the partial or total collapse of facades. The introduction of the sanitary facilities upstairs has resulted in disastrous accidental leaks in floors and walls. This is evidenced by collapsing, repairs, rotting of wood, loss of clay material at conduit location.

Discussion

Analysisof the main results of the in-situ characterization of constructive typologies andvulnerability factors

Auscultation of structures at different stages of the degradation process reveals many weaknesses, elementary with regard to the rule of the art. This reveals an obvious lack of local seismic culture, due to a moderate and non-recurring regional historical seismicity. The earthquake-resistant measurements, tie rods, massification of walls, buttresses, bracings, wooden stiffeners, etc., present in other seismic regions, are little known in the local tradition. At the end of this diagnosis, many vulnerability factors emerge, the main of which are:

1. The deficiency of the interconnections of the built system elements, walls/floors and walls/roofs,
2. The deficiency of the stone apparatus and weakness or absence of connections between longitudinal-walls, gable-walls and shear-walls.
3. The weakness of the mortars,
4. The deficiency of the mode of adduction of the frames.

1. Concerning the relation between the structural elements of the built body, it was noted the absence of connections walls/floors and walls/roofs, necessary for an overall reaction as *abox*, fundamental to a good mechanical resistance of this type of construction. According to D'Ayala,

> such an arrangement, allowing the transfer of interstitial and dynamic actions of the elements working in bending out-of-plane towards elements working in in-plane shear, leads to a global response better suited to the resistance of materials, therefore to high performance and lowering damage levels. (D'Ayala, 2014)

2. The wall apparatus, lack of transverse connection, bond-stone and throughband, essential for resistance to static and dynamic seismic stresses. The absence of toothing-stones uniting longitudinal walls and splits deprives the cells in their lenght of wind-bracing capable of limiting the out-of-plane effects of horizontal and seismic actions.

This type of disorder has often been solved by empirical measures with a dissipative effect, in particular by metal tie rods under certain conditions of organization of the masonry. These aim to re-establish the connection between perpendicular walls and control the relative displacements, thus reducing the load stress results transmitted to the substrate and the risk of breakage and punching.

If the original structural typology and the first transformations were able to withstand the test of time despite intrinsic weaknesses, they nevertheless remain vulnerable to strong seismic stresses and sudden transformations. Proof of this is given by the section of the walls, no longer meeting the required seismic standards (Zacek, 1996). This type of structure, common in the Mediterranean basin, shows great fragility to out-of-plane collapse mechanisms (Giuffré, 1993). On this subject, seismic archeology reveals a massification of the walls in many historical cores with recurrent seismicity, to compensate for undersizing. To this end, it is necessary to accurately assess the geometry of the devices and to quantify the volumes of stone, mortar and the distribution and dimensions of the interstices, with a view to subsequent studies on mechanical behavior and modeling (Quelhas et al., 2014).

3. It was noted that the breakageof the masonry occurs mainly within the joints and in the wall lining, indicating a significant difference in resistance between the sandstone rubble and the low consistency and erosive earth mortar. The models of prediction of lateral behavior of the walls require a good knowledge of the resistance to compression, bending and shearing of the joint. In addition, experimental tests on unreinforced masonry must be based on suitable methods able to provide the most credible mechanical properties.

4. Morphologically, the houses, although they have some aptitudes to resist an earthquake (rectangular shape, low height, low center of gravity), present a mode of cell adduction (figures 8-9), constituting the one of the most severe vulnerability factors that has been diagnosed. This was the cause of multiple disorders and extensive collapses in urban aggregates during the 2003 earthquake. These same characteristics observed in Castelluccio-di-Norcia (Italy) generated particularly destructive mechanisms (Valluzzi et al., 2007).

In this context, it is important to initiate a reflection on the independence of frame structures in reconstruction operations, in accordance with calculations results, laboratory tests and simulations.

A theoretical protocol for characterizing the structural performance of the constructive typology representative of the case study

The status of classified historical nucleus, requiring the conservation of traditional materials and techniques, favors non-destructive physical and behavioral tests, more likely to reveal results in conformity with reality. These will be followed up in the laboratory, with tests that cannot be carried out *in-situ*, through the reproduction of structural models. The tests to be carried out could take the form of an experimental program adapted to the seismic, typological, structural and pathological characteristics of the building, based on visual diagnostic data. Many studies come up against the difficulty of defining constitutive laws and modelingso-called discrete structures, in particular because they are differentiated by the heterogeneity of the components in the transverse and longitudinal sections of the walls (Quelhas et al., 2014). For this reason, *in-situ* observation is a prerequisite for a significant contribution.

Even though a technique may seem transposable, local peculiarities such as the quality of the stone, the mortar, the implementation, must be considered. An illustrative example is the very heterogeneous load distribution of joist floors in the walls (figure 15), the stacked stone effect and other defects, finding few suitable modeling applications. It emerges from this historical ensemble obeying a stratification by successive additions of buildings, a multiplicity of incongruous constructive responses, unsuited to the seismic context. For their behavioral evaluation, similar typologies are often assimilated to contemporary or traditional monumental construction methods, to freestone elements and regular devices and building shapes, allowing finite element calculation methods.

These readings reveal the complexity of the common building typologies, made of small rubble and earth mortar, without adequate homogeneity and connections. This form, being anisotropic and microscopic, cannot be subjected to the finite element method whose experiments generally lead to erroneous results. In this context, current research is more oriented towards the method of discrete elements, which is based on the principle of micro-modeling, capable of accounting for the phenomena of divided media, such as masonry, granular media or contact surfaces (Taforel, 2012).

From this observation, on a theoretical level, some experimental and numerical characterization methods adapted to the study context are suggested. The latter result from the crossing of data provided by local seismicity, the *in situ* characterization of constructive typologies and vulnerability factors, with the literature on the study of masonry structures using the discrete element method.

For the Dellys Kasbah, there are many reasons for using discrete methods, particularly the discontinuous nature of the heterogeneous components masonry. Although regular in shape, rubble stones vary in size and lean earth mortar has brittle shear behavior. Cracks located exclusively in the mortar or at the stone / mortar interface, require taking into account the discrete nature of the environment, by dissociating the mortar from the rest of the masonry, to locate the deformation and more easily estimate the behavior in the ultimate state (cracks, ruptures, dislocation of blocks) (Bui, 2013).

The protocol proposed here is summarized in the following steps:

1. Assessment of global seismic vulnerability on the basis of typological data,

2. *In situ* characterization of stresses and modulus of elasticity by the Flat-Jack technique,
3. Assessment of disorders by the NSCD method,
4. Classical laboratory characterization tests of masonry and its constituents.

1. Assessment of the overall seismic vulnerability on the basis of typological data

The established corpus of 120 houses (figure 7), allows a quick assessment of the seismic vulnerability on the scale of the study area of the Kasbah, thanks to the RISK-UE level 1 method (figure 16). This one has the advantage of using the data provided by the *in-situ* characterization, relating to local seismicity, to the typology of walls, floors, roofs, giving rise to the attribution of a vulnerability index (IV). It can also take into account other factors influencing the behavior of the building such as the level of aggregation, the height of the building or the unevenness of the ground. The total value of the vulnerability index is calculated as follows: Total IV = IV + ΔVR + ΔVM (ΔVR being the regional vulnerability factor and ΔVM the additive coefficient (aggravating factors). Based on the vulnerability index, vulnerability and fragility curves are determined by introducing the macroseismic intensity (EMS98), allowing the assessment and distribution of the probabilities of damage to the building (Combescure & Gueguen, 2005). The table of vulnerability indices associated with the different Risk- typologies EU, gives values between 0 (not vulnerable) and 1 (very vulnerable), which can be read as follows:

- The most probable vulnerability index (IV), representing the vulnerability class,
- The plausible interval of the vulnerability index (IV+) and (IV-),
- The minimum limits (Ivmin) and (Ivmax) of each element of the typology.
- The average damage rate (µD) defining the vulnerability curve is determined from the vulnerability index (IV) or (IVtotal) and the seismic intensity (I), according to the equation:

$$\mu_D = 2.5\left[1 + \tanh\left(\frac{I + 6.25\,V_I - 13.1}{2.3}\right)\right]$$

Secondly, given the seismic experience feedback from the city of Dellys, the results of the Risk-UE application based on the condition of the building restored without taking into account the damage criterion, can later be compared with the post-seismic state provided by the diagnosis of the corpus of 120 houses. On this basis, it is possible to verify the reliability of this approach and the calculation parameters considered (Zacek, 1996; RILEM, 2004).

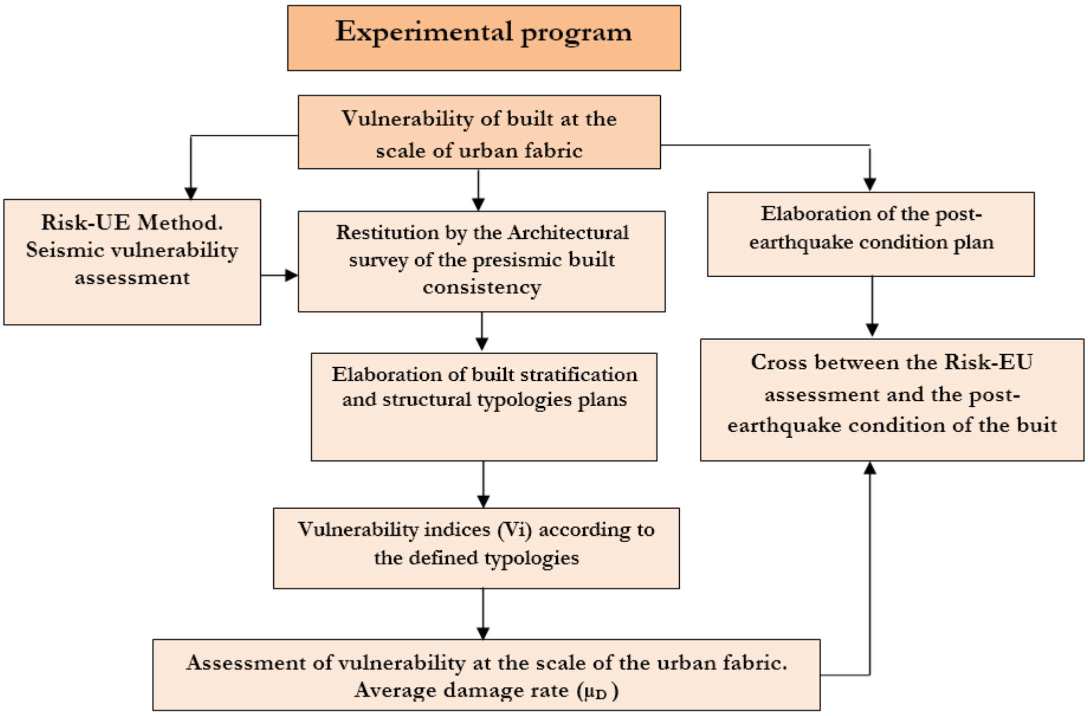

FIGURE 16.
Risk-U seismic risk assessment, experimental program, at the scale of the Dellys Kasbah fabric
Source: own work

2. In-situ characterization of stresses and modulus of elasticity by the Flat-Jack technique

In the seismic characterization studies of unreinforced masonry (URM), the compressive strength of the mortar is an important parameter for estimating the lateral strength of the wall (Moretti, 2017). For the Dellys Kasbah, whether for the consistency of the supporting structure (composition of the mortars, masonry equipment, etc.), or those of the pathologies and transformations induced by static and dynamic work (stacked stoneeffect, heterogeneity of charges), it is difficult to reconstitute the conditions in situ in the laboratory. Binda claims that today scientists take it as a reference to test the properties of masonry in existing building, as it saves considerable time and costs and allows a non destructive execution (Binda et al., 2007). Cescatti for his part, associates its relevance with the difficulties of characterization in laboratory, where it is impossible to recreate by samples the undisturbed representation of the organization and the connections of the components, in particular for very heterogeneous rubble and mortar masonry (Cescatti et al., 2016).

The data necessary for the evaluation of structural behavior, control of compressive stresses, deformation properties, loads applied to masonry, are obtained by the technique of hydraulic jacks, increasingly used by engineers of the built heritage. For Gregorczyk and Lourenço (2000), this versatile and powerful technique provides important information on the mechanical properties of historic constructions. Cescatti et al., Indicate that the results of double Flat-Jack tests extended to the traditional irregular stone and brick frames of central and northern Italy, reveal certain analogies and provide consistent information on the mechanical properties of each typology (reference to the subdivision of masonry classes in Italian standards NTC08 (Cescatti et al., 2016). The load-bearing capacity is measured by means of the Flat-Jack (Gregorczyk & Lourenço, 2000) introduced in a horizontal slot, perpendicular to the surface of the wall or then for the case study present in the space of the joint previously emptied over a certain depth. This causes stress relief and brings the gauge points closer to the displacement reference field, fixed above and below the cylinder. The latter, a kind of bladder formed of thin stainless steel blades, connected to a hydraulic pump, is pressurized progressively with a compressive stress, greater than the value of the real stress, to restore approximately the initial state (figure 17).

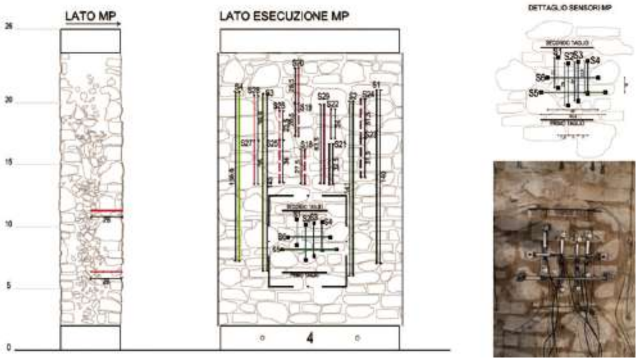

FIGURE 17.
Measurements by flat jacks in rubble stone masonry
Source: Dalla Benetta, 2012

The displacements induced by the cutting and then by the jack are then measured by a removable extensometer. By this technique, we deduce both the value of the elastic modulus (of Young) and the measured or calculated strain data, sufficiently precise to estimate the stresses due to expansion, movement or differential movement in masonry (RILEM, 2004). This measurement method with Flat-Jack appears to be suitable for the sedimentary rubble masonry of the Dellys Kasbah, with relatively regular laying beds (figure 10). However, it is desirable, when dealing with differently loaded and stressed double walls, to perform these tests independently on each wall. It is possible to evaluate in-situ the forces due to the heterogeneous loads of the original floors (figure 16), as well as those subjected to the loads of rigid replacement floors (figure 6); tests for which it is difficult to reconstitute similar conditions in the laboratory. The standards governing this technique for single and double Flat-Jacks are ASTM (American Standards of Technical Material): C1196-92 of 1992 and RILEM (International Meeting of Laboratories and Experts of Materials), LUMD2-TC76LUM of 1991. The tests with single Flat-Jack are intended to determine the stress in the wall and those with double Flat-Jack, the parameters of deformability and resistance. A test with six Flat-Jacks are developed to obtain information on the shear resistance, a parameter which is fundamental to determine the seismic vulnerability.

3. Assessment of disorders by the NSCD method

In order to assess the deterioration of the walls of the Dellys Kasbah, it is essential to consider the discrete nature of the environment, for which the deformation of the mortar joints is to be sought. As for the choice of modeling, according to Taforel, it depends on the appreciation of the quality of the masonry, leading to attribute to the material heterogeneous characteristics relating to the microstructure (properties of the blocks, geometry of the assemblies, grain size, characteristics of the joints) (Dalla Benetta, 2012). This imposes *in-situ* the in-depth characterization of the construction system and the materials. For the masonry of the Kasbah, the rubble / mortar interface is recognized as being the fragile environment, within which fractures occur under compressive, tensile and shear stresses. For this, a computer code that can be used in laboratory is necessary to complete the *in-situ* tests. This involves necessarily the use of microscopic modeling, the only one able to consider the interaction of a multitude of collections of objects (Taforel, 2012).

For weak-bonded masonry, similar to those of the Dellys Kasbah, Al-Hout consider that the discrete element method (DEM) is better indicated than the finite element method (FEM), in particular to reproduce the behavior at the limit state (Al-Hout, 2016). P. Taforel underlines that the DEM methods "allow the taking into account of the effects of the microstructure on the macroscopic behaviors"; He adds that they have the capacity to model their components and their surroundings, as well a material as a structure for varied and complex behavioral descriptions such as the state of equilibrium, the collapse, the localization of the deformation, fracture, dissipation, etc. (Taforel, 2012).

The non-Smooth Contact Dynamics Method (NSCD), designed for the context of masonry works, takes into account the laws of interaction that are not necessarily regular (Bisoffi-Sauve, 2016). It differs from other calculation methods by considering potential shocks.

The LMGC90 computer code implementing the NSCD method, offers great possibilities of behavior models (rigid, elastic, elastoplastic, etc.) (Taforel & Dubois, 2018). Based on the modeling of a large number of objects interacting with each other, it makes it possible to study the stability of the walls, by restoring the details of the geometry of the blocks and the pressure calculated in the mortar joints, taking into account the influence of the design model and the behavior of the joint. This modeling makes it possible to evaluate the stability and safety of the masonry under static or dynamic seismic loads. The RCC contact law introduced in the LMGC90, takes into account a cohesion with a progressive damage parameter of the joint and an energy dissipation at the level of the friction of the stone-mortar interface (Bisoffi-Sauve, 2016). On the basis of the disorders emerging from the variety of recurring structures identified at the Kasbah, it is possible to develop models to be subjected to digital or laboratory rupture tests. These models would reproduce the layouts of buildings, in accordance with the mode of construction and the process of evolution and transformation observed *in-situ*. The levels of structures to be considered are:

- Wall segments with devices deemed inoperative with different variants of stone and earth mortars (figure 3).
- Wall segments with fixtures (addition of bond-stones andthroughbands, correction of thestacked stones effectand discontinuity of laying beds) (figure 10) and on the other hand, a qualitative improvement of the homogeneity and the consistency of existing mortars.
- The walls orthogonal connexion faults, longitudinal-wall / cross-wall and longitudinal-wall / gable-wall (figures 12-13), for which lateral resistance tests will be carried out first on the existing configurations, and subsequently, on other configurations integrating toothing stones and connectors.

On the scale of built aggregates, it is necessary to model and verify by numerical tests the recurrent geometries, involving the connective systems as well as the unevenness of soils, recognized during the *in-situ* diagnosis as significant vulnerabilities, in the same way as the weakness of the mortar (figures 7-8-9).

4. Classical laboratory characterization tests of masonry and its constituents

A classic program of mechanical resistance tests involves the different typological characteristics of the materials, masonry and corresponding vulnerability factors.

Laboratory tests could be extended to models reproducing masonry geometries, with the variety of stone and mortar identified *in-situ* (figure 3). Secondly, tests for improving the behavior of the existing masonry should be continued by modifying the stone devices and the quality of the mortars. New compression, traction and shear tests could then be compared with those carried out previously (figure 16). *In-situ* identified mortars should be characterized taking into account the factors of vulnerability to discontinuities noted in horizontal and vertical joints (figure 10), as well as their nature, composition and resistance.

For this, it is necessary to use tests on models reproduced in the laboratory. The identification of the basic components of existing mortars, as well as the control of the aptitudes of mixtures, consolidation and rehabilitation is based on experimental techniques aiming to know the mineralogical nature and petrography of the components as well as the mechanical characteristics of resistance to flexion and compression (figure 18). The interest in analyzing both degraded and intact mortars from a body of buildings representative of the Dellys Kasbah, is to recognize the original characteristics as well as the alterations at multiple exposures. The many criteria prevailing in this choice are the exposure to sea breezes and driving rains, the orientation to prevailing winds, sun, splashing rainwater, cracked parts, etc.

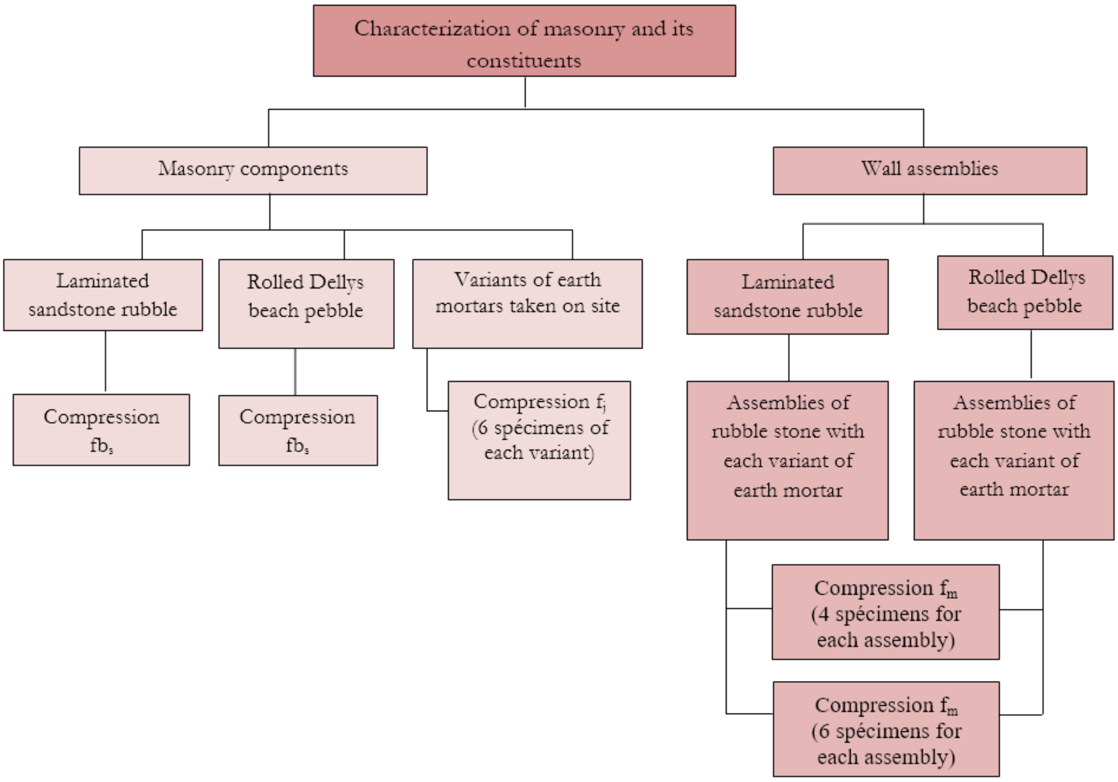

FIGURE 18

Experimental program for characterization of masonry variants and components

Source: own work

Conclusion

In terms of correlation between architectural typological characteristics and construction techniques, weaknesses of materials and implementations, original structural arrangements, transformations and evolutions, as well as seismic diagnosis, this research is a contribution to the knowledge of the vulnerability of constructions to static forces and seismic dynamics of the Dellys Kasbah. It therefore constitutes a field of future research on the improvement and recovery of the structural system. Therefore, it can be continued with calculations and models of seismic collapse mechanisms, on the basis of intrinsic parameters recorded at multiple levels of the building. Given the little interest in research on the rehabilitation of minor built heritage in Algeria, the resulting results will be a premise for the constitution of a database for the built typologies of the geographical and cultural areas of maritime Kabylia and of the Mediterranean.

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Notes

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