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Seismic Performance of Masonry Buildings in Algeria

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***Abstract*—**Structural performance and seismic vulnerability of masonry buildings in Algeria are investigated in this paper. Structural classification of such buildings is carried out regarding their structural elements. Seismicity of Algeria is briefly discussed. Then vulnerability of masonry buildings and their failure mechanisms in the Boumerdes earthquake (May, 2003) are examined**.**

***Keywords*—**Masonry building, seismic deficiencies, vulnerability classes

I. Introduction

MASONRY is one of the oldest building materials and has been considered the most durable. It has been used for construction of buildings since ancient times. Masonry buildings still represent a great majority of buildings in some regions, especially in Europe. According to the functional requirements, existing materials (stone, adobe and brick), traditional practices, place of construction (urban or rural areas) and construction period, a wide variety of masonry buildings exist. Northern Algeria happens to be a region of high seismicity, because it straddles the boundary between the African and Eurasian plates. However, not many large earthquakes occurred during the first part of the twentieth century when this region were experiencing a high growth rate, and it was during that period that many unreinforced masonry buildings were constructed. Masonry buildings are found in urban areas in Algeria. There are wide variations in construction materials and technology, shape and number of stories. Masonry houses in rural areas and suburbs of urban centers are generally smaller in size, built as separate structures and typically used by a single family. Multi-family residential buildings in urban areas are frequently containing a commercial ground floor and residential apartments above [1]. The number of stories varies from two to six in urban centers (Fig. 1 and 2).

Fig. 1 Stone masonry building in Algiers (multi-family residential buildings containing a commercial ground floor and five stories)

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Stone and adobe are widely used as construction materials for residential buildings in Algeria. Some buildings of this type have a regular structural layout with thick walls uniformly distributed in both directions. Poor quality of mortar still used. Floors are usually of timber joists, sometimes on stone or brick vaults, not anchored to the walls. Brick masonry was used for buildings in urban areas from the last half of the XIX century onwards. Structural layout is frequently irregular in this type and reinforced concrete slabs can be found [1].

II. Building Components and Classification

A. Building Components

The components of a stone masonry building are: walls, floors, roof and foundations.

The walls are vertical elements which support the floor or the roof. Stone masonry walls are constructed from stone boulders bonded together with mortar (Fig. 4). The walls can be defined as *structural walls*; carrying their own weight together with vertical and horizontal loads, or *as non-structural walls*; used to partitioning the space. Structural walls are considered as *load-bearing walls*; which carry both vertical loads from the floor structures (and their own weight) and the horizontal loads.

Floor and roof systems include masonry vaults and timber joists or trusses. In some cases, steel beams support shallow brick masonry arches. In multi-story buildings, jack arches are often found at the ground floor level and timber joist floors at upper levels. Timber floor construction includes wooden beams covered with wooden planks, ballast fill, and tile flooring. In most cases, timber joists are placed on top of walls without connection.

Foundations support the wall weight and provide an interface between the soil and the building structure. In most cases, stone masonry walls are supported by continuous stone masonry strip footings (Fig. 4). In some cases, footings do not exist at all.

B. Classification

Three groups are considered:

- Rural houses with mud, adobe, stone and brick walls, with flat or inclined roofs, found in different parts of Algeria
- Unreinforced masonry buildings in urban areas
- Reinforced masonry buildings in urban areas

Fig. 2 Stone masonry building in Algiers with irregular structural layout

Fig. 3 Masonry buildings in Casbah (old center of Algiers)

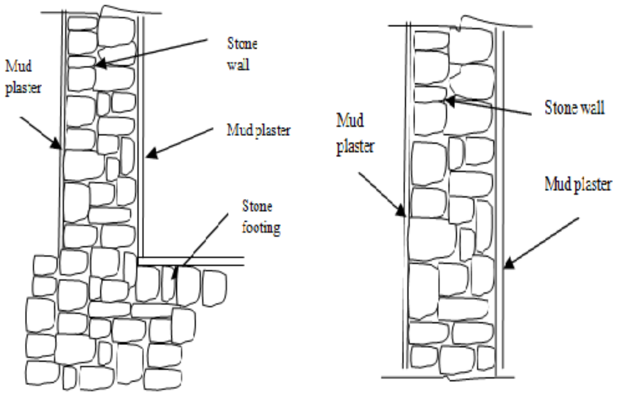

Fig. 4 Typical stone masonry foundation (left) and stone wall (right)

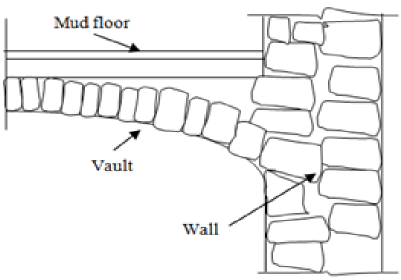

Fig. 5 Stone masonry vault supported by stone walls

III. Seismicity of Algeria

In the Mediterranean region, the current tectonic activity is due to the convergence between the African and Eurasian plates [2]. The neotectonic deformation and seismic activity of the northern Algeria result directly from the interaction between these two plates. The seismic events have been located in the Tellian Atlas of Algeria which is the most active area and where, approximately, all the seismogenic zones are located. Historically, the north of Algeria knew several earthquakes [3], among which some were catastrophic (Algiers 1716 (Io= IX), Oran 1790 (Io=XI), Mascara 1889 (Io= IX), El Asnam 1980 (Ms=7.3), Constantine 1985 (Ms= 6.0), Tipasa 1989 (Ms=6.0), Mascara 1994 (Ms=6.0) and Algiers 1996 (Ms=5.7)). The earliest one occurred in 1365 in Algiers. It destroyed the city and was followed by a tsunami [4]. The latest one that affected Algiers region is the Boumerdes earthquake, on May 21st, 2003 (Io =X, Ms=6.8) [5]. Its epicenter was located in the sea at about 100 km northeast of Algiers city (Fig. 6).

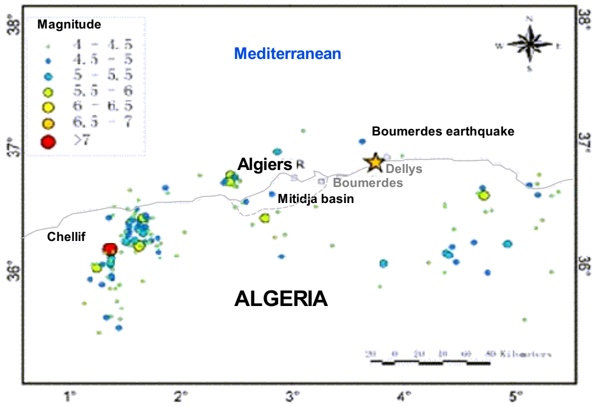

Fig. 6 Seismicity of Algeria since 1973 (USGS)

IV. Vulnerability Study

A. Boumerdes earthquake of 2003, behavior of masonry buildings

Unreinforced masonry has shown poor performance in past earthquakes. The reasons for this poor performance are the inherent brittleness, lack of tensile strength and lack of ductility; that is, a lack of the properties given to reinforced masonry by the steel reinforcing [5]. Cracks occur in a brittle material due to earthquake forces, subsequent pulses cause uncontrolled displacement and collapse.

Of the great number of masonry buildings subjected to the Boumerdes earthquake on May, 21st, 2003, many were severely damaged and some collapsed. The following damages have been observed on masonry buildings [5], [6]:

1) Horizontal cracks between walls and floors
2) Vertical cracks at walls intersections
3) Out of plane collapse of peripheral walls
4) Diagonal cracks in wall piers
5) Cracks in spandrel walls
6) Partial or complete disintegration of walls
7) Partial or complete collapse of the building

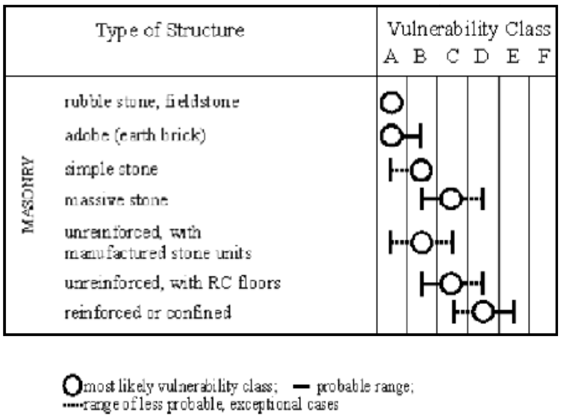

Fig. 7 EMS-98 typologies of masonry buildings

Fig. 8 Partial collapse of walls due to the 2003 Boumerdes earthquake

The observations of the behavior of masonry buildings when subjected to the Boumerdes earthquake have shown that the vibrations of the buildings are dependent on how the walls are interconnected and anchored at the floor and roof levels. In the majority of observed masonry buildings where the timber joist is not anchored to the masonry (without ties or tie-beams) walls tend to separate along their joints or intersections. Vertical cracks occur near the intersection.

B. EMS-98 Typologies of Masonry Buildings

For masonry buildings, European Macroseismic Scale, EMS-98 [7], considers seven typologies varied in construction materials and technology. They are unreinforced masonry buildings (rubble stone and fieldstone, adobe, simple stone, massive stone, unreinforced with manufactured stone units and unreinforced masonry with reinforced concrete (RC) floor) and reinforced or confined masonry buildings. Six classes of decreasing vulnerability are proposed by the scale (A to F) (see Fig. 7). Descriptions for masonry buildings typologies are provided in the following.

Rubble stone and fieldstone: heavy constructions built with non worked stones and poor quality of mortar. Their resistance to horizontal forces is low. Their most probable vulnerability class is A.

Adobe: constructions in earth or with earth bricks. Earth is mixed with water and used as a conglomerate poured into wooden moulds.

Dried earth bricks were also used with mortar placed in between. Their most probable vulnerability class is A.

Simple stone: constructions in hewn or cleft worked stones. Large stones are used to connect the walls in the corners. These constructions have better resistance and their most probable vulnerability class is B.

Massive stone: constructions built with large squared stones. These buildings are resistant to horizontal actions, so, their most probable vulnerability class is C.

Unreinforced masonry with manufactured stone units: constructions in old brick masonry. Floors are with masonry vault, wooden or steel beams. In some cases metal tie rods are used to connect the walls. Their resistance to seismic actions is good, but also influenced by the size, the position and the number of openings. Their most probable vulnerability class is B.

Unreinforced masonry with RC floor: recent masonry buildings, built with bricks or cement blocks with RC floors. At the floor level, generally, there are tie beams. Their most probable vulnerability class is C.

Reinforced or confined masonry: horizontal or vertical steel is inserted in reinforced masonry in mortar joints. In this type of buildings, masonry is built inside a RC frame and represents the main structural element. The most probable vulnerability class for this typology is D.

C. Vulnerability Classes - Case of Algiers area

In a recent seismic vulnerability study of buildings in Algiers area [8], 15259 masonry and RC buildings were inventoried. For each building, the following characteristics are considered:

1) Building type (house, building, precarious)
2) Building use (dwelling, educational…)
3) Age of building – code era
4) Number of floors
5) Structure system
6) Plan and vertical irregularity
7) State of preservation

The analysis of the inventoried buildings provides the following percentages (Fig 9 and 10):

1) Buildings designed before 1962 represent 52% of the total. They are buildings or individual houses with masonry or reinforced concrete.
2) 42.5% are masonry buildings.
3) Masonry buildings are classes A and B, with respectively 22% and 20.5%.
4) M1 typology, which characterizes unreinforced masonry buildings with 3 floors or less, represents the higher percentage with 37.73%. It is the predominate typology of the building stock in Algiers.
5) M2 typology characterizes unreinforced masonry buildings with more than 3 floors.

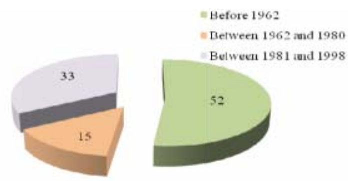

Fig. 9 Distribution of buildings according the construction period

Fig. 9 shows also the percentages of buildings designed after 1962; they are RC buildings. The category of buildings designed after 1981 are built, according to the first Algerian seismic code (1981) [9].

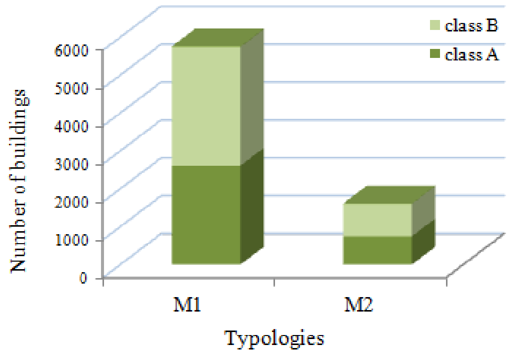

Fig. 10 Distribution of vulnerability classes into each typology

The vulnerability of each category is quantified by the distribution of its buildings in different vulnerability classes. These are defined by their vulnerability or fragility curves. Fragility curves defining the probability *P* of reaching or exceeding each damage grade, D_K (k= 0 - 5), are obtained using:

$$P(D \geq D_k) = \sum_{j=k}^{5} p_j \quad (1)$$

Five damage degrees are defined by the EMS-98 as; D1: Negligible to slight damage, D2: Moderate damage, D3: Substantial to heavy damage, D4: Very heavy damage and D5: Destruction.

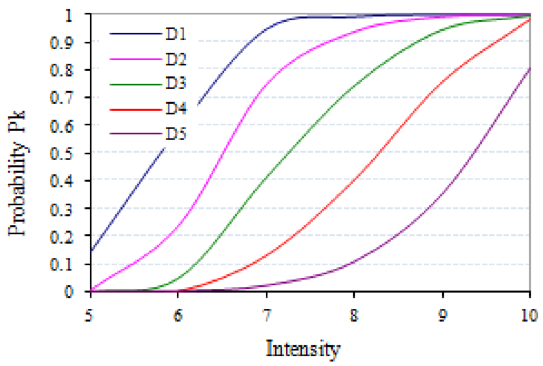

Fig. 11 Fragility curves for class A masonry buildings

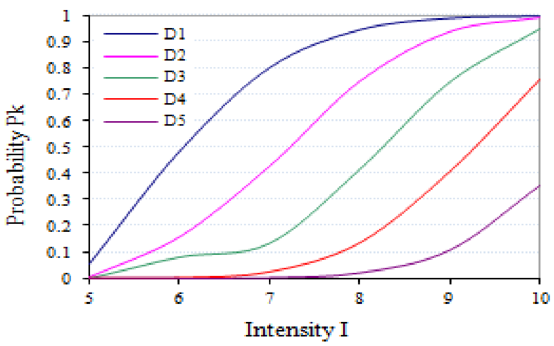

Fig. 12 Fragility curves for class B masonry buildings

D.Seismic deficiencies

When subjected to earthquake, horizontal inertia forces are induced in the structural system of the masonry building. Inertia forces are transferred from the floor into the walls, causing bending and shearing effects, and from the walls into the foundations.

Masonry buildings have shown poor performance in past earthquakes. The deficiencies of this type of construction are [10]:

Lack of structural integrity: seismic performance of unreinforced masonry is depending of the connection of walls at the intersection and to the floor or roof. When the walls are well connected, there is a rigid floor and the building vibrates as a monolithic box [10]. The following damage patterns are caused by the lack of integrity:

- Damage and separation of walls at intersections
- Floor and/or roof collapse from inadequate wall-floor (or wall-roof) anchorage

Roof collapse: when the walls are not connected to the roof, collapse is often caused. Roof collapse can also be caused by the collapse of walls subjected to shear forces and gravity loads. Heavy roofs contribute to seismic vulnerability of masonry buildings.

Out of plane wall collapse: this collapse mechanism was observed when connections between the cross walls and long walls are inadequate. This failure mechanism is characterized either by vertical cracks developed at the wall intersections, or by tilting and collapse of an entire wall.

In plane shear cracking: piers subjected to shear forces can experience diagonal shear cracking (X-cracking). Several factors influence the in plane failure mechanism of stone masonry buildings, including pier dimensions, opening sizes, wall thickness, building height and masonry shear strength.

Poor quality of construction: the use of mixed structural units (adobe and stone for a wall construction) and systems results in variable wall strength and stiffness in different parts of a building. This can cause torsional effects. Quality of mortar is also one of the main reasons for structural damage of buildings. When the mortar used for construction is made of mud instead of cement or lime, the mortar becomes the weak link and prevents a proper bond between the mortar and the stones.

V. CONCLUSION

According to the functional requirements, existing materials, traditional practices, place of construction and construction period, a wide variety of masonry buildings exist in Algeria. They are mainly unreinforced masonry buildings.

Past earthquakes have revealed the high vulnerability of stone, brick and adobe masonry buildings, which caused high human and economic losses. The seismic vulnerability of masonry buildings is due to their heavy weight and, in most cases, the manner in which the walls have been built, interconnected and anchored at the floor and roof levels. Algiers masonry buildings stock has vulnerability class A and

B, and, in case of stronger earthquakes, the damage will be high.

Moreover, if the quality of construction and materials is inadequate, damages of various degrees occur. The use of mixed structural units and systems, and poor quality of mortar are the main reasons for structural damage of masonry buildings.

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