A Survey on Seismic Reinforcement Systems of Adobe Buildings in Iran

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Abstract—**Regarding the fact that a vast part of Iran plateau is covered with desert lands, adobe has been used as the main building material, especially in historic buildings. Although the large number of earthquakes happen in Iran, adobe structures have no resistance to dynamic actions such as earthquakes. Today, various seismic reinforcement systems have been employed in such buildings. This research indicates that each technique has different results in implementation and functional scopes. Considering the lack of practical analysis of these techniques in previous researches, the present paper tries to find out the positive and negative points of each technique as the research strategy in a descriptive-analytic-comparative way. The result declares that these prevalent reinforcement systems are in accordance with brick buildings' regulations, and it is necessary to provide seismic reinforcement systems in accordance with adobe buildings' seismic behavior and adobe material traits.**

Index Terms—**Iran, adobe buildings, reinforcement, earthquake.**

I. Introduction

Iran, an area with a high seismic risk, is located on the Alpide belt. Throughout history, severe earthquakes have happened in this area, which have caused huge devastations and claimed many lives. The experience of earthquakes in Iran indicates that the main factor for widespread devastations on economy and human casualties is the high level of vulnerability of buildings and infrastructural systems. With regard to the huge number of masonry buildings and their technical and implementation weaknesses, the huge devastations are mainly due to their high vulnerability [1]. Masonry buildings are fragile, brittle structures, and are considered the most vulnerable structures during severe earthquakes [2]. A wide variety of raw materials, both natural and artificial, is used for the production of traditionally and industrially made masonry units. Masonry building is classified in diverse types by different materials such as brick, adobe, stone, and concrete [3].

Adobe buildings, as the main issue in this paper, have been constructed in large number in Iran especially in villages due to the low-cost and ease construction of adobe structures. Despite their advantages, adobe constructions have some problematic characteristics. If not properly reinforced, this type of construction can exhibit a deficient response to seismic actions due to the properties of adobe masonry, such as large mass, limited tensile strength, fragile behavior, and softening and loss of strength upon saturation. Under horizontal actions, these structures can suffer severe structural damage and sometimes collapse, causing innumerable human and material losses. The statistics on losses caused by recent earthquakes in regions where constructions are mainly composed of adobe clearly attest to the deficient behavior of these structures [4].

The main purpose of reinforcement is to achieve a structure designed carefully based on principles of earthquake-resistant methods. These methods vary for different structural types [5]. In recent years, various methods are applied for reinforcing adobe buildings having low elasticity modules against the seismic load. Croci investigated seismic actions in historic buildings and categorized the precautionary procedures of minimizing these actions into two types: 1-improving structural behaviors, and 2- reducing seismic influences [6].

But in some cases, the resistance methods are not sufficient in adobe buildings and it is observable that applying up-to-date scientific approaches and improving prevalent systems are so essential.

II. The Earthquake Effect on Adobe Buildings

Despite a low elasticity modulus of adobe compared to that of other building materials, as long as the building is undamaged, it will respond elastically for a short time. But as seismic ground motion increases, the stresses in wall exceed the tensile capacity of adobe material and cracking occurs. As cracks develop, the dynamic response characteristics of the structure undergo drastic changes. The other impact factor is substantial cracks nearly always exist in adobe buildings as a result of past earthquake, wall slumping, or foundation settlement [7].

In addition to mechanical characteristics of adobe, the main factors of vulnerability of adobe buildings in earthquakes are summarized as follows: poor quality of materials, lack of reinforcements or horizontal bond beams, lack of proper integrity in walls, especially in corners and intersections, lack of foundation and horizontal bond beams beneath the walls, heavy roofs, using mud mortars with low sticking quality, building long walls, placing openings near the corners, building wide openings, short lintels above openings and constructing high buildings using adobe (more than one floor) [8].

III. Reinforcement Systems in Iran

As the result of horizontal motion of the ground, the inertial force will be increased in top level of mass structure (usually at the roof level). This inertial force is transferred from roof slab to walls and columns, then to the foundation

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and finally to the subsoil. All these structural elements (roof, walls, columns and foundation) and their contacts must be designed in a way that inertial forces are transferred through them, without affecting them. It is noticeable that walls and columns are the most important elements of transferring inertial forces. Walls are often built with fragile materials such as masonry ones, and this is the reason that they are too weak to bear the horizontal inertial force along their thickness during earthquakes [9]. Therefore, proper implementation of seismic-resistant systems will increase elasticity and load absorption capability [10]. This is presented by Fig. 1.

As mentioned earlier, diverse reinforcement systems of adobe buildings are implemented in Iran, each one having several advantages and disadvantages in various technical and implementation aspects. This research was an attempt to explore the above-mentioned issues.

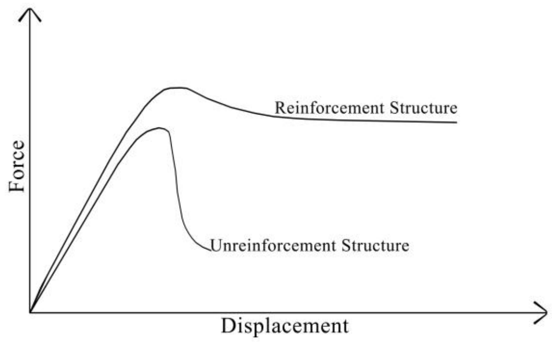


Fig. 1. Seismic reinforcement structure [11].

A. Shotcrete

The first step in implementing this method is to remove the installations and decorations of the walls to reach the brick and adobe materials, in order to eliminate materials such as plaster that weaken the concrete. Then, the flooring must be removed to reach the foundation. For the next step, bars are placed in the foundation with specific distance from each other and the wall must be equipped by steel mesh, this is shown in Fig. 2 [12]. To make the reinforced wall and its new shotcrete an integrated element, shear anchors must be set between the wall and the new shotcrete, as it is presented in Fig. 3. The epoxy and grout can be used for fixation of these anchor [13].

Fig. 2. Shotcreting.

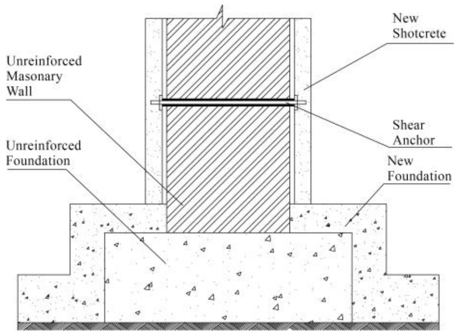


Fig. 3. Shotcrete detail.

Advantages:

Providing proper contact between wall and foundation.

Not shrinking the building's space.

Not changing the architecture.

Disadvantages:

Removal of the building's installations for shotcreting and reimplementing them after proceeding.

Irreversibility of using concrete in historic buildings as the main choice for seismic reinforcement system.

Damaging and removing the decoration.

The risk of smashing the adobe by seismic force of shear anchor in earthquakes.

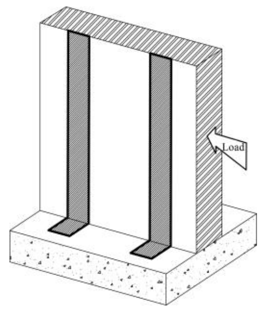
Requiring special equipment for shotcreting.

B. Application of Fibers

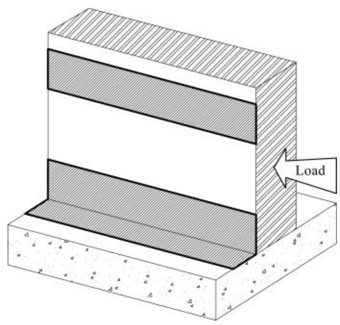
Today, diverse types of fibers have been used for reinforcing adobe structures, the most prevalent of them being categorized into two types: polymer and natural fibers.

FRP (fiber reinforcement polymer):

The most prevalent FRP types are classified as GFRP (glass fiber reinforced polymer), CFRP (carbon fiber reinforced polymer) and AFRP (aramid fiber reinforced polymer). They are all fixed on structural elements by adequate glue, which is compatible with materials, and also their forms and positions depend on the force entered which is presented in Fig. 4-6.



(a) Flexural reinforcement



(b) Shear reinforcement

Fig. 4. Layout of FRP plates.

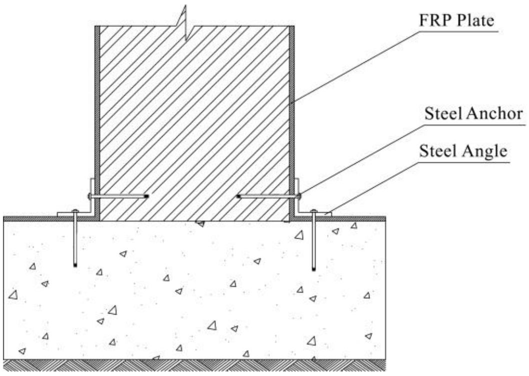
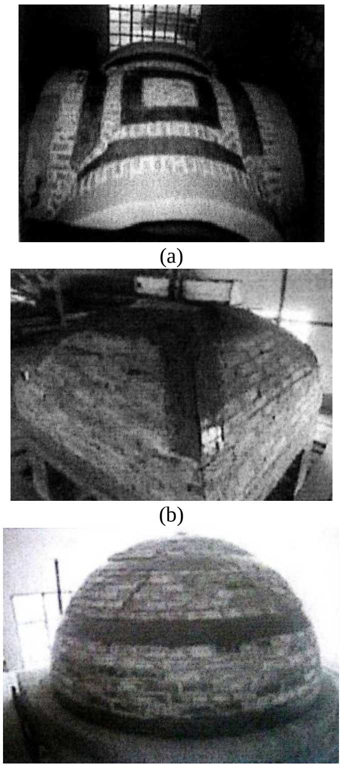


Fig. 5. Application FRP plate.



(a)

(b)

(c)

Fig. 6. Structural elements reinforced by FRP [14].

Geogrid fibers:

Additionally, geogrid fiber is another type of polymer fiber which is set in mesh style on structural elements and connected to foundation in various ways.

The researchers found that it is possible for the walls to disintegrate into large blocks during severe ground shaking, however the mesh will prevent the wall from falling apart, and collapse will be avoided [15].

Advantages:

Resistance against moisture and corrosion.

Having high resistance quality while having low weight.

Not damaging the view of building especially in historic ones.

During the earthquake, geogrid mesh can hold the materials and prevent disintegration.

Not requiring specific equipment for application.

Having proper tensile strength.

Providing proper contact between all structural elements and making an integrated structure.

Disadvantages:

Removing installations and decorations in historic buildings.

Efficiency is not guaranteed in long term.

Having high cost.

Having insufficient mechanical characteristics in pressure mode.

Polymer fibers have different thermal coefficient of expansion compared to traditional materials in temperature variations.

Natural fibers:

These fibers are made of palm trees and after being processed, would be placed in the required parts. They are widely used in Arg-e-Bam, mostly applied for reinforcing vaults. They are connected to the foundation and walls by GFRP wire or geogrid mesh, as it is shown in Fig. 7.

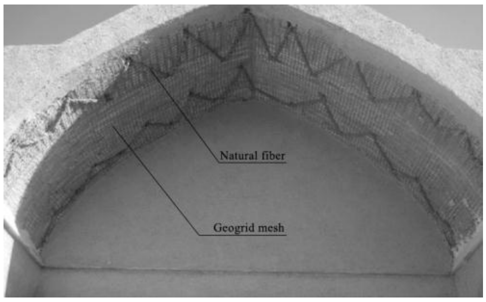


Fig. 7. Application of fibers in Arg-e-Bam.

Advantages:

Being in accordance with historic structures.

Reversibility; especially in historic buildings.

Having minimum manipulation in the building.

Having economic efficiency.

Disadvantages:

Requiring extra examinations to enhance the strength of the fiber tensile.

Not functioning properly if that structure and fibers are not integrated.

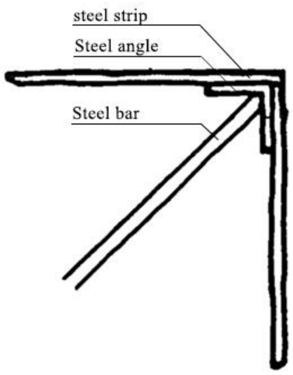
C. Application of Cold Rolled Steel Profile

Reinforcement of roof:

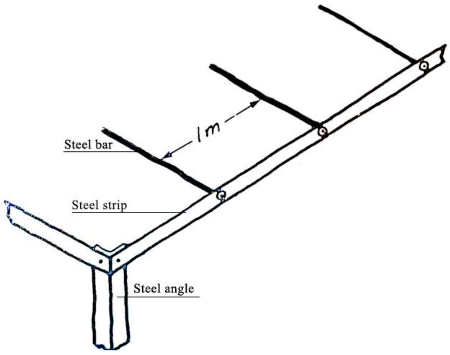
As is shown in Fig. 8 (a), for reinforcing these types of elements, 12 mm bars must be welded in diagonal position to the steel angle.

Reinforcement of vault:

Due to the lack of proper bar function in diagonal position, the use of bars in intervals of 1 meter is proposed to be welded to steel angle so that all resistance elements can function as an integrated structure that is presented in Fig. 8 (b).



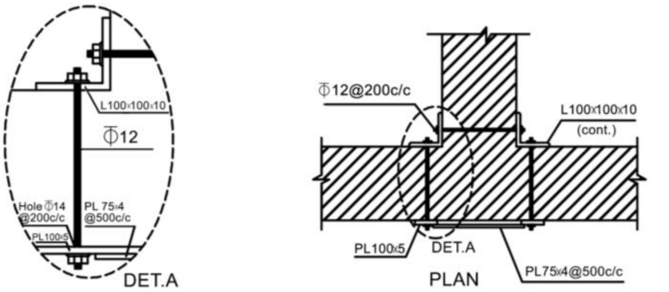
(a) Roof reinforcement



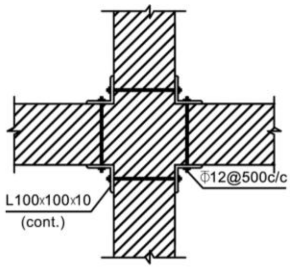
(b) Vault reinforcement
Fig. 8. Application of cold rolled steel profile [16].

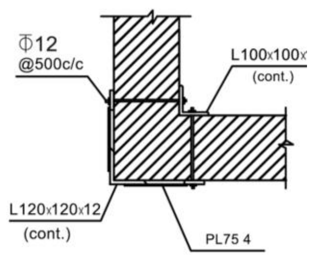
Reinforcement of walls:

As referred in Fig. 9 (a) (b) (c) (d), using cold rolled steel profiles is currently common in systems for reinforcing adobe buildings. Various profile forms such as angled or rectangular section profiles with required dimensions are set in the wall sides and are connected to the walls by steel anchors.

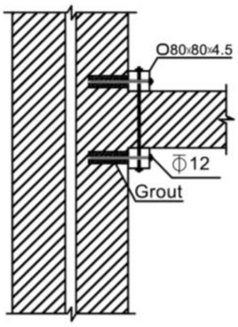


(a)





(b) (c)



(d)
Fig. 9. Application of cold rolled steel profile [17].

Advantages of application of cold rolled steel profile:

Reversibility with minimum manipulation especially in valuable historic buildings.

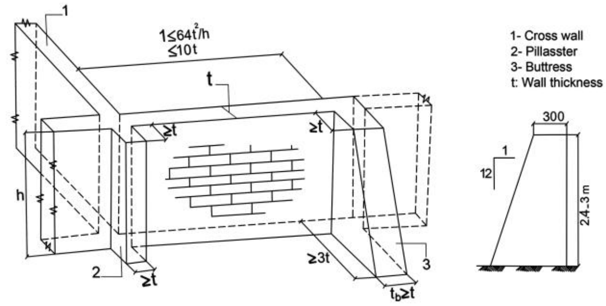
Merging the foundation, walls and roof as an integrated structure.

Disadvantages of application of cold rolled steel profile:

Probability of adobe smashing due to small section of bars in an earthquake.

D. Application of Buttress

Buttresses are provided at critical locations to increase the overall stability and strength of a building. They act as restraints, preventing the inward or outward collapse of walls. Buttresses must be used in addition to wall reinforcement to ensure adequate seismic safety, Fig. 10 [18].



(a) Cross wall and buttresses (b) Tapered wall
Fig. 10. Guideline for buttresses construction.

Advantages:

Not changing in architectural features of buildings.

Reversibility of implementation.

Visually congruent with historic building.

Possibility of adding buttress after accomplishing building construction.

Disadvantages:

This system is implemented merely in buildings with exterior adjacent space.

It is implemented merely to reinforce exterior walls.

This method only responds to out-of-plane force.

It needs to construct new foundations for buttress.

The foundation of both buttress and building must be connected.

E. Uncommon Seismic Reinforcement Systems

In some cases, the proposed seismic resistant techniques are not common and practical for adobe buildings, among which is arming the wall with bars. To do this, it is suggested to use 12 mm bars in vertical and horizontal positions, which is shown in Fig. 11.

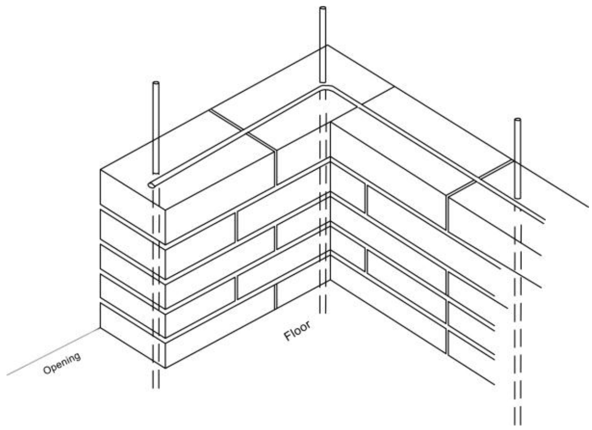


Fig. 11. Application of bars for wall reinforcement [19].

Advantages:

Providing proper contact between the foundation and walls.

Sustainability of buildings with regard to space and area.

Disadvantages:

The probability of the adobes being smashed due to seismic force employed to the bars with limited cross section.

Not providing proper contact between walls and the roof.

Implementing this method in existing structures requires extensive manipulation and minimizes the use of this technique to a large extent.

As referred in Fig. 12, applying wood timbers that are fixed vertically to the structure by steel strip on four sides is another method.

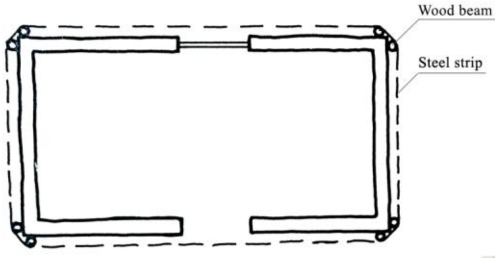


Fig. 12. Application of wood beam and steel strip [20].

Advantages:

No manipulation in interior space especially in historic building.

Possibility of removing the reinforced elements.

Having economic efficiency.

Disadvantages:

Decaying and erosion probability due to different types of insects.

This method cannot be implemented in medial space.

Not providing proper contact between foundation, walls and ceiling.

Not providing proper contact between steel strips and the structure that causes no simultaneous seismic functioning between the structure and reinforcement elements.

In case of low diameter of wood bond beams, adobes may be smashed during earthquake.

Another system is using horizontal wood bond beams in sections of wall that are fixed to each other and to walls by nails. A wood bond beam can be applied in two cases: 1- after accomplishing wall construction, 2- in the middle of wall section that is presented in Fig.13 (a) (b) and Fig. 14.

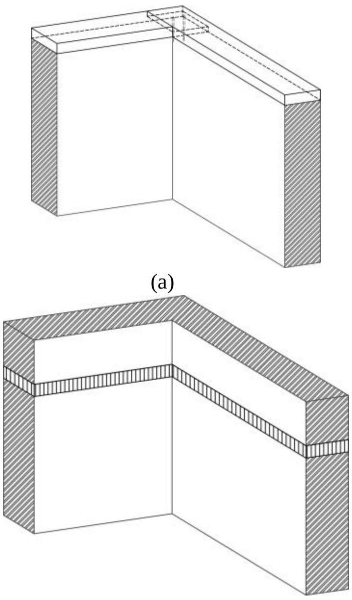


Fig. 13. Application of wood bond beam in wall.

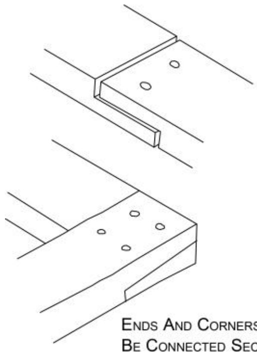


Fig. 14. Detail of wood bond beam application [21].

Advantages:

Having economic efficiency.

Having minimum manipulation.

Reversibility of the system especially in historic buildings.

Having low weight and high resistance quality at the same time.

Disadvantages:

Decaying of wood bond beams due to different types of insects

No co-function for the two parts of the wall on top and bottom of the wood bond beam.

No proper nail attachment between the wood bond beam and walls.

IV. Seismic Reinforcement Systems Applied in Other Regions

Today, with the dramatic development in technology, various methods have been applied in different parts of the world for seismic reinforcement of adobe buildings which can be the useful schemes for improvement of reinforcement systems in Iran. However, none of these methods mentioned in this part are applied in Iran. This issue can be the result of different factors such as financial matters, low accordance with territorial conditions of the region, and in some cases, these systems are not practical in adobe structures, especially in historic ones in Iran.

It is necessary to state that this section tried to introduce systems that are particularly in accordance with adobe buildings, not all types of masonry buildings.

A. Nylon Straps

According to Fig. 15, nylon straps were placed horizontally or vertically, forming a loop either around the entire building or around an individual wall. The straps were passed through small holes in the wall and the two ends were knotted together [22].

Fig. 15. Nylon straps application.

B. Cane or Timber Internal Reinforcement

This type of reinforcement consists of placing an internal grid, with vertical and horizontal elements, able to bond efficiently with the structure, improving its seismic performance. The vertical elements should be conveniently anchored to the foundation and to a ring beam on top of the walls. As it is shown in Fig. 16, bamboo canes or eucalypt dry timber is recommended for these reinforcements [23].

Fig. 16. Cane or timber internal reinforcement.

C. Cane External Reinforcement

Canes are placed vertically and externally to the wall, on both sides, inside and outside. Ropes are then positioned horizontally tying the vertical canes along the walls and involving the structure. In order to connect the two grids—outside and inside grids— and thus confine the earthen structure, small extension lines are placed connecting the two grids, crossing the wall from one side to another through holes, made at each 30–40 cm. Fig. 17 shows an example of this type of reinforcement applied to a real-scale model tested at the PUCP [24].

Fig. 17. Cane external reinforcement

D. External Bamboo Reinforcement with Internal Horizontal Wire Mesh

Adobe wall panels were reinforced with internal chicken wire mesh placed horizontally every three courses. Polypropylene strings were woven through the mesh and its ends were left free, perpendicular to the wall. After the wall was finished, the strings were used to attach vertical bamboo reinforcements placed externally on both sides of the wall, as it is referred in Fig. 18. An upper timber ring beam completes the system. The vertical bamboo reinforcements were secured to the ring beam, thus ensuring the complete support of the wall [25].

Fig. 18. Application of external bamboo.

E. Strengthening with Boundary Wooden Elements

This alternative consists in installing wooden elements in the wall plane, on both faces simultaneously which is presented in Fig. 19. The elements are interconnected to each other by through bolts whose previously drilled hole is filled with cement mortar [26].

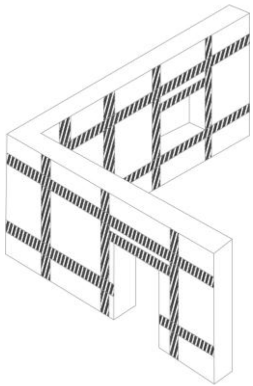


Fig. 19. Installation of boundary wooden elements.

F. Used Car Tire Straps

As it is presented in Fig. 20, this scheme uses circumferentially cut straps from the treads of used car tires for tension reinforcement. Continuous straps pass through holes drilled in the adobe walls to wrap them horizontally every 600 mm and vertically every 1.2 m approximately. Vertical straps pass under the foundations, rise up the walls, and are nailed to the timber wall top plate [27].

Fig. 20. Application of car tire straps

G. Polypropylene Bands (PP Bands)

PP-band mesh making process is very simple and do not require a skilled labor. For PP-band retrofitted construction, ordinary straws were placed at specified intervals. After the construction of the house, PP-band mesh is placed inside and outside faces and connected in out of plane direction with the help of connectors as shown in Fig. 21. For the sake of better holding, PP-band has wrapped around the roof, door and window openings [28].

Fig 21. Application of Polypropylene bands.

Table I features seismic reinforcement systems implemented throughout the world, compared with the ones in Iran. Regarding the fact that the large number of adobe buildings in Iran are classified under historic buildings, and selecting seismic reinforcement methods in these structures has some limitations, and also with regard to the fact that the reinforcement of existing adobe building is one of the key points of the present paper, this table is divided into two main categories: existing buildings and historic buildings.

TABLE I: COMPARISON OF REINFORCEMENT METHODS IN IRAN WITH OTHER REGIONS' ONES

Methods	applied in Iran	applied in other regions	applied in existing building	applied in historic building
Shotcrete	√	√	√	√
Application of fibers	√	√	√	√
Application of cold rolled steel profile	√	√	√	√
Application of buttress	√	√	√	√
Steel bars	√	√		
Wood beams and steel strip	√	√	√	√
Wood bond beam in wall	√	√		
Nylon straps		√	√	√
Cane or timber internal reinforcement		√		
Cane external reinforcement		√	√	√
External bamboo with internal horizontal wire mesh		√		
Boundary wooden elements		√	√	√
Car tire straps		√	√	√
Polypropylene bands		√	√	√

V. CONCLUSION

According to the study, masonry buildings are generally classified in two reinforced and unreinforced groups. There are also three subcategories for unreinforced buildings including brick, stone, and adobe structures. Regarding the mechanical characteristic of structures and their seismic behavior, it is clear that the reinforcement method differs for each.

As a conclusion, seismic resistance regulations, for both reinforced and unreinforced structures, is mostly designated in accordance with the brick structures seismic behavior which is generalized to other masonry buildings such as stone and adobe structures. According to the mentioned regulations, it has evaluated that the given methods of reinforcing adobe buildings, as the key research points, are not executable for some, or they are not in accordance with seismic behavior of the adobe buildings, so partial destruction may happen as the result of an earthquake. Also, it must be note that all of the mentioned methods in this article do not consider the building as an integrated structure and while focusing on reinforcement of the walls, leave the other elements of building, like foundation, vaults, and ceilings, aside.

The key important thing about the reinforcement of adobe building is that the vast majority of Iranian historic places have been built by adobe. This fact highlights the importance of observing principles while selecting and carrying seismic reinforcement methods and among the most noticeable ones are reversibility and less manipulation.

Eventually, what is possible to elicit from the article is that the given techniques for reinforcement of adobe buildings are based on brick structures regulations and are not in accordance to behavior patterns of adobe building. Also, we can certainly say that the seismic behavior of adobe structure elements is not analyzed by experimental studies yet and these techniques are still based on assumption regardless the analysis of adobe buildings behavior in confronting with an earthquake. However, it is necessary to bring adobe building, as an unreinforced structure which is influenced in many Iranian buildings, into experimental analysis in order to study its reaction against seismic actions. Thus, an integrated specific regulation must be passed with considering the mechanical and seismic behavior of adobe materials and also all adobe building elements.

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