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General Perspectives on Seismic Retrofitting of Historical Masonry Structures

Baris Sayin, Baris Yildizlar, Cemil Akcay and
Tarik Serhat Bozkurt

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Abstract

This chapter focuses on retrofitting of historical masonry structures from the point of seismic resistance based on failure analysis. In historical structures, restoration applications have become necessary because their life cycle of structural and nonstructural members is completed due to natural result of material structure, environmental conditions, and/or user errors. One of the most important intervention decisions in restoration stages carried out in historical buildings is known as retrofitted of the structure. The choice techniques of retrofitting of the structural members are becoming a very important issue in the scope of restoration of historical masonry structures belonging to the cultural heritage. Additionally, it should be decided to optimally preserve such buildings' original forms and to make interventions to increase the building's service life; in this regard, it is important to preserve the structures' historical identity and constructional value. Therefore, retrofitting applications have become essential to prevent the damage level and to have adequate level of structural strength in order to resist dynamic effects such as earthquakes. In this chapter, it is aimed to determine the main principles by using conventional and modern techniques within the scope of laboratory tests and numerical approaches in recovering the historical structures.

Keywords: historical structures, retrofitting, numerical approach, visual inspection

1. Introduction

With respect to ICOMOS 2001 document, a full understanding of the structural behavior and material characteristics is essential for any conservation and restoration project regarding the architectural heritage. It is suggested that the work of analysis and evaluation should be

done with multidisciplinary approach, such as earthquake specialists, architects, engineers, and art historians. Additionally, it is considered necessary for these specialists to have common knowledge on the subject of conserving and upgrading or strengthening the historical structures [1].

Masonry constructions in many countries worldwide are characterized by inadequate resistance to earthquakes loading. The use of appropriate techniques for retrofitting of historical masonry structures should be made by referencing to additional structural system and members as well as repair and retrofitting on period after built of the mentioned structures, and this fact is evaluated in terms of the protection of the original identity as well as the cultural value of the structures [2].

The preservation of the original form in the retrofitting applications of historical structures is taken into consideration and thus transferring building's historical identity to future generations may be possible. Besides that, the need for refunctioning of the structure, improvement of repair and strengthening techniques over time, technical specifications in force, and collaboration of experts of different disciplines leads to the development of new solutions in the restoration applications.

Repair and strengthening applications are commonly applied as part of restoration works of historical masonry structures for recent years [3–21]. Until 1980, the applied practices consist of removing floor arch or timber floor by preventing load-bearing masonry wall, building a secondary load-bearing system apart from the present bearing system by supplying a RC load-bearing system inside large internal spaces, and ruining architectural structure by joining columns and beams inside spaces.

In this study, seismic retrofitting applications in historical masonry structures are presented within the scope of laboratory tests and numerical analyses based on a cross-disciplinary study of civil engineering and architecture.

2. Failure analysis

Structural failures and their investigation have become an active field of professional practice in which experts are retained to investigate the causes of failures, as well as to provide technical assistance to know the root cause. Failure need not always mean a structural collapses. It can make a structure deficient or dysfunctional in usage. It may even cause secondary adverse effects: (i) Safety failure (injury, death, or even risk to people), (ii) functional failure (compromise of intended usage), and (iii) ancillary failure (adverse effect on schedules, cost, or use) [22–24].

Failure analysis and prevention are significant parameters to all of the engineering disciplines. The materials engineer often plays a head role in the analysis of failures, whether a component or product fails in service or if failure occurs in manufacturing or during production processing. In all cases, one must determine the cause of failure to inhibit future occurrence, and/or to increase the performance of the structure [25]. Generally, procedure for failure analysis

includes: (i) collection of data and samples, (ii) preliminary examination, (iii) nondestructive inspection, (iv) mechanical testing, (v) selection and preservation of damaged surfaces, (vi) macroscopic and microscopic examination, (vii) preparation and examination of metallographic sections, (viii) damage classification, and (ix) report writing. In this chapter, the mentioned procedures are considered.

3. Intervention strategies

One of the most important intervention decisions in restoration carried out in historical structures is retrofitting of the structure. Article 10 of the Venice Charter (1964) remarks that “Where traditional techniques prove inadequate, the consolidation of a monument can be achieved by the use of any modern technique for conservation and construction, the efficacy of which has been proven by scientific data and experience” [1].

Retrofitting applications in historical structures are performed in accordance with the intervention decisions based on conventional and modern techniques. The intervention solutions must rely on cost-benefit analyses and take into account their socioeconomic impact on society. An obvious requirement is to minimize as much as possible the disturbance of the owners of the building during the building rehabilitation. The financial resources available decisively influence the intervention solutions for the particular purposes, including labor work capacity, equipment, materials, duration of the work, etc. It is also compulsory to have alternative strategies for intervention and to evaluate the decrease in building vulnerability with various strategies [26].

The intervention strategy and the intervention techniques must take into account the following criteria: (i) seismic hazard level at the construction site, (ii) characteristics of the building's intended use (architectural constraints, original occupancy of the building, building structure, technical equipments within the building, etc.), (iii) building safety as a response to daily activities, mainly related to the seismic safety (structural vulnerability, vulnerability of nonstructural elements, appliances or/and equipments, building exposure or value, etc.), (iv) required level for building performance (life safeguarding, immediate occupancy after earthquake, preventing building collapse, etc.), (v) economic criteria, including insured and reinsured value of the building, and (vi) technological capability available at the site.

4. Retrofitting principles

As a rule, it is worth stating the preliminary consideration before the description of the retrofitting techniques. Once the technique is proposed, it should be experimentally studied to understand the best application procedure and also its effectiveness. Even so, no general repair and strengthening method exists due to variability of historical masonry structures in materials and construction techniques. On the contrary, methods are mostly determined according to different masonry characteristics.

Appropriate site and laboratory investigations should always be carried out before reinforcement application through: (i) an accurate geometrical survey of the structure's morphology; (ii) characterization of the constituent materials, e.g., stones and of the mortars in masonry structures; (iii) survey of the physical and mechanical decay; and (iv) crack pattern survey. Based on these considerations, it is possible to choose between several systems of retrofitting and application techniques.

Three important preservation principles should be kept in mind when undertaking seismic retrofit projects: [26]

- Historical materials should be preserved at the largest extent possible and not replaced wholly with other new materials in the process of seismic strengthening.
- New seismic retrofit systems, whether hidden or exposed, should respect and should be compatible to the architectural and structural integrity of the historical structure.
- Seismic work should be “reversible” to the largest extent possible to allow future removal for the use of future improved systems.

While seismic upgrading work is often more permanent than reversible, care must be taken to preserve historical materials to the historical appearance of the building.

In addition to the above principles, the general aim of structure conservation is to preserve the cultural significance of the place where the building is culturally aggregated. Places of cultural significance should be safeguarded and not left at risk in a vulnerable state.

The different intervention works are defined in various manners and documents from various countries, as well as in general literature. The relationship between the stages for seismic rehabilitation of historical buildings is presented in **Figure 1**.

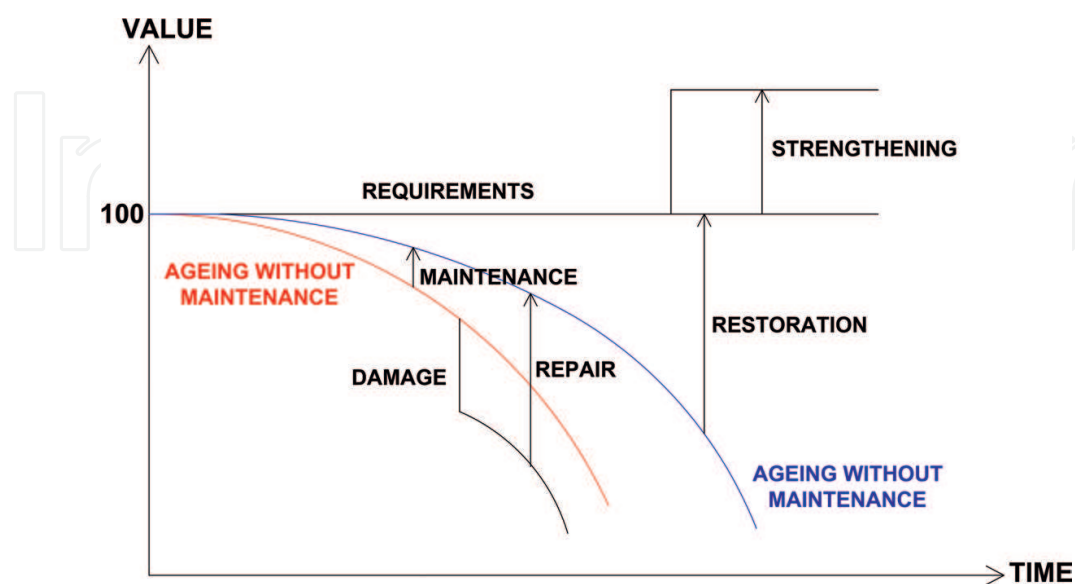


Figure 1. Value alteration diagram of a building [26].

The seismic retrofitting methods can be classified as follows, as far as their target is concerned:

- a. In case the target is the increase of stiffness and structural strength, the most effective method is the addition of walls in the existing frames. What follows is the method of adding truss bracings, the method of adding walls as an extension of existing columns, and the use of composite materials.
- b. In case the target is the increase of plasticity, the method that is recommended is the application of jacketing on a number of selected columns, as well as the use of composite materials.
- c. In case the target is the simultaneous increase of strength, stiffness, and plasticity of the structure, any seismic strengthening method can be used taking into consideration the required degree of increasing each of the above-mentioned characteristics. In case that the necessary increases are very high for all the three characteristics, the addition of new vertical members is generally inevitable.

5. Structural evaluation of masonry structures

5.1. Historical process of the structures

Within the scope of examined masonry structures, in order to determine structural changing or the construction time of an examined structure, it should be investigated whether or not the structure is in place using ancient maps. In the stage of the restoration project, historical photos and old maps are utilized in collecting data and documents on the building facade; therefore, information on floor height, storey count, roof patio, roof form of the structure, relationship with the neighboring structures, and location of the windows is obtained.

5.2. Existing status of the structures

The current state of an examined structure must be defined within the context of the structural and nonstructural members and the position in the plane must be given. Three-dimensional (3D) laser scanning method should be used to determine the geometric dimensions and structural damage of the structure in detail. Then, the structural supplements in the historical process of examined structure must be presented in detail. Thus, the differences between the first period and the current situation of an examined structure will be clarified.

5.3. Field study

Samples are gathered from various points of a structure during laboratory test phase of the study and after then analyses are performed. Thereby, axial compressive strength of the masonry walls, shear strength, bulk density, and thick- and thin-plaster compounds are derived. Moreover, mechanical characteristics of bricks and pointing fillings are determined.

5.3.1. *Shear strength of walls in situ*

Shear strength index of brick-mortar in masonry walls are defined based upon shear tests which are performed in different points in the structure in relation to standard. Samples are compressive strength and bulk density tests are performed on such samples—taken representing the brick-mortar-brick system—in the laboratory.

5.3.2. *Mechanical and physical properties of mortars and brick samples*

Samples from the solid brick blocks and pointing filling mortars are gathered from an examined structure. Single-axis compressive strength and bulk density tests are performed on brick blocks. For the purpose of determining the dead weight of the wall, density of filling mortars between the bricks is considered.

5.3.3. *Elastic modulus of walls*

In consequence of the tests performed on an examined structure, in parallel with the data and previous experiences acquired from other masonry structures having comparable historical process, construction conditions, and materials, it is decided that the elastic modulus, taking into consideration the condition of the existing walls, can be used on the structural model.

5.4. Laboratory analysis

As a laboratory study, physical test and chemical analysis are carried out on samples taken from a historical building. Subsequently, the proposal mixtures of plaster and mortar for restoration are determined according to the laboratory test results. The locations of samples from the masonry ruin are determined. Properties and detailed visual definition of the provided samples are obtained. Then, samples are taken from different points of the examined structure during lab test stage of the study and analyses are carried out. The samples are exposed to chemical, physical, and mineralogical tests, such as the ratio of binders, aggregates, and mineralogical compositions, and textural properties of the mortar samples are analyzed, and the cause for deteriorations is determined by visual analysis, spot tests analysis, ignition loss analysis, reaction with acid, and petrography. Before starting the analyzes, it is examined that the texture, color, state (integrity) of the samples; color, size, approximate quantities, apparent organic additives and type of aggregates in the contents of the samples. After that, the size distribution, particle properties of acid insoluble materials, and protein/ oil contents are determined. Samples taken are examined by content analysis within the scope of related standards along with visual detailing. Consequently, axial compressive strength of the masonry walls, shear strength, bulk density, and thick and thin plaster compounds are obtained. Also, mechanical characteristics of bricks and pointing fillings are obtained.

5.5. Numerical analysis

In the numerical analysis carried out with general purpose, finite element analysis software, period values, modal participation mass ratios, and total modal participation mass ratios

corresponding to the 12 modes are calculated for an examined structure in modal analysis. The period values are found out for x- and y-directions. For each earthquake direction in the regulations [27], shear stresses on the walls are attained by rating the horizontal force coming to the horizontal load-bearing members to horizontal section area of masonry walls. After that, calculated values are compared to the experimental shear stress ones. Shear stresses of all walls in both directions of a masonry structure are determined to be adequate to cover the shear stresses under earthquake effects.

5.5.1. Structural model

FE analysis of a multistorey masonry structure under seismic loading is performed. Wall shear strength to be used in numerical analyses is determined individually for each of the storey. The structural performances are determined based on the existing building's load-bearing data obtained by using linear elastic analyses. According to the analyses, principles defined as per related country's local provisions and standards, all analyses are carried out using a general purpose FE software [28, 29]. In terms of evaluation of the existing structures, the structure is analyzed considering four different building performance levels for the existing or strengthened buildings, in addition to various level earthquake definitions. The performance levels are specified as: (a) operational, (b) immediate occupancy, (c) life safety, and (d) collapse prevention or near collapse (**Figure 2**).

Building performance can be defined qualitatively from the point of: (i) safety afforded building occupants, during and after an earthquake; (ii) cost and feasibility of restoring the building to preearthquake circumstances; (iii) length of time the building is removed from service to conduct repairs; and (iv) economical, architectural, or historical effects on the community in general. These performance properties will be squarely related to the extent of damage sustained by the building during an earthquake.

In the numerical analyses performed under a described earthquake design, it is specified that the existing system meets the conditions set forth for life safety performance level. For an earthquake with 10% recovery possibility in 50 years, it is determined that the shear strength of all the walls in both directions of the masonry building is ordinarily adequate to

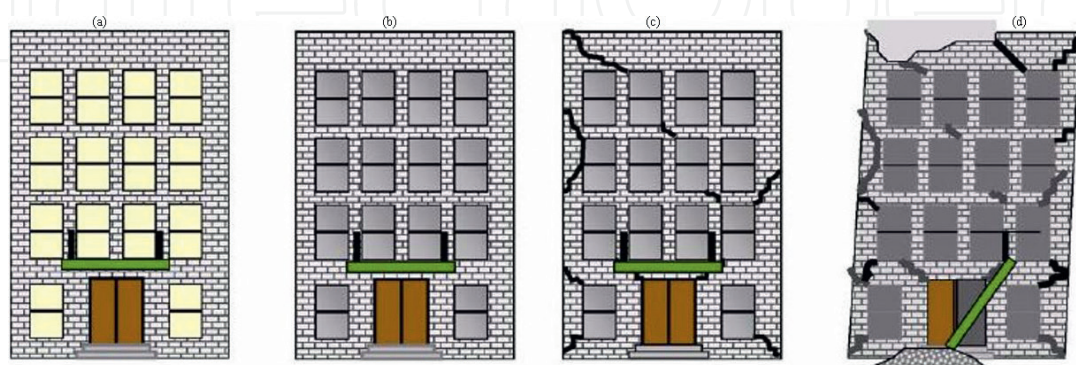


Figure 2. Levels of building performance: (a) operational, (b) immediate occupancy, (c) life-safety, and (d) collapse prevention [30].

meet the shear forces occurring under the subject to earthquake effects. In that case, it can be underlined that a structure meets that “immediate usage performance level”; however, due to insufficiencies not meeting a masonry structure definitions of the structure and partially determined irregularities, “life safety performance level” should be used to evaluate, rather than “immediate usage performance level.”

Building performance levels typically comprise a structural performance level that describes the limiting damage state of the structural systems, plus a nonstructural performance level that describes the limiting damage state of the nonstructural systems and components. A structure examined by using mode combination method is calculated under earthquake loads; all acceptances and obtained values are determined in accordance with the Turkish Earthquake Regulation. A three-dimensional model of an examined structure is prepared. In the prepared model walls and slabs that are horizontal structural members are modeled as shell element in the element library of the FE analysis software. Mechanical properties of the structural members in the model are transferred to the structural system via the data obtained from the experimental studies mentioned above.

5.5.2. Analysis of structures

5.5.2.1. Compliance with earthquake regulation

In determining the structure’s performance, controls are made based on local or international earthquake regulations [26]. A three-dimensional linear finite element analysis of examined multistorey masonry structure under seismic loading is carried out.

The following checks should be evaluated in accordance with seismic regulation:

- Control of the total maximum length of the masonry walls
- Nonsupported length between the vertically connected masonry wall axes to the plane of any masonry wall is checked in according to earthquake zone
- Limit conditions in door and window gaps in the walls
- The height of each storey should be checked in masonry buildings

Based on the regulation, supported walls in masonry structures should be as regular and arranged as a symmetrically or close to symmetric, and construction of local basement should be avoided. The structure is examined considering these criteria and it is determined whether the structure is regular or not on the plan.

5.5.2.2. Modal analysis

Twelve modes are calculated for the building in modal analysis and period values corresponding to the modes are presented. Participation mass ratio and period values are examined and the vertical and horizontal period values are obtained. Data presented demonstrate that which direction is more rigid than the other direction.

5.5.2.3. *Checking of shear stress in walls*

Shear stresses on the walls are obtained by proportioning the horizontal force coming to the horizontal load-bearing members to horizontal section area of masonry wall for each earthquake direction in the earthquake provision. Calculated values are compared to the experimental shear stress values. Shear stresses are calculated individually for each storey and wall across building height. Total shear force is calculated for FE analysis for each direction by proportioning the total section area in that direction, and principal stress comparisons are made on the shell elements together with shear stress for each storey.

Storey shear forces obtained from analysis are compared to the forces that are experimentally obtained and shear stress checking is carried out in the structure. Shear performance on x - and y -directions is presented. Shear strength of all the walls in both directions of the masonry building is determined to be adequate to cover the shear forces under earthquake effects. Also, it is checked whether the checking meet the rules for the structure geometry and design.

6. The retrofitting applications of masonry structures

In the retrofitting stage of the structures, plaster analyses and mechanical tests are conducted on the samples taken from the examined structure. After that, the structure's existing 3D computer model is prepared and members that are inadequate in terms of strength are determined. Within the scope of the analysis, it is found that the structure can be converted to the original form of the structure. In this regard, featureless additions, which are not related to the original structure, are removed and restoration applications are carried out. In the scope of restoration applications, structural cracks on the walls are repaired using the injection method. Moreover, jack-arched floor, exterior facade walls, interior walls, and door/window gaps using different techniques are strengthened.

As a cross-disciplinary study must be carried out in the strengthening stage of the historical building, improved or changed details are manufactured with the approval of engineering and architecture disciplines. Retrofitting applications include: (i) walls, (ii) jack-arched floors (volta slabs), (iii) door and window gaps, and (iv) foundations. In this section, retrofitting applications illustrating the effectiveness of the described method will be presented. It should be noted that the presented applications are for example only and are not intended to be exhaustive.

6.1. Retrofitting of masonry walls

6.1.1. *Retrofitting of cracks in masonry walls using injection technique*

In an examined structure, it is decided that masonry walls will be strengthened removing plastering on masonry walls, detection of structural cracks and strengthening using the method of injection in accordance with supervisor decisions regarding strengthening masonry walls.

It is aimed to increase the bearing capacity of masonry walls using injection method, as filling the structural slots inside the masonry walls with lime binder injection mortar.

Following completing plaster removal on all masonry walls, structural cracks are determined. Repair mixture ratios are determined based on the gathered samples, and the mixtures are prepared. The mixture is applied to the cracks by means of manual injection. Integration is ensured using steel clamp members in larger cracks and anchorage elements on the walls are anchored via epoxy.

As it takes time to settle the injection compound into the wall, application is repeated periodically. The compound inside the pipe is penetrated into the interior walls in time, the pipes are continuously injected, and this process is continued until the gaps are filled. **Figure 3** shows possible injection application in the walls.

6.1.2. Retrofitting of masonry walls in-plane using carbon fiber wrap

Carbon fiber wrap can be used in tensile stress areas on wall members to strength dynamic effects, e.g., earthquake. First, applied carbon fiber locations are specified on the facades. Carbon fiber wrap is positioned between window gaps and storey levels and also disguised under plaster layer. **Figure 4** shows possible carbon fiber application in the walls.



Figure 3. Injection application in the walls after plaster removal: (a) structural cracks, (b) preparation of wall surface for injection, and (c) injection application by manual technique.



Figure 4. Carbon fiber wrap applications on masonry walls (a and b).

6.1.3. Retrofitting of internal walls using rebar grids technique

After having completed the existing plaster removal from the vertical load-carrying members, internal wall strengthening is applied. In this respect, anchorage holes per square meter are drilled on masonry walls and filled with epoxy (**Figure 5**).



Figure 5. Retrofitting of the internal walls after plaster removal: (a–c) rebar grid technique and (d) application of thick plaster.

6.2. Retrofitting of jack-arched floors

Floor system strengthening consists of two separate parts: (i) Strengthening without removing jack-arched floors, which are positioned on the hallways and assumed as the original ones and (ii) applications of steel beam system installation is applied with the aim of lighting the weight of the building as removing featureless RC additions. **Figure 6** presents a similar application about floor strengthening.



Figure 6. Retrofitting of jack arched slabs: (a) removing top layers of the slab, (b) welding of shear rebar over I-profile beam, (c) steel tie, (d) connections of stainless steel ties between the masonry walls, (e) anchorage of stainless steel, and (f) topping concrete application on slab.

6.3. Enhancement of lateral stability of door and window gaps

The locations and dimensions of original windows and doors are based upon a restoration process, and all infilled the windows and doors are opened on the facades in the current situation. Then, it can be strengthened the window- and door-gaps with steel plate to increase the strength in order to resist dynamic effects according to results of 3D analysis (**Figure 7**).



Figure 7. Retrofitting of door and window gaps using steel plates (a and b).

6.4. Retrofitting of foundations

For foundation strengthening, it is managed that all masonry walls are to move together by tying them with each other with bond beams and RC foundations and also aimed to transfer the load of the building to foundation system once and later to the ground (**Figure 8**).

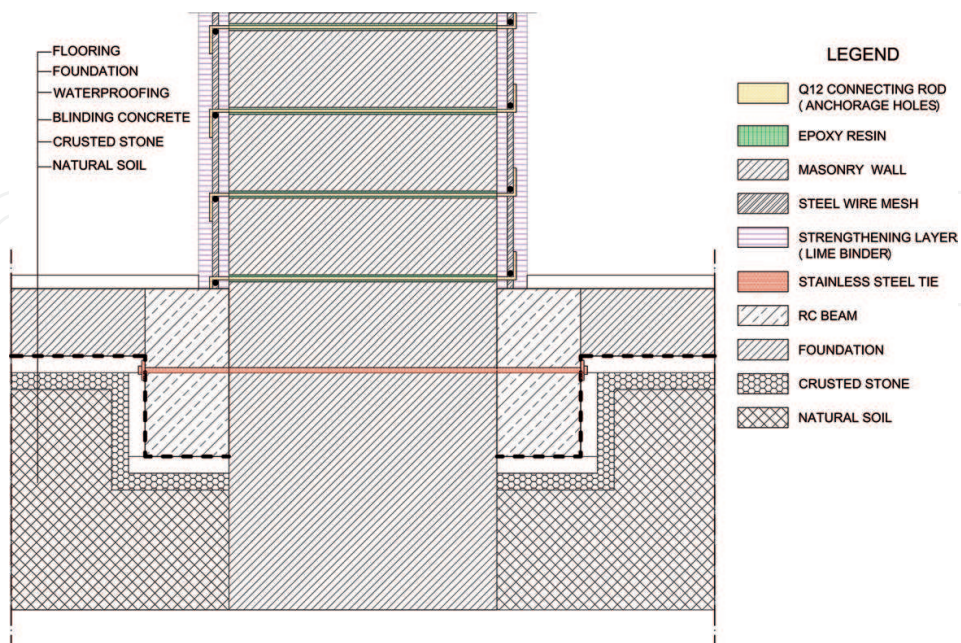


Figure 8. Retrofitting of foundations in masonry structures.

7. Conclusion

The chapter provides a general overview on the retrofitting of historical masonry structures which have critical issues in terms of seismic resistant. It is concluded that the retrofitting process is suitable as a practical tool for retrofitting applications. Retrofitting techniques of masonry structures are highly effected from the scientific and technological advances. Through the last decades, many retrofitting techniques have been proposed and applied to the structures. Accuracy of retrofitting methods depends mainly upon analyses of examined structures and classification techniques. The efficiency of the retrofitting for historical masonry structures is directly related to the suitability of the used methods or techniques with retrofitting principles. Moreover, needless to say that in addition to the retrofitting of the structures, maintenance and repair of the structures also plays a major role in its service life.

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Author details

Baris Sayin^{1*}, Baris Yildizlar¹, Cemil Akcay¹ and Tarik Serhat Bozkurt²

*Address all correspondence to: barsayin@istanbul.edu.tr

1 Department of Civil Engineering, Istanbul University, Istanbul, Turkey

2 Department of Architecture, Istanbul Technical University, Istanbul, Turkey

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