REVIEW ARTICLE

Review of the Methods for Strengthening and Retrofitting Cultural Heritage Structures

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Received: 13/01/2020 **Accepted:** 15/03/2020 **Available online:** 30/06/2020

ABSTRACT

The history of each country is the identity of its people, and the preservation of originality and culture is considered a social value. Moreover, the maintenance of valuable buildings that reflect the path to the growth of human civilization is of particular importance. To achieve various goals, including the development of the tourism industry, each country tries to prevent the destruction of historic buildings, or to resuscitate them by applying various methods of restoration and retrofitting. Iran being an ancient civilization has many valuable historical buildings. Traditional construction materials included masonry materials such as clay and mud, stone, wood, and brick. Because of the weakness in physical structure and a lack of allowable shear and tension strength, those heritage structures are susceptible to strong forces such as earthquakes. Studies on historical sites and heritage complexes in Iran, indicate no fundamental work has been done in this regard, and practically measures have been taken without any improvement in the structural performance of the buildings. To minimize the damage on historical buildings to the least possible extent, the seismic behavior of such buildings against the seismic forces could be enhanced through special strengthening techniques. This paper is the result of the desk research using descriptive-analytic method, which includes classifying the main elements of historical building's structure, their possible weaknesses, and a review of reinforcement and restoration resolve methods for each structure.

Keywords: Seismic Retrofitting, Cultural Heritage Structures, Strengthening Methods, Traditional Masonry Structure

1. INTRODUCTION

Strengthening and retrofitting structures is one of the essential steps to reduce damage. For instance, in order to reduce earthquake induced damages, which is an integral part of natural disasters, fundamental planning is needed. Experience has proven that even weak earthquakes have destructive effects on historical structures. Strengthening involves increasing the seismic capacity of existing buildings. The seismic behavior of existing buildings is affected by the inadequacy of the main structure, the strength loss of old materials, and the exhaustion of bearing elements during the lifetime of the building. Therefore, retrofitting of damaged and undamaged buildings is an urgent need. Strengthening is not possible without analysis and engineering calculations and doing numerous experiments (Fischetti, 2009).

Access this article online

DOI: 10.25079/ukhjse.v4n1y2020.pp45-56 **E-ISSN:** 2520-7792

The three main features that increase the vulnerability of historical buildings to natural disasters such as earthquakes include the following: exhaustion of the material, low-strength material, and structure heaviness; accordingly, the solutions to protect these buildings against earthquake should be in the direction of eliminating these shortcomings.

2. FACTORS AFFECTING THE DETERMINATION OF SEISMIC RETROFITTING METHODS OF HISTORIC BUILDINGS

Considering the climatic conditions of Iran, most of the historical buildings are made of mud, brick, or traditional masonry materials. Thus, studying the behavior type of such buildings against earthquake
Considering the climatic conditions of Iran, most of the historical buildings are made of mud, brick, or traditional masonry materials. Thus, studying the behavior type of such buildings against earthquake forces and the amount of resistance and ductility of materials used in them can be influential in selecting an appropriate seismic retrofitting method. In most structures, there are no resisting elements against the earthquake forces. Generally, in order to study the seismic retrofitting of historical buildings, the following fundamental points can be noted (Molaei et al. 2014).

2.1. Structural System

Historical structures suffer from heavy losses owing to the lack of a complete transmission path, irregularity in the plan, the insufficient shear strength of the walls, the lack of coordination of structural elements, and, ultimately, the lack of a proper foundation (Afshari, 2017 **;**Code No.360, 2007)**.**

The main weakness of these structures against earthquake loads is the lack of ductility, which decreases the absorption of earthquake forces in comparison with ductile structures. In the case of continued seismic loads, the main bearing elements of the building suffer serious structural damages. The masonry materials used in the historical buildings are often fragile and non-ductile, and the used mortars such as lime mud cause poor adhesion between the mudbrick pieces, and the earthquake induced lateral forces produce shear and bending forces in brick and mudbrick walls. The forces cause the layers to move on each other owing to the weak bond between the rows and ultimately result in failure in the walls (Chavoshan et al.**2012**; Afshari, 2017)**.**

2.2. Walls

Strengthening a masonry building should be considered thoroughly. In all the strengthening methods, increasing the strength of outer walls, which have not much resistance against lateral loads because of the lack of ductility, is taken into consideration (Vaisi, 2011)**.**

2.2.1. Brick Wall Failure Modes

The failure modes of a separated brick wall are divided into two main groups of in-plane and out-of-plane failures. In the case of in-plane failure that the wall is subjected to a high vertical load and the wall height to length ratio is less than one, the shear failure mode occurs. Moreover, if the height to length ratio is greater than one (approximately equal to 2) and the vertical load is too high, there is still the possibility of shear failure. If the shear strength of the wall is small and the lateral load is large in comparison to the vertical load, then sliding shear failure will occur. In this case, the wall height to length ratio is usually less than 1.5 to 1 and about 1 to 1. If the shear strength of the wall is sufficient and the column height to length ratio is 2 to 1, then flexural failure occurs (Tayefi Nasrabadi et al. 2008)**.**

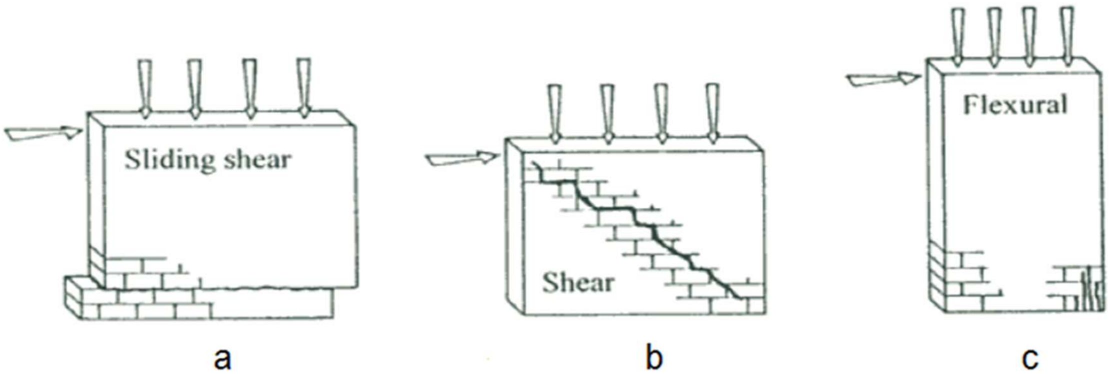

Figure 1. Typical failure modes of unreinforced masonry walls, subjected to in-plane loads: (a) Sliding Shear failure, (b) Shear failure, and (c) Flexural failure (Garbin et al., 2007)

Historical buildings are constructed with materials and techniques resistant to compressive forces and do not have the proper resistance against shear and flexural stresses. Therefore, the insufficient resistance of historical buildings to lateral loads will lead in collapsing of such historic monuments (Afshari, 2017).

2.3. Ceiling Systems

The main imperfections and weaknesses in the roofs of such buildings are (Code No.360, 2007):

1- Heavy-weight ceilings.
2- Lack of uniformity and coherence in the ceilings.
3- Lack of proper connection between the ceiling and the walls.
4- Lack of adequate strength rigidity in flat ceilings.
5- Inappropriate restraining of arched and domed roofs against the drift.

2.4. Foundation Systems

The main imperfections in the foundations of such buildings include (Code No.360, 2007):

1- Non-uniform foundation settlement.
2- Erosion of foundation soil over time.
3- Lack of uniformity and coherence in the foundation.

3. IMPLEMENTATION METHODS FOR SEISMIC RETROFITTING OF VALUABLE HISTORICAL BUILDINGS

3.1. Walls (Increased ductility and load-bearing capacity)

3.1.1. Steel mesh and shotcrete method

In this method, the wall plasterworks are destroyed and removed up to the surface of the brick so that the wall surface is free of materials such as plaster and harmful substances for concrete. Flooring at the foot of the walls is also removed until the bottom of the wall (tie-beam) is reached. Then, rebars are placed in the tie-beam with specified and certain intervals and the wall meshing is performed. After that, the concrete is sprayed with a minimum thickness of 3 cm. The wall surface is processed again (Tayefi Nasrabadi et al., 2008; Ghiassi et al., 2011)

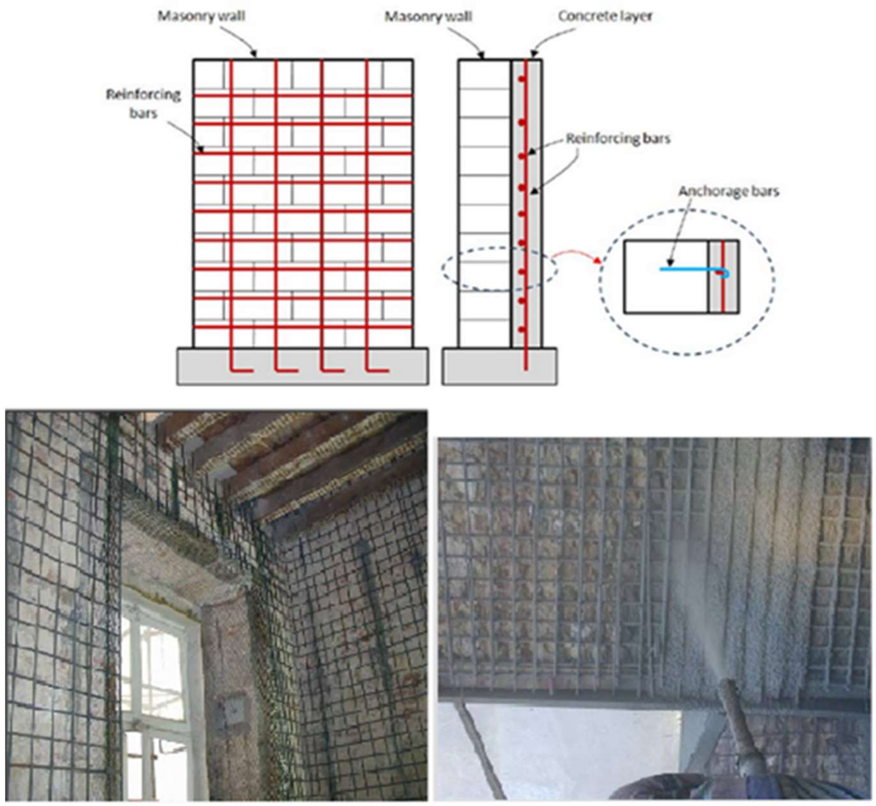

Figure 2. Typical detail of masonry wall strengthening with reinforced concrete layer (Ghiassi et al., 2011; Meireles et al., 2013)

Advantages (Tayefi Nasrabadi et al. 2008)**:**

- The method is well-known and applicable on walls**.**
- It occupies a small space beneath the building**.**
- It makes no changes in the building architecture**.**
- Almost uniform stiffness is distributed at the building.

Disadvantages (Tayefi Nasrabadi et al. 2008)**:**

- The wall plaster must be completely removed**.**
- The implementation is prolonged owing to destruction and thinner re-execution of plasterworks**.**
- Inability to exploit the building during retrofitting operations**.**
- It requires special equipment for doing shotcrete operation.

3.1.2. Grouting

Grouting is one of the most effective and economic solutions for increasing the shear and flexural strength of old and historical buildings. Through Grouting, it can be penetrated into the structure components without damage and destruction, and by injecting expanding cements and epoxy resins, the cohesion and integrity of the structural elements can be increased. Mortars used to connect mudbrick and brick walls are lime mud or sometimes mud types that have no resistance to earthquake induced tensile and shear forces. Therefore, the mortar between brick layers (rows) is removed using special grinders and the grooves created are rinsed thoroughly with water and then, special epoxy adhesive is injected inside the rows. The epoxy adhesion increases the shear and flexural strength of the wall against earthquake lateral forces (Afshari, 2017).

Figure 3. Increasing the shear and flexural strength of a brick wall with grouting (Afshari, 2017)

3.1.3. The use of high-strength fiber reinforced polymers

New materials that have made a fundamental change in retrofitting of building are included fiber reinforced polymers (FRPs). FRPs consist of high-strength fibers in a resin matrix. These fibers can be made of carbon (CFRP), glass (GFRP) or aramid (AFRP). The tensile strength of this fiber in a longitudinal direction is several times that of steel.

In addition to having high tensile strengths, FRP has two other advantages, including:

Light weight and durability in different environmental conditions makes it possible to retrofit historical buildings. FRPs can be produced in a variety of shapes such as plate, strip, rebar, and mesh. One of the most effective and simple methods is using FRPs on external surfaces of structural elements, such as walls. These fibers used in various structural elements because they are easy to use and have high flexibility. The use of FRP in different elements and connection points, such as the connection of walls can significantly increase the bearing capacity and the ductile behavior in historical masonry buildings.

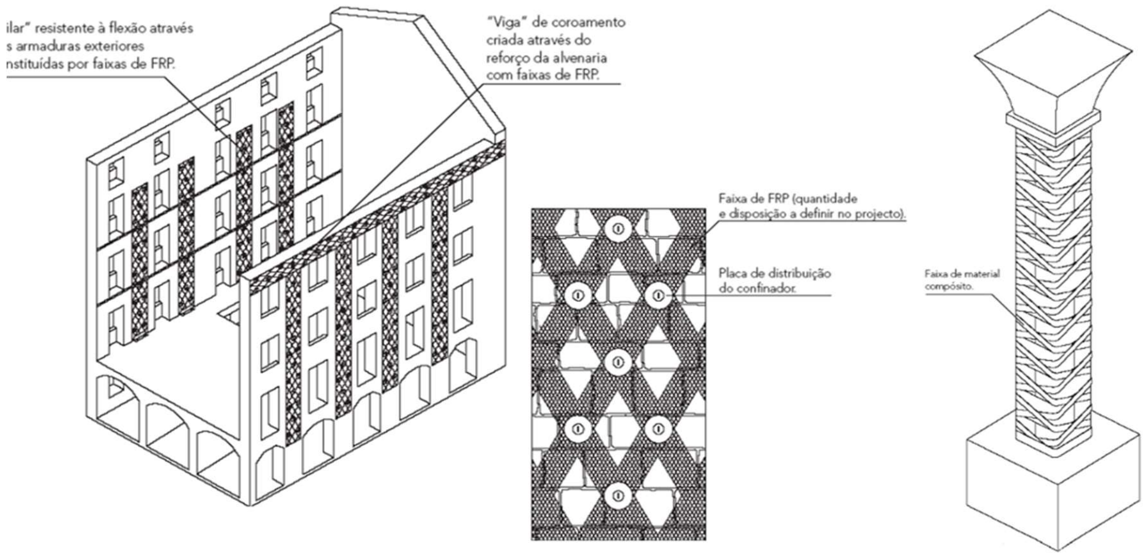

Figure 4. Application of CFRP/GFRP on building, wall and column (Meireles et al., 2013)

In 2007, the experts of this industry studied the latest achievements at London city. One of the important conclusions of this conference was to identify the high potential of these fibers for being used in the retrofitting of historical structures. Today, the use of frp method for reparation and retrofitting is taken into consideration throughout the world. [3] In repairing historical buildings, the use of frp may have most advantages and the least loss on the beauty of that texture. However, its behavior has not been tested over long time under different temperature and humidity conditions, and further research is needed. The seismic analysis of unreinforced masonry structures is a new topic. Most experts emphasize that masonry structures are not of adequate flexibility to resist earthquakes (Jalilian et al., 2011).

Advantages (Chavoshan et al., 2012 ; Jalilian et al., 2011) **:**

- It occupies a small space beneath the building.
- It makes no changes in the building architecture.
- High strength and stiffness to weight ratio.
- Design flexibility.

Disadvantages (Vaisi, 2011)**:**

- The wall plaster must be completely removed.
- Very high cost of raw materials.
- Need for high technology for implementation.

3.1.4. Reinforcing the walls

One of the methods of repairing and retrofitting of the structural elements of the historical buildings is the injection of expanding cement grouts or special epoxy resins inside the pores formed between the structural components. In this case, the injecting material fills the holes and pores between the masonry materials and causes uniform distribution of stresses between the various components of the structure. The lateral bearing capacity of the building increases with increasing the flexural and shear strength of the used materials. Of course, using this method in combination with other techniques, such as grouting, can be more effective. In historical buildings, to retrofit mudbrick and brick walls, the pores inside the walls are first filled with expanding cement grout, and, in the second stage, the adhesion of the mortar and its cohesion to the old materials are strengthened by injection of epoxy resin inside the wall rows (Afshari, 2017).

Advantages (Vaisi, 2011)**:**

- Keeping the originality of the building considering enhancing the quality of the main materials.

- Minimizing damages and manipulation of architectural coverage.

Disadvantages (Vaisi, 2011)**:**

- Need for high technology for implementation.
- Need for doing tests after grouting to ensure the performance.

3.1.5 Embedding concrete and steel structural elements inside the long walls (invisible form)

Sometimes, in many historical structures, such as citadels, forts, and castles, there are very high and long mudbrick walls that surround the building's area. They have a large thickness without lateral restraint and are overturned because of the non-tolerable earthquake lateral forces (perpendicular to the wall). In order to prevent the overturning of these walls, it is possible to put concrete or steel columns in their webs according to the position and the material of the wall and in the end, all the evidence of retrofitting can be modified using the previous coating without significant change in the apparent quality of the building (Afshari, 2017 ; Mohebali et al., 2014).

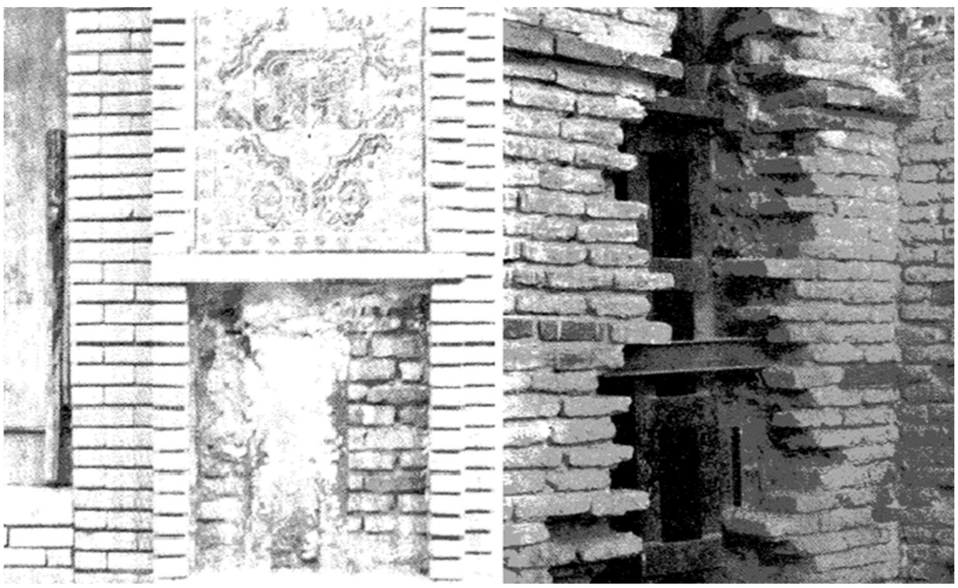

Figure 5. Embedding steel structural elements inside the wall "invisible form" (Mohebali et al., 2014)

Advantages (Vaisi, 2011)**:**

- Ease of implementation owing to the presence of useless and hidden spaces, including wind catcher.

Disadvantages (Vaisi, 2011)**:**

- Impossible to assure appropriate interaction of old and new elements.
- The implementation time is prolonged because of destroying and rebuilding plasterwork.

3.1.6 Using seismic damper inside walls

The dampers are a seismic bracing system in buildings and bridges that act only against the various vibrations caused by earthquake and do not play any role in bearing static loads. This makes it easier to predict the behavior of a structure under seismic loading. While usually materials can provide critical damping of about 5%, by using seismic dampers along with lateral bearing elements or structural joints, we will be able to increase the damping of the structure by more than 50%, which means a significant amount of dissipation in the earthquake load. Adding dampers, is considered as a rather unusual strategy for seismic retrofitting. Adding dampers reduces the overall displacement of the structure, response acceleration, and the lateral displacement of the interior floor, which will be associated with rescuing structural and nonstructural damages. Moreover, the architectural problems in the design of buildings is reduced (Meireles et al., 2013).

Advantages (Vaisi, 2011)**:**
- Reducing force exerted on the wall and preventing failure,
- No need for replacement after the earthquake event.

Disadvantages (Vaisi, 2011)**:**
- The necessity of existing column or vertical column-tie connected to it
- Destroying the wall in order to embed the dampers.

3.2 Ceilings, portal, and domes

In this section, practical solutions for the retrofitting and strengthening of wooden ceilings and barrel vault are presented, by applying which, the strength and stiffness of the ceilings and their rigidity against the lateral forces of the earthquake can be increased. Improvement of ceilings in general is performed by considering the following basic principles (Tayefi Nasrabadi et al. 2008).

3.2.1. Reducing Ceiling Weight

Wooden ceilings: In these ceilings, a relatively thick layer of thatch plaster is used to seal the ceiling, and it is usually used from a new thatch plaster layer to re-insulate the previous layers that increases the weight of the ceiling. To reduce the ceiling weight, one of the following solutions can be used: The soil and the thatch are first removed from the ceiling and after placing a wooden plate on the ceiling main beams, the created surface is used as mold and thin a layer of reinforced concrete (having a thickness of 5 cm) is implemented on it that is connected to the walls (Tayefi and Nasrabadi et al. 2008).

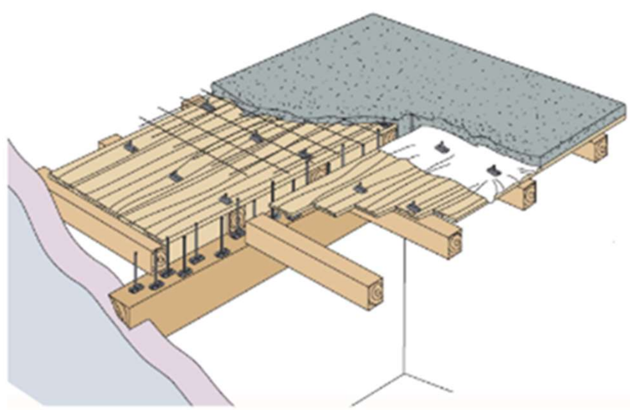

Figure 6. The reducing wooden ceilings weight with a cooperating reinforced concrete slab (Meireles et al., 2013)

3.2.1.2. Barrel-vault ceilings: In this type of roof, owing to the arched brick vault, the roof uses a lot of heavy materials for filling and flooring, including soil brick. It is possible to reduce the floor weight by replacing these with mineral pumice or concrete foam in the flattening (Tayefi Nasrabadi et al. 2008).

3.2.2. Increasing Rigidity of the Ceilings

Flat ceilings are one of the most important and effective elements of the structural members that play the most role in absorbing and distributing earthquake lateral forces between the vertical elements of the structure. The ceilings of historical buildings are mostly barrel vault, wooden beam, and dome or arch ceilings, which owing to insufficient rigidity cannot absorb seismic forces from the earthquake and suffer heavy damage in severe ground motions.

Therefore, to increase the rigidity of the ceilings, we must (Afshari, 2017):

- Remove the entire loads accumulated over the ceiling.
- Implement a two-sided rebar mesh on the ceiling with a maximum mesh size of 50 cm and rebar of size 12 mm in diameter.
- Implement concrete tie at the four sides of the ceiling, in such a form that the rebar meshes are placed inside it.
- Implement a 5-cm layer of concrete on the barrel-vault ceiling.

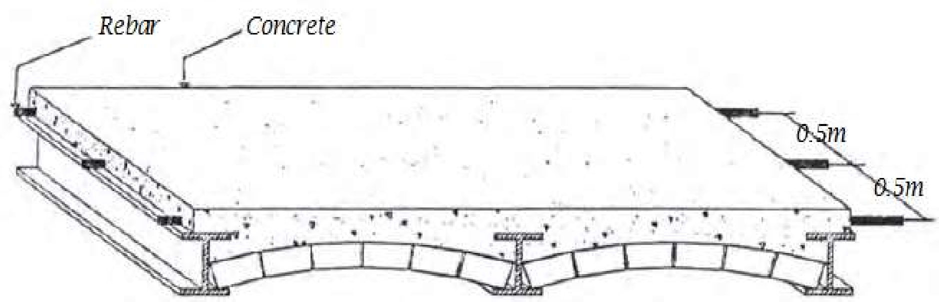

Figure 7. Typical detail of increasing rigidity of the ceilings (Afshari, 2017)

3.2.3. Appropriate connection of ceiling to wall

A major drawback of the structure of this type of buildings is the lack of adequate connection between the components of the structural elements. One of the main weaknesses is connection of ceiling to wall (Afshari, 2017).

3.2.3.1. Reinforcing the connections of several types of traditional ceilings to wall

- **Wooden ceilings:** The connection of the wooden ceiling to the walls is carried out by steel restraints. In this case, the main beams of the roof are nailed or screwed into steel straps, and the straps are restrained to other steel plates behind the wall using screws after passing through the wall thickness (Tayefi Nasrabadi et al., 2008).
- **Barrel-vault ceilings:** To strengthen the connection of vertical walls to the ceiling, before pouring the reinforcing concrete into the ceiling, several holes with at least 50 cm in height should be constructed vertically on the wall at a maximum intervals of 30 cm and vertical rebars of no.14 should be embedded in them using epoxy resins or expanding grouts. The free end of the rebars, which are placed inside the collar (beam-tie) around the ceiling,
- should be bent at an angle of 90° and inserted to a length of 50 cm inside the reinforcement of the ceiling, and then the ceilings and coils are simultaneously concreted (Afshari, 2017).

Barrel-vault roof (portal): To eliminate the thrust forces in a portal, steel packing operation is performed (using concrete, wood, steel profile), which is performed in the following stages (Mohebali et al., 2014)**:**

- First, precaution, protection, and shoring operations and the elimination of danger are carried out in the building.
- Digging the foundation and material separation should be done under the supervision of experts, so that the historical layers and the main foundation are not damaged.
- Because these tensile materials must be hidden (hidden steel), it is necessary to

examine the location of the materials before embedding them, and the materials used should be carefully numbered and removed, so that after performing the operations, they are exactly installed in their original location in such a way that there is no significant change in the appearance of the building at the end.

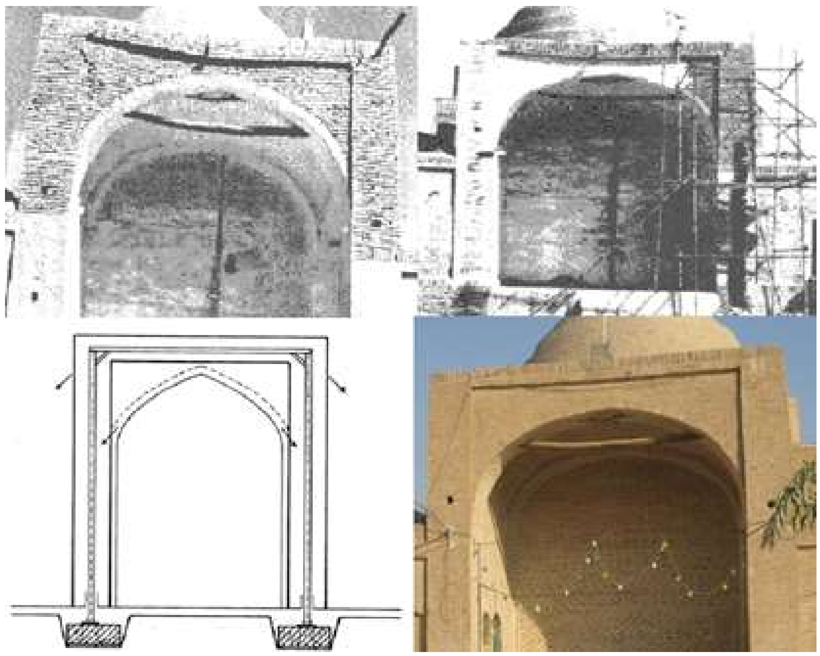

Figure 8. An example of the reinforcement of a portal with steel packing (Mohebali et al., 2014)

Strengthening of domes: The use of materials with expanding property is a very good choice for pre-stress strengthening in historical buildings. Because not only do they structurally reduce the tension, deformation, and, finally, the cracks in the masonry structure by creating a uniform pre-stress, but their use is consistent with the rules of restoration of the historical structures in terms of minimizing manipulation in the building. By injection of these materials into the gaps of the mortar in areas of the dome where tensile cracks exist, it is possible to avoid expansion of the cracks and creating new cracks in the dome, and thus strengthen the dome against the vibrations from earthquakes and any other loads that can lead to create tensile stresses (Sahab et al. 2011).

3.3. Foundation

Foundation is one of the most effective and important elements in the path of complete transmission of earthquake lateral loads that play the main role in earthquake energy absorption and transfer it to the structure. Therefore, it is expected to give it special attention in the retrofitting and strengthening of historical buildings. Because of their old age, the foundations of historical buildings are usually made of lime concrete with rock, which is relatively good against compressive forces, however the soil beneath foundation that is composed of various types such as alluvial, clay, gravel, and sandy soil, are getting compacted and settled under stresses caused by seismic loads and the heavy structure and eventually causes an asymmetric and heterogeneous subsidence of the building. The subsidence causes heavy damages to historical and old buildings. So, using different injection methods, the soil density under the foundation should be increased significantly and, finally, by increasing the compressive and shear strengths, it should be able to overcome the pressures caused by the earthquake dynamic loads and the heavy weight of the building (Afshari, 2017)

3.3.1. Injecting concrete below the foundation

The drills that are inserted into the ground by impact are guided below the foundation, and a mixer is used in order to homogenize the grout fluid during injection. After blending water and cement with the ratio of 1:2 in the mixer, the cement grout is injected through special hoses into the hole. The injection process continues to 5 atm, and owing to the pressure, the grout enters the soil pores under the foundation and combines with sand and soil grains, forming an integrated resistant body. The compressive and shear strengths of the foundation are increased because of the increase in the soil and the foundation becomes able to resist the pressures from seismic loads, without subsidence (Afshari, 2017).

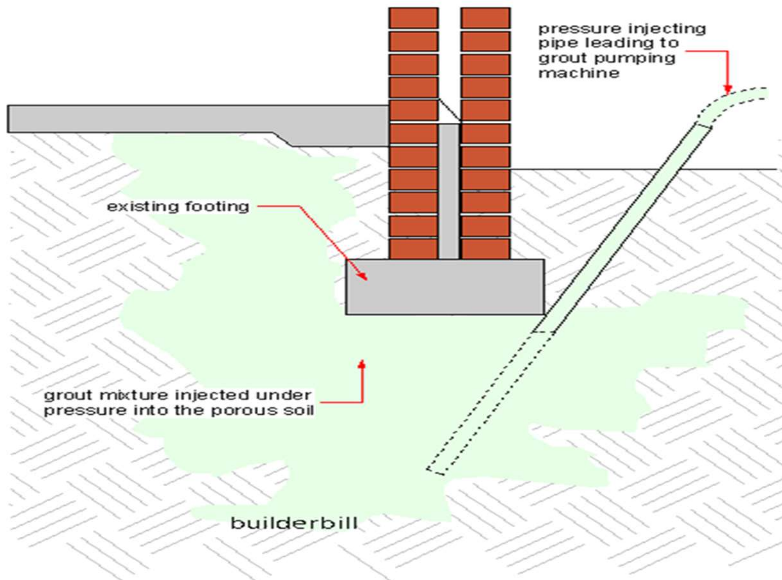

Figure 9. Underpinning - Injecting a grout mixture into the sub soil under the weak foundation (Ghiassi et al., 2011)

4. Conclusion

Valuable historical buildings and cultural heritage have to be preserved regarding their cultural and historical value. The compressive strength of the building materials in such structures are much higher than their tensile strength. In this paper, attempts were made to review a number of conventional methods, in which attention is paid to the most important issue in the maintenance of historical monuments, including the preservation of the totality of the building and the exterior and interior views without excessive disturbance. These retrofitting techniques improve strength properties of old structures by:

- Increasing building ductility.
- Increasing integrity of the elements
- Completion of the load transferring process to the foundation.

REFERENCES

Afshari, M.H. (2017). Seismic Improvement Methods of Valuable Historical Buildings Against Earthquake. *International Conference on Civil Engineering, Architecture and Urban Planning of Contemporary Iran*. Tehran, Osweh University - Tehran - Shahid Beheshti University. https://www.civilica.com /Paper-CICEAUD01-CICEAUD01_0489.html

Chavoshan, M,. Ghalenouei, M & Naseri, H.R. (2012). Examining seismic behavior of masonry buildings and strengthening them by CFRP composites. *1sth Regional Conference on Civil Engineering & Environment, Qazvin, Islamic Azad University, Qazvin Branch*

Fischetti, D.C. (2009). *Structural Investigation of Historic Buildings: a Case Study Guide to Preservation Technology for Buildings, Bridges, Towers and Mills, John Wiley & Sons.*

Garbin, E., Galati, N., Nanni, A., Modena, C., & Valluzzi, M. R. (2007). Provisional design guidelines for the strengthening of masonry struc- tures subject to in-plane loading. *Proceeding of tenth North American masonry conference* (pp. 3-5). Retrieved from http://www.researchgate.net

Ghiassi, B., Soltani, M., & Tasnimi, A.A. (2012). Seismic Evaluation of Masonry Structures Strengthened with Reinforced Concrete Layers. *Journal of Structural Engineering.* 138(6).

Jalilian, A.A., Shabani, v., Esmaeilzadeh, S, (2011). New methods of strengthening historical monuments. *03rd*

National Congress on Urban Development. Sanandaj, Islamic Azad University, Sanandaj Branch. https://www.civilica.com/Paper-NCUD03-NCUD03_137.html

Meireles, H., Bento, R. (2013). Rehabilitation and strengthening of old masonry buildings. *Março de*. 0871-7869. Retrieved from http://www.pdfslide.net

Mohebali, M.H., Moradi, M.A. (2014). Road, Housing and Development Research Center. *Book of twelve lesson on restoration*. Ministary Of Housing And Urban Development, Iranian Urban Development And Revitalization corporation, Tehran, Iran.

Molaei, M.R., Barazin, M.B., Saba, H. (2014). Investigating the effect of suppositories on strengthening foundations and soil improvement. *15th Students Conference on Civil engineering*, Urmia, Urmia University of Civil Engineering Student Association. https://www.civilica.com/Paper-CESC15-CESC15_137.html

Sahab, M.Q., Moeini, S.M., (2011). Reinforcement of brick domes in historical buildings and analysis of reinforced domes with the help of ABAQUS software. *6th National Congress of Civil Engineering* , Semnan, Semnan University. https://www.civilica.com/ Paper-NCCE06-NCCE06_0088.html

Nasrabadi, A.A.T., Mehrabadi, M.H.R. (2008). Strengthening building structures against earthquakes. *National Conference on Resilience of Iran*. Yazd, Yazd University. https://www.civilica.com/Paper-IRNC01-IRNC01_093.html