ASIAN JOURNAL OF CIVIL ENGINEERING (BHRC) VOL. 18, NO. 3(2017)
PAGES 433-449

SEISMIC VULNERABILITY OF TRADITIONAL MASONRY ARCHES, VAULTS AND DOMES

T. Mahdi[1*]
Structural Engineering Department, Road, Housing and Urban Development Research Center, Tehran, Iran

Received: 25 July 2016; **Accepted:** 26 September 2016

ABSTRACT

Arches, vaults and domes are common features in the cultures of old civilizations. They were usually made of sun-dried bricks, fired bricks or stones with different types of mortar. The majority of these components are vulnerable to seismic effects. To present a viable study on their seismic vulnerability, all the factors influencing their behavior need to be investigated. In this paper, the construction materials used and the structural features of these elements are briefly described. Furthermore, the different aspects of using numerical methods for analyzing these elements are discussed. Finally, measures needed to improve their resistance are suggested.

Keywords: Masonry; arch; vault; dome; seismic vulnerability; soil movement.

1. INTRODUCTION

Vaults and domes were used extensively in the roofing of ancient buildings. They were the favored choice for large-space monumental coverings for centuries. Unlike the traditional construction technique of prismatic members, the construction technique used in arches, vaults, and domes allow building large and complex structural shapes completely in compression without having tensile stresses. In the past, masonry was the ideal material to fit with these structural shapes. Furthermore, arch was one of the most distinctive elements of Roman, Islamic, and Gothic architectures.

According to historical records, many arches, vaults and domes were subjected to severe earthquakes in the past without sustaining large damage. The many historical monuments around the world that remained safe during many centuries are living examples of this fact. The Pantheon, St Peter's dome, the Segovia Aqueduct, Spain, and the red dome in Maragheh, Iran are few examples of such monuments. Furthermore, in recent years, many arches, vaults and domes had survived the effects of earthquakes with little or no damage.

[*]E-mail address of the corresponding author: mahdi@bhrc.ac.ir (T. Mahdi)

This has been demonstrated in the 1999 Kocaeli Earthquake. Most of the main compounds of mosques, having single dome with multiple semi-spherical domes, were generally intact or suffered very slight damage [1-2]. On the other hand, the losses occurred during recent earthquakes have proven that there is an urgent need for improved knowledge of the seismic behavior of these parts of buildings [2-11]. In order to have proper rehabilitation schemes, a better understanding of the structural behavior of such parts under lateral loads is needed. Furthermore, some knowledge on the construction materials and the traditional techniques used in the past, are necessary. Moreover, investigations on the cracks developed and the collapse modes observed during past earthquakes are quite essential prior to the start of any rehabilitation scheme. In the following sections, discussions on these subjects are given.

2. MATERIALS AND CONSTRUCTION TECHNIQUES

Masonry is a heterogeneous material that consists of units and joints. Therefore, the performance of a structural masonry element is dependent upon the properties of the constituent materials and the interaction of the materials as an assemblage. In the following subsections, the properties of the constituent materials are considered.

2.1 Earth

The combination of economic necessity, deep cultural and social traditions, the need for little or no experience to build earth buildings, and material availability make the use of this kind of buildings inevitable [13]. Earth buildings have many favorable characteristics for construction especially in arid regions. They provide very good insulation against hot and cold climates. Nevertheless, earth buildings are highly susceptible to cracking, rising damp and salt damage, erosion, termite infestation, and generally loss of section cause irregularities in strength, stiffness and mass which mainly contribute to their poor performance under earthquake conditions.

Adobe or sun-dried brick buildings are among the most popular traditional ones. Sun-dried bricks are soil bricks made in various sizes by hand molding. Small-size vaulted roofs were commonly made using this kind of bricks with mud mortar. According to historical records, the first known true arch was made about 4000 BC of Sun-dried bricks and bitumen [12].

2.2 Fired brick

Fired brick is manufactured by mixing clay raw material with water and by firing the mixture at high temperatures. In fact, drying and firing processes are crucial parameters to determine the final properties of bricks [3].

Soluble salts and other impurities are one of the most important factors of brick decay and are frequently found in old clay brick fabrics [14-15]. Their formation is influenced by porosity, which in turn depends on the quality of the raw clay and the burning temperature [3]. Poorly fired bricks lose their strength as their area and volume gradually decrease through scaling, and wear and tear [2]. Generally, porosity is an important parameter concerning clay bricks due to its influence on properties such as chemical reactivity, mechanical strength, durability and quality of the brick. The quality of the brick, both in terms of strength and durability, increases with the decrease of the porosity [16]. In countries where temperatures fall below 0°C, the water inside the pores can freeze leading to surface delimitations, disintegration or cracking. Moreover, in the presence of soluble salts, the volume increase caused by the crystallization of the salts can cause severe damage [16].

The compressive strength is an important property of clay bricks that enables the evaluation of material's ability to withstand the compressive loads present in the structure. The value of the compressive strength is strongly influenced by the characteristics of the raw material (raw clay, amount of water and additives) as well as by the production process. Therefore, the quality of the raw material, together with an adequate firing time and temperature, are fundamental aspects when high compressive strength is required [16].

2.3 Stone

Strong stone units and narrow mortar joints were highly recommended to be used for true arches, vaults, and domes. This can be made possible by precise cutting, centering, bedding, placing and pointing of stones in these arches [17]. However, random native stone units were also used for moderate spans. The use of these later units requires a large proportion of mortar along the arch ring to distribute the bearing forces between the stones within the arch ring. In some times, the presence of layers of clay or other impure materials inside stone units may eventually lead to their wearing, spalling or cracking [2].

2.4 Mortar

The mortar binds the blocks and transmits the compression forces. This is particularly important when vaults and domes are built with the corbelled technique, explained in section 4.1. In this technique, the quality of the mortar is essential to stick the blocks onto each other.

In construction of different buildings in different periods, a variety of mortars has been used. Mortar can be clay, bitumen, gypsum, lime/cement based mortar, glue or others. Lime mortar is generally used in humid areas. In constructing traditional vaulted structures, lime mortar has been used in China and Bengal [18-19], while gypsum has been the typical mortar in Persia and Middle East [20-21].

3. CAUSES OF DETERIORATION

Traditional masonry buildings can be subjected to various environmental and loading conditions depending on their use and geographic location [2]. The most important factors that cause building's deterioration are given in the next subsections.

3.1 Humidity

All kinds of masonry buildings are more or less susceptible to rainwater or rising humidity. To prevent the deterioration of structural elements in long term, water from roof or underground should be controlled [3].

3.2 Soil movements

Soil movements and deformations can disturb the equilibrium and cause instability. To minimize the effects of this problem, loads need to be distributed uniformly. An example of such practices can be seen in the Pantheon. The cylindrical wall of the Pantheon contains within its thickness a series of arches which inside correspond to niches and empty spaces. The Roman has used these arches, which in reality are "relieving arches" built inside the solid masonry walls, to influence the soil settlements during the construction, shrinkage and viscous phenomena [7].

The foundations need to be rigid to make the whole building move uniformly. If the foundation and soil are subjected to different loading conditions, or if part of soil is saturated, relative settlements and cracks are expected in the structure. Famous examples of historical constructions in risk due to soil settlements are the Cathedral of Mexico City and the tower of Pisa, and constructions in risk due to a deficient structural conception are the Cathedral of Pavia and the Cathedral of Florence.

In vaulted structures, a convex pattern of settlements produces an outwards rotation of the supporting walls, which adds to that of the thrust of vaulted roofs [22]. In corbelled arches, such rotations can create situations so severe that collapse often ensues, while in true arches, outward displacements of the supports cause slippage between their blocks [3]. Furthermore, during an earthquake, movements in the soil may cause cracks in the building. In the 1999 Kocaeli Earthquake, Turkey, settlement of ground under one of the corners of Mihrimah Sultan Mosque caused the fall of limestone blocks from the outer arch of the main dome [1].

3.3 Site effects

Besides direct effects of soil movements, site response played an important role. The geological properties of the site are highly influencing the frequency content of the earthquake motion that the structure receives. Furthermore, the ground motions recorded on soft sites have significantly higher intensities than those recorded on rocks.

During the 1999 Kocaeli Earthquake; despite its distance of approximately 130 km to the epicenter, the Fatih Mosque of Istanbul, Turkey had sustained some losses. The main columns and several structures of the mosque were cracked and light damage localized at the crown of one of its four main arches had occurred [9, 23]. In past earthquakes, many losses including the cracking and collapse of the main dome of the Fatih Mosque were reported [23]. Instrumentation readings from the building in the past and especially from the 1999 Earthquakes of Kocaeli and Düzce indicate that such losses were caused by the local site conditions [9, 23]. These same conditions that led to amplification of the ground motions during past earthquakes had played a major role in the structural damage experienced in the 1999 Kocaeli Earthquake.

3.4 Insufficient material strength

In order to have a structural system that carries loads for a long period, the construction materials should retain their strength as they go through freezing-thawing cycles, humidity and temperature variations, and other harsh climate and environmental conditions [2]. Thus, and as discussed in section (2), the use of high quality materials is quite important in the survival of these buildings.

For arches, vaults, and domes, the properties of the mortar significantly influence the strength of the entire roof. Deterioration of mortar binding the masonry units, especially poor quality mortar including mud or low quality lime, can reduce the strength and stiffness of the roof considerably [2]. In past earthquakes, the use of low quality or poorly made mortars was one of the main reasons that caused the failures of domes and vaults [2, 4].

3.5 Other factors

In addition to seismic effects and the factors discussed in the previous subsections, traditional buildings are influenced by other environmental factors that include bacteria, termite infestation, grass, fungus, wind, and acid rain [2-3, 24]. Furthermore, loading from continuous traffic and heavy trucks can lead to vibrations and excessive loads on foundations. Similarly, the use or occupancy of the structure may change and create larger unexpected loads [2].

4. STRUCTURAL ELEMENTS

The presence of an effective roof capable of resisting vertical and lateral loads and transmitting seismic loads between vertical members is quite essential for any structural system. Thus, any deficiency that exists in the vertical or horizontal load-carrying systems would increase the possibilities of building's collapse during seismic events.

In analyzing traditional masonry vaulted structures, the classic limit analysis has found general acceptance. It is founded on four main assumptions [25]: (1) masonry units have infinite capacity in compression, (2) but zero capacity in tension, (3) masonry units are infinitely rigid, and (4) friction is high enough between voussoirs[1] so that they cannot slide one on another. Based on these assumptions, the followings results are concluded:

- The static analysis of masonry structures is a problem of stability which is based solely on geometry.
- Individual blocks are not free to slide or crush, but they are free to separate, or hinge. Hinges form when the thrust line[2] can no longer be contained within the masonry. At this point, the masonry can no longer support the applied loads, and the structure is no longer in equilibrium without hinging [26-28].

It must be noticed that the limit analysis are primarily applied to structures under pure compression. Thus, they are more appropriate for traditional masonry structures that incorporate vaults and arches to transfer loads instead of slabs and beams.

In recent years, the behavior of these structural systems under lateral loads has been extensively investigated. However, still little is known about the structural performance of vaulted structures undergoing earthquake actions. In general, the behavior of these elements depends on type of vaulting (cross vault, barrel vault, ribbed vault, dome, etc.), type of support (interaction of these elements with their columns, pillars, or walls), profile of the generating arch, structural thickness, rise and span, loading conditions, and the characteristic

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[1]Voussoirs are the wedge-shaped pieces which make up the arch ring in modern (true) arches.

[2]The thrust line is the path on which internal forces in a structure transport external loads to the supports.

of the material used. In the following subsections, the most common structural features of these elements are described.

4.1 Arches

The arch can have many architectural and structural functions. The modern arch known as the true arch was widely used by Romans as well as other civilizations in the Ancient Near East, the Levant, and Mexico [3]. As shown in Fig. 1; and as part of the courtyard buildings located in the hot-humid climatic regions, arches are used to face the courtyard. Furthermore, arches may be used as a façade hiding the main structure behind it, as shown in Fig. 2. In this later case and due to out-of-plane forces, arches were separated from the structure behind.

Structurally, arches are the elements that span a horizontal distance carrying its own weight and other loads totally or mainly by internal compression. Arches can be classified according to geometrical shape, which is one of the most important parameters and essential to determine their structural behavior. Circular, elliptical, pointed, basket-handle, and four-centered arches were among the most widely used in traditional buildings. As a geometrical shape, the arch is a fundamental element since it forms the basis for the evolution of vaults and domes.

Figure 1. Arches facing the central courtyard in Yazd, Iran

Figure 2. Partial collapse of the small arches, the 2003 Bam Earthquake, Iran

Although the masonry units have minor tensile stresses, the structure naturally tends to accommodate the small displacements in the abutments due to differential settlements or the shrinking and wear and tear of mortar through the formation of the three hinges in arches [29]. The formation of a three-hinge arch in fact implies that one of the infinite numbers of balance positions of the structures has been determined by external conditions, so that the line of thrust can be calculated [29].

The curvature behavior of the true arch is exceptionally efficient, since pure compression stresses are developed in it. Practically, the arch ring itself is built using dry stone wedge-shaped blocks or voussoirs. This technique allows the compression force to be always close at right angles to the joints between two voussoirs with limited shear forces and minimum slippage [3, 25].

In many if not all practical cases, the weight of a masonry arch dominates. The ideal shape that an arch would take under its own weight can be visualized by showing a wire, suspended between two points. Other kinds of loading can be incorporated in this model by adding equivalent weights. Consequently, more than one thrust line is formed and all lines of thrust have to be contained within the arch [30]. For non-symmetric loads like seismic or wind loads, when the line of thrust deviates from the middle third, the arch get tensions but it may not collapse. In such cases, it is common to observe cracks in specific locations on the arch; however, as long as there are only three hinges, the structure is statically determined and no further displacement occurs [29]. Collapse will happen only when the line of thrust becomes tangent to a point of the arch section and a fourth hinge would be formed [29]. Thus, failures occur because of the excessive movements of the thrust line and not due insufficient material strength [30-31]. The differences in the position of the thrust lines give an indication of the necessary width of the arch [30].

Using the corbelled arch technique, overlapping blocks are usually placed on the top of each others, looking much like a series of steps. From the other side of the entryway, another staircase rose to meet its counterpart. The advantages of the construction of corbelled arches are the ease and simplicity in cutting the stones. However, both "rocking" and "sliding" conditions need to be satisfied to have equilibrium. According to the sliding conditions, the thrust at each level cannot exceed the shear resistance, linked to the friction angle and the overhanging weight. In this respect, true arches behave much better than corbelled ones since only pure compression stresses are developed in them [3].

To design the vertical supports upon which an arch rests, it is important to define their thrust lines. For simple symmetrical loads, the thrust line will pass down the middle of the vertical support. In a building with non-symmetric loads, the vertical supports on which the arch is supported need to accommodate the horizontal thrust generated by it [29, 31]. One possible solution for this problem is to make the vertical supports massive enough to buttress the thrust and conduct it into the foundation (Similar to the buttresses provided for the Roman triumph arches). Another solution can be achieved by adding additional vertical loads similar to the pinnacles of a Gothic cathedral [17, 31]. In all these cases, the horizontal thrusts must be taken by tension elements similar to the tie-rods, explained in section 4-4.

In ancient arched stone bridges and Roman aqueducts, the use of multi spanned arches of similar spans and rises, are quite common. In such cases, the vertical supports only need to carry the vertical loads, since the thrust of one arch counteracts the thrust of its neighbors, and the system remains stable as long as the arches at either end of the row are buttressed.

In spite of the fragility of masonry, masonry arch is capable of ductile behavior. In other word, a masonry arch will deform appreciably while maintaining load-carrying capacity before reaching its peak load. However, under transverse loading due to lateral earth or seismic action, an arch structure is more fragile [17].

4.2 Vaults

A vault is a one-way roofing system that transfers loads by arch action through a single curved plane to continuous supports. The stresses within the vault are primarily compressive. Traditional vaults were constructed in different shapes and forms. They present different static behavior according to their geometry, masonry strength, construction techniques, and so forth. Among the many types of known vaults, barrel vault (semicircular), groined vault, cloister vault, pointed vault, segmental vault, catenary vault, and ribbed vault are among the mostly used ones in traditional buildings.

As a result of lateral forces, the movement of the springers is always the factor that creates major damage or is the cause of collapse. Such failures are usually due to excessive deformations and lack of tie beams at the level of the roofs. In such cases, the failure of the supporting structures would lead to the collapse of the roofs. In many earthquakes, this form of failures was the dominant one. In some other cases as shown in Fig. 3 walls remained relatively intact while the roofs completely collapsed. In this later case; and as a result of having a heavy roof and a weak wall-roof connection, tensile stresses are generated in the parallels near the springers and a plane of failure often appear there [3]. To eliminate these tensile stresses, springer movements need to be prevented. In traditional buildings, this can be achieved partially by providing buttresses [3], and tie rods [3, 32]. Another type of failures may occur due to longitudinal movements of the vault. In this type, cracks in the end walls connected with the vaults are expected to occur. As shown in Fig. 4, partial or complete collapse of the end wall may follow such longitudinal movements.

Figure 3. Failure of a vault and surviving of walls in the 2003 Bam Earthquake, Iran

Figure 4. Failures at the intersection line of the vault with the end wall in the 2003 Bam Earthquake, Iran

In other cases when the displacement is relatively small, minor cracks at the intersections of the roof with the walls or longitudinal and transverse cracks in the vault are expected to occur. Examples of such cracks are shown in Fig. 5.

Figure 5. Longitudinal and transverse cracking in the vault, the 2003 Bam Earthquake, Iran

Considering the massive wall supporting the vault as a plane stress problem, it is not easy to pierce the walls with large windows or doors without developing concentrated stresses near the openings. Furthermore, and to take care of the thrust of the vault as an out of plane force exerted on the wall, it is important to have a solid massive wall since the existence of openings in the supporting walls destabilizes the vault [33]. To deal with the demand for large windows and thin walls, it is important to use buttresses [3, 31]. Another solution can be achieved by using the ribbed vault. This system is a complex of vaults and arches that divide the vault into a number of bays. The webs of vaults between adjacent arches may be coursed in different ways [33]. Generally, ribbed vaults have the advantage of producing lighter vaults and more economical construction [3].

4.3 Domes

The dome is a structural form, which distributes loads to supports through a doubly curved plane. They are usually designed to be capable of supporting applied loads without large deflection and excessive displacements. Similar to arches, domes develop internal meridional forces that transfer loads to their supports. For domes loaded axisymmetrically by their self-weights, the forces are compressive and increase in magnitude from crown to their bases. However, and unlike arches, domes due to their polar symmetry can resist bending forces produced by quakes by developing internal hoop forces that act in the latitudinal directions as parallel rings.

Masonry domes were constructed in different shapes and forms. They present different static behavior according to their geometry, masonry strength, construction methods, and so forth. Among the many types of known domes, hemispherical, pointed, cloister, segmental, and faceted domes are among the mostly used in traditional buildings. They were produced in the form of single-shell, double-shell, and triple-shell domes [33].

The early domes were supported by placing them directly on bearing walls. In this way, vertical forces are directly transmitted from the top to the ground. An example of such practices can be seen in the Pantheon. This structure; built in the 2nd century, is apparently a very simple structure made of a solid masonry cylindrical wall and a hemispheric dome of the same diameter (around 43 m). Plans other than the circular one has also used for the dome; including dodecagonal, hexagonal, octagonal and square horizontal plans [33]. Among these systems, the square support system is the most popular one. The square plan can be performed by four walls, four columns, eight columns or 12 columns [33]. However, the problem with domes is solving the transition from the round dome onto the square building. The three methods for solving this problem: (1) using the squinch, where corners of the square room were filled in to provide a base for the dome, (2) using the pendentive which is a triangular piece which is narrow toward the square structure but wide at the base of the dome, and (3) using a belt just beneath the dome through the use of triangular pieces of stone. In some cases, and due to the lack of these arrangements [4-5] or due to bad construction details [29], failures of domes occurred. Furthermore, the existence of openings like doors and windows in the supporting walls destabilizes the dome structure. To overcome this problem, early architects used arches to transfer stresses from the dome to either side of the opening [4]. One popular arrangement that prove its credibility in past earthquakes is the dome on four arches, shown in Fig. 6.

To resist the horizontal seismic movement in this system, the joint between the arch and the pillar must be inclined and the pillar must have enough width to keep the resultant forces within the central part. An example of a dome with a wide pillar is shown in Fig. 7.

Figure 6. A relatively acceptable performance of a dome on four arches in the 2005 Zarand Earthquake, Iran

Figure 7. A relatively acceptable performance of a dome with wide pillar in the 2005 Zarand Earthquake, Iran

Danger in the dome can occur when any large horizontal movements are created in the supports, leading to deformation of the drum and thence directly to the dome [3]. In this respect, the most important structural element to make a dome safe is the ring beam at its bottom. The presence of this beam help to limit the horizontal displacements and the tensile hub stresses. As for the cracks, the typical pattern to be found in most cases is that of meridian cracks that correspond to tensile stresses present in the parallels. Thus, it can be concluded that the main weakness of most domes is the stiffness and strength of their supporting structures [7, 21, 29]. In another word, the collapse of a dome mostly follows the failure of its supporting pillars or walls, as shown in Fig. 8. However, the weakness or the deterioration of the dome's material can play some role in the collapse of the dome as well [4, 21].

Figure 8. Collapse of a dome following the failure of the supporting walls in the 2005 Zarand Earthquake, Iran

4.4 Tie rods

In traditional buildings, wooden or steel tie rods are used to take care of any possible tensile stresses developed as the results of seismic forces or any excessive lateral displacements [3, 32]. In rest condition, when only vertical loads are applied to the structure, the arch lateral thrust can be largely or entirely resisted by the buttress action developed by the abutments. As a result, the uses of tie-rods contribute to guarantee an efficient connection between the constituting parts of the structure and take care of any extra thrust induced on the bearing walls [29, 34-35]. Furthermore, they can be useful in providing adequate response to the whole arch thrust during seismic events [36-37]. This was demonstrated clearly after the 2009 earthquake in Abruzzo, Italy [38].

The tie-rods should be placed, preferably, at the level of the bearing (in arches and vaults), or along parallel circles (in domes). They should be installed with a slight degree of pre-stressing, in order to guarantee that they will always be under tension. Such tie-rods couple the displacement of springing of arches (or top of pillars), inhibiting the formation of typical 5-hinges symmetric and 4-hinges asymmetric collapse mechanisms [39].

Figure 9. The use of wooden and steel tie rods, Kerman Province, Iran

5. NUMERICAL METHODS

In the last six decades, an enormous growth in the development of numerical tools for structural analysis has been achieved. At the present, numerical simulations play fundamental role in providing insight into the structural behavior and to assess/retrofit existing masonry structures.

Assessment of masonry systems are mostly performed using the finite element method. However, the definition of the parameters necessary to properly feed such numerical simulation presents in many cases significant difficulties and requires a good engineering experience [40]. An overview of possible approaches for the numerical modeling of masonry structures is presented in References [41-47].

Despite the considerable research efforts done in the last decades and the wide spreading of the finite elements method, traditional approaches based on simplified assumptions similar to those of Heyman [25] are still the norm in engineering practice. Based on the limit state analysis, the macro element approach has been developed [48]. Through three decades of use, this approach has proven its ability to give rapid assessment for historical buildings [49-52]. In this later approach, the necessity to evaluate the response of individual portions of the structure (macro elements) that can manifest an independent behavior in occasion of a seismic event is stressed [53]. Macro elements are defined by single or combined structural components (walls, floors, arches, vaults and domes), considering their mutual bond (potential damage pattern, cracks, borders of poor connections, etc.) and restraints (e.g. the presence of tie rods or ring beams), the constructive deficiencies and the characteristics of the constitutive materials. They behave independently as a whole without any support by other portions of the building, but they follow kinematic mechanisms, both out- and in-plane [48]. Furthermore, failure in these elements is due to a loss of equilibrium rather than the stress exceeding the ultimate material capacity [54].

6. DISCUSSION AND CONCLUSION

When dealing with an existing structure, the lack of information on the structural detailing, on the material properties and on the original design could be crucial for a correct assessment of its vulnerability under a seismic event and the subsequent definition of an adequate retrofit strategy. Therefore, it is important to identify the measures necessary to improve the earthquake resistance of traditional buildings in general; and arches, vaults, and domes in particular. Measures that can be considered can be summarized as follows:

1. Definition and application of optimal modeling strategies for determining the load bearing capacity of structural members.
2. Studying the different techniques used in traditional buildings.
3. Definition of the seismic vulnerability of these members according to simplified methods; the "Macro Element" approach is one such method.
4. Carrying in situ tests and developing monitoring programs suitable for traditional buildings.
5. Specifying methods to repair the load-transfer system between vaulted roofs and walls below.
6. Providing measures to deal with the deficiencies of traditional buildings, and in particular the following ones:

a. Weak soil or /and improper foundation
b. Deficiencies in the load carrying structural system
c. Insufficient material strength
d. Heavy roofs
e. Weak connections

7. Due to the many deficiencies and factors mention in (6), many cracks are developed. Survey and drawing of these cracks are important to define the state of the structure and its possible causes.

The present study has tried to investigate many of the points mentioned above. Based on the information given in this paper, it can be concluded that most traditional masonry buildings had major defects prior to the earthquake. The applications of some sort of dynamic loads in an earthquake would increase the damages that already exist and in sometimes would lead to the collapse of these buildings. In order to minimize the losses in these events, further numerical studies need to be carried out to understand the behavior of traditional buildings under normal and seismic loads. Investigating the performance of arches, vaults and domes as independent identities is also essential in understanding such behavior. Comparison of the findings of these investigations with the pattern of failure observed in past earthquakes is quite important for the early diagnosis and accurate treatment of these buildings.

REFERENCES

1. Japan Society of Civil Engineering (JSCE). *The 1999 Kocaeli Earthquake, Turkey-Investigation into the Damage to Civil Engineering Structures*, 1999.
2. Dogangun, A, Sezen, H. Seismic vulnerability and preservation of historical masonry monumental structures, *Earthquakes and Structures*, ***3***(2012) 83-95.
3. Croci, G. *The Conservation and Structural Restoration of Architectural Heritage,* WIT Press, Southampton & Boston, 2007.
4. Mahdi, T. Performance of traditional arches and domes in recent Iranian earthquakes, *13th World Conference on Earthquake Engineering*, Vancouver, Canada, 2004, paper No. 2871.
5. Mahdi T. Performance of traditional arches, vaults and domes in the 2003 Bam Earthquake, *Asian Journal of Civil Engineering*, **5**(2004), 209-21.
6. Maheri, MR. Performance of building roofs in the 2003 Bam, Iran Earthquake, *Earthquake Spectra*, **21**(2005) S411-S424.
7. Croci G. Seismic behaviour of masonry domes and vaults Hagia Sophia in Istanbul and St. Francis in Assisi, *1st European Conference on Earthquake Engineering and Seismology*, Geneva, Switzerland, 2006, paper K8.
8. Mahdi T. Seismic vulnerability of arches, vaults and domes in historical buildings. In Asteris, PG, Plevris, V (eds.), *Handbook of Research on Seismic Assessment and Rehabilitation of historical Structures*, IGI Global, 2015, pp. 401-447.
9. Bal IE, Gulten Gulay F, Vatan M, Symrou E. Historical earthquake damages to domed structures in Istanbul. In Asteris PG, Plevris V (eds.), *Handbook of Research on Seismic Assessment and Rehabilitation of historical Structures*, IGI Global, 2015, pp. 649-673.
10. Arcidiacono V, Cimellaro GP, Ochsendorf JA. Analysis of the failure mechanisms of the Basilica of Santa Maria Di Collemaggio during 2009 L'aquila Earthquake, *Engineering Structures*, **99**(2015) 502-516.
11. Cancino C, Lardinois S, D'Ayala D, Ferreira CF, Dávila DT, Meléndez EV, Santamato LV. *Seismic Retrofitting Project: Assessment of Prototype Buildings*, the Getty Conservation Institute, Los Angeles, 2012.
12. Lee JA, Mason TO. Brick and tile, *Encyclopaedia Britannica*, Chicago.
13. Gavrilovic P, Sendova V, Ginell WL, Tolles E. Behaviour of adobe structures during shaking table tests and earthquakes, *11th European Conference on Earthquake Engineering*, Paris, France, 1998.

14. Baronio G, Binda L, Charola AE. Deterioration of bricks with and without perforations due to salt crystallization, *7th International Brick Masonry Conference*, Melbourne, Australia, 1985.
15. Brocken H, Nijland T. White efflorescence on brick masonry: Towards prediction of efflorescence risk, *13th International Brick/Block Masonry Conference*, Amsterdam, Netherland, 2004.
16. Fernandes FM. *Evaluation of Two Novel NDT Techniques: Micro Drilling of Clay Bricks and Ground Penetrating Radar in Masonry*, Ph.D Thesis, Universidade do Minho, 2006.
17. Boothby TE, Anderson AK. The masonry arch reconsidered, *Journal of Architectural Engineering*, **1**(1995) 25-36.
18. Carran D, Hughes J, Leslie A, Kennedy C. A short history of the use of lime as a building material beyond Europe and North America, *International Journal of Architectural Heritage*, **6**(2011) 117-46.
19. Hasan P. *Sultans and Mosques: The Early Muslim Architecture of Bangladesh*, I.B. Tauris, London, UK, 2007.
20. Arce I. Umayyad arches vaults & domes: Merging and re-creation contributions to early Islamic construction history, *2nd International Congress on Construction History*, Cambridge University, 2006.
21. Maheri MR. Seismic vulnerability of post-Islamic monumental structures in Iran, a review of historical sources, *Journal of Architectural Engineering, ASCE*, **10**(2004) 160-166.
22. Meli R, Sánchez-Ramírez R. Criteria and experiences on structural rehabilitation of stone masonry buildings in Mexico City, *International Journal of Architectural Heritage*, **1**(2007) 3-28.
23. Berilgen MM. Evaluation of local site effects on earthquake damages of Fatih Mosque, *Engineering Geology*, **91**(2007) 240-53.
24. Langenbach R. Soil dynamics and the earthquake destruction of the Arg-e Bam, *Journal of Seismology and Earthquake Engineering*, **5-6**(2004).
25. Heyman J. *The Masonry Arch*, Ellis Horwood Limited, Chichester, UK, 1982.
26. Heyman J. *Structural Analysis: A historical Approach*, Cambridge University Press, Cambridge, UK, 1998.
27. Huerta S. The analysis of masonry architecture: A historical approach, *Architectural Science Review*, **51**(2008) 297-328.
28. DeJong MJ. *Seismic Assessment Strategies for Masonry Structures*, Ph.D Thesis, Massachusetts Institute of Technology, 2009.
29. Politecnico di Milano *(*POLIMI*).* Inventory of Earthquake-Induced Failure Mechanisms Related to Construction Types, Structural Elements, and Materials (Report No D3.1). Italy: New Integrated Knowledge Based Approaches to the Protection of Cultural Heritage from Earthquake-Induced Risk, 2010.
30. Vermeltfoort AV. Analysis and experiments of masonry arches, *Proceedings of the 3rd International Seminar on Structural Analysis of Historical Constructions*, Guimarães, Portugal, 2001, pp. 489-498.
31. Gordon JE. *Structures*. Penguin, Harmondsworth, Middlesex, England, 1978.

32. Gedik HY, Sesigur H, Celik OC, Cili F. Effect of wooden ties on the behaviour of historic stone masonry vaults, *8th International Masonry Conference*. Dresden, 2010.
33. Hejazi MM. *Historical Buildings of Iran: Their Architecture and Structure*, Computational Mechanics Publications, Southampton & Boston, 1997.
34. Oliveira DV, Lourenco PB. Repair of stone masonry arch bridges, *Proceedings of Arch Bridges '04*, Barcelona, Spain, 2004, pp. 451–458.
35. Giuriani E, Marini A. Experiences from the Northern Italy 2004 Earthquake: Vulnerability assessment and strengthening of historic churches, *Proceedings of the 6th International Conference on Structural Analysis of Historical Constructions, SAHC08*, London, **1**(2008) pp. 13-24.
36. Giuriani E, Gubana A. Extrados ties for structural restoration of vault, *6th International Conference on Structural Studies, Repairs and Maintenance of Historical Buildings – STREMAH*, Dresden, 1995.
37. Lagomarsino S, Podestà S. Seismic vulnerability of ancient churches: I. Damage assessment and emergency planning, *Earthquake Spectra*, **20**(2004) 377-94.
38. Selim Gunay M, Mosalam KM. *Structural Engineering Reconnaissance of the April 6, 2009, Abruzzo, Italy, Earthquake, and Lessons Learned*, PEER Report 2010/105, Pacific Earthquake Engineering Research Center, Berkeley, California, USA, 2010.
39. Calderini C, Lagomarsino S, Rossi M, DeCanio G, Mongelli ML, Roselli I. Shaking table tests of an arch-pillars system and design of strengthening by the use of tie-rods, *Bulletin of Earthquake Engineering*, **13**(2015) 279-97.
40. Casarin F. *Structural Assessment and Seismic Vulnerability Analysis of a Complex Historical Building*, Ph.D Thesis, University of Trento, Universita degli Studi di Padova, 2006.
41. Lourenco PB. Experimental and numerical issues in the modeling of the mechanical behavior of masonry, *Proceedings of the 2nd International Seminar on Structural Analysis of Historical Constructions*, Barcelona, 1998.
42. Boothby TE. Analysis of masonry arches and vaults, *Progress in Structural Engineering and Materials*, **3**(2001) 246-56.
43. D'Ayala D. Numerical modeling of masonry structures. In M. Forsyth (Ed.), *Structures and Construction in Historical Building Conservation*, Blackwell Publishing, 2007, pp. 151-172.
44. Roca P, Cervera M, Gariup G, Pela L. Structural analysis of masonry historical constructions: Classical and advanced approaches, *Archives of Computational Methods in Engineering*, **17**(2010) 299-325.
45. Atamturktur S, Sevim B. Seismic performance assessment of masonry tile domes through nonlinear finite-element analysis, *Journal of Performance of Constructed Facilities*, *ASCE*, **26**(2012) 410-23.
46. Atamturktur S, Laman JA. Finite element model correlation and calibration of historic masonry monuments: Review, *The Structural Design of Tall and Special Buildings*, **21**(2012) 96-113.
47. Tralli A., Alessandri C, Milani G. Computational methods for masonry vaults: A review of recent results, *The Open Civil Engineering Journal*, **8**(2014) 272-87.

48. Munari M, Valluzzi MR, Saisi A, Cardani G, Modena C, Binda L. The limit analysis of macro-elements in masonry aggregate buildings as a methodology for the seismic vulnerability study: An application to Umbrian City Centers, *11th Canadian Masonry Symposium*, Toronto, Ontario, 2009.
49. Lagomarsino S. A new methodology for the post-earthquake investigation of ancient churches, *11th European Conference on Earthquake Engineering*, Paris, France, 1998.
50. D'Ayala D, Speranza E. Definition of collapse mechanisms and seismic vulnerability of historic masonry buildings, *Earthquake Spectra*, **19**(2003) 479-509.
51. Lagomarsino L, Resemini S. The assessment of damage limitation state in the seismic analysis of monumental buildings. *Earthquake Spectra*, **25**(2009) 323-46.
52. Giresini L. *Modelling Techniques and Rocking Analysis for Historic Structures: Influence of Vaulted Systems in the Seismic Response of Churches*, Ph.D Thesis, University of Pisa, Italy, 2014.
53. da Porto F, Silva B, Costa,C, Modena C. Macro-scale analysis of damage to churches after earthquake in Abruzzo (Italy) on April 6, 2009, *Journal of Earthquake Engineering*, **16**(2012) 739-58.
54. Valluzzi MR, Cardani C, Binda L, Modena C. Seismic vulnerability methods for masonry buildings in Historical centres: Validation and application for prediction analyses and intervention proposals, *13th World Conference on Earthquake Engineering*, Vancouver, Canada, 2004, paper No. 2765.