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IMPROVING THE SEISMIC RESISTANCE OF CULTURAL HERITAGE SITES-OLD BAZAAR OF GJIROKASTRA, ALBANIA

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ABSTRACT

Masonry, as one of the oldest construction techniques, has been used in historical sites. Assessment of structural performance under seismic effects is a very important step for restoration process of historic buildings that represent construction techniques and material characteristics of their era. Following a methodology that includes research, diagnostics, safety analysis and the determination of effective reinforcement intervention techniques must be done in respect of the historical values and the original conception of the building.

Often, the application of the same levels of safety used in the analysis of new buildings requires very serious structural interventions that are almost impossible from the point of view of compatibility with historical architectural values. In these cases, the methodologies of structural intervention in buildings with historical values justify different or lower levels of safety compared to new buildings.

The complexity of the geometry of these objects, the often-unforeseen characteristics of the original materials used, the different construction techniques, the lack of complete knowledge of existing damages that have occurred over time for various reasons, and the current lack of applicable codes complicate the restoration process. Also, the limitations in inspecting or taking samples in buildings with historical value, often results in relatively limited information on the characteristics of the existing materials used.

The philosophy of structural restoration is: meeting the criteria for minimal intervention in compatibility with the original structure to achieve maximum performance.

The most innovative reinforcement techniques include post-tensioning and special anti-seismic devices that reduce the action of seismic loads on the structure.

INTRODUCTION

Stone masonry generally resists compression well, has a moderate resistance to sliding and poor resistance to tension. Consequently, it is designed to work in compression and sometimes in sliding or shear. Damage to the masonry structure takes the form of cracks in tension or shear, caused by:

- o deformations from loads e.g.; non-uniform settlements,
- horizontal loads beyond the limits of the bearing capacity of the structural element e.g.; thrusts of arches.
- deformations of the stone or expansion of the filling, in masonry structures composed of stone on the external and internal faces respectively, and inside of mortar mixed with crushed stone waste in smaller dimensions.
- The spaces created in the masonry are referred to as ”cracks” which are distinguished in:
- fragmentation of the structural units of the building (parts of detached masonry) that pose a potential risk of partial or complete collapse
- opening of horizontal or vertical joints.

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The causes of damage or cracks in the masonry are:

- Non-uniform deformations
- Increased horizontal loads
- Eccentric loads
- Local loads at the joints of the steel ties
- Possible defects during the work of masonry, cladding, etc.

The technique used for repair or reinforcement depends on whether the cracks are active or inactive. If they are active, they must be treated with priority over the others.

The structural assessment of an existing building, together with the data from the drawings, is based on:

o The physical condition of the building; damage during its operation, visible or not signs of overstressed condition.

o The careful determination of the stress paths in the structural system.

o Verification of the dimensions of the structural elements.

Figure 1. Before restauration of Old Bazaar of Gjirokastra, Albania

Repair and reinforcement of walls and columns

Compatibility

For all types of construction, the repair material must be compatible with the original material. This applies to stone, brick or masonry mortar.

The quality of the repair mortar affects the performance of the masonry against the environment and atmospheric changes. If it is weak and porous, it will erode quickly. If it is strong, it will remain almost unchanged and impervious to moisture, etc.

Care must be taken in the ratio between Portland cement and lime, since as is known, increasing the amount of cement by replacing lime increases resistance while significantly reducing permeability in the masonry joints. The masonry joints in this case create traps for rainwater, which is prevented from draining down, remaining in the joints. The water in the joints at low temperatures freezes, causing tensions in the masonry stones that lead to the collapse of the sides of the stone or brick masonry, significantly damaging it on the external facades.

Another objective of using high-resistance mortar M≥30 (cement:lime ratio; 1:0.5)is to prevent the possible sliding of the stones, according to the horizontal joints. This sliding occurs when the masonry is subjected to differential settlements which lead to the appearance of cracks in the horizontal joints as a result of the action of large shear loads. These cracks created according to the horizontal joints must be avoided as they are more difficult to repair than cracks in joints or elsewhere, as they completely unbalance the geometry of the walls.

However, the consensus remains on the use of masonry bonding mortar with characteristics as close as possible to the original.

Improving tensile strength

In cracked walls as a result of tensile stresses, caused by non-uniform settlements or by the impact of wooden arches or roof beams, although in some cases the causes cannot be completely eliminated, it is beneficial to ensure tensile strength in the opposite direction to that of crack growth. This can be achieved by fixing tie rods (iron rods with diameter d=30÷32mm) anchored visibly (outside) or invisibly (inside the section) to the external walls, provided that closed and unbroken quadrilateral (multi-angular) rings are created.

Placing tie rods in holes that are then injected with 1:2 cement mortar is recommended as it is closer to the original solution, Fig.2.

Where the cracks are larger and more visible, in the upper elevations of the basement walls or arches, a reinforced concrete strip with a width of no less than 1/3 of the wall section should be placed, on the inside (invisible) or on the inside of the perimeter walls. This method of reinforcement is most advisable to do by placing the reinforced concrete strip on the inside of the wall (invisible), as it increases the contact surface of the new reinforced concrete strip with the wall, improving the resistance to horizontal pull of the masonry more effectively.

With the objective of minimizing the use of non-original materials, it is recommended that in cases where the cracks are not serious, wooden corner joints (2÷3 pieces where there are no existing wooden beams) be used with brackets distributed uniformly along the height of the wall, or at the level of the existing wooden beams (when there are existing wooden beams).

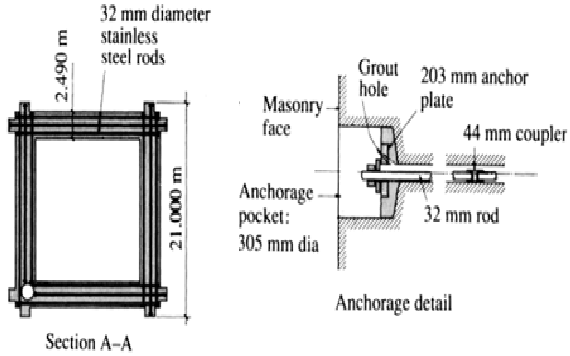


Figure 2. Typical bracing detail for improving tensile strength

Anti-seismic reinforcement

In general, the most important element in the seismic reinforcement of stone masonry buildings remains: ensuring rigidity in plan; the horizontal planes of the walls maintain their original shape. This element provides for:

- The corners of the wall joints to remain rigid (elimination of hinges)
- The joints with the internal transverse walls to not allow the perimeter walls to work independently. The T-shaped joints to remain rigid, avoiding independent horizontal displacement of the walls.

This requires that the floors constructed work in their plan as diaphragms or rigid plates that connect the walls at floor level.

From this point of view, the replacement of amortized wooden floors with reinforced concrete slabs is justified by creating a rigid horizontal floor structure with higher performance against seismic loads referred to the existing wooden floor.

However, it should be noted that the construction of floors with reinforced concrete structures increases the mass at floor levels, resulting in an increase in the inertial forces induced in the vertical structure by the earthquake.

An important principle that must be respected remains: the complete union or connection of the vertical structure (walls) with the horizontal structure (floors).

The method of construction will be determined for each object on site, before the start of the works. The experience of previous earthquakes has proven that the walls in the perpendicular direction to the floor support are damaged or destroyed more than those in the other direction, as a result of the lack of horizontal connections of the floor supports. The placement of additional horizontal connections or anchors in the perpendicular direction walls is an alternative to limiting free horizontal displacements.

It should be noted that seismic vibrations cause a temporary reduction in the effect of permanent gravitational preloading, reducing the bearing capacity of horizontal anchors at the connection joints. Where the vertical loads of the walls are insufficient to counteract the seismic effects; e.g. at the upper levels of the walls at the basement levels, the bearing capacity of the walls in tension in the vertical direction must be ensured.

Following this argument, it is recommended with reservations to implement reinforced concrete (anti-seismic) columns inside the walls (in corners at distances ≤8m) as an element that improves the tensile resistance of the masonry in the event of earthquake vibrations.

Taking into account that the placement of reinforced concrete anti-seismic columns is visually unjustified and the cooperation with the masonry is sometimes incomplete (when they are not connected to the perimeter of their section with the wall), the alternative of implementing vertical holes in the wall with a diameter d=1/4÷1/3 of the wall thickness should be used.

In these holes pass iron ties which are fixed at the lower level of the foundation (1÷2 mortar injection) and at the upper level of the wall, the sub-floor (anchored with metal plates). The implementation of such holes requires the use of water and pressurized air.

Water should be allowed to drain from the horizontal discharge holes to relieve hydrostatic pressure. During the opening of vertical holes, air can create dust chambers inside the hole. To eliminate them, it is recommended to clean with pressurized water before injection.

A more advanced method is to use tie rods that are fixed at the two extremes of the wall height. By pulling them, the masonry is pre-positioned in the vertical direction in a state of compressive stress.

The advantages of compressive preloading for masonry are:

o increase in the shear resistance of the masonry

o increase in the natural frequency ω of free vibrations, as a consequence of increasing the rigidity of the stone masonry.

Increasing the natural frequency ω by removing it in numerical values from the frequency of forced seismic vibrations ω_d significantly reduces the possibility of resonance during an earthquake. Preloading, by avoiding the opening of the joints, increases the damping capacity of the structure, i.e., increases the earthquake resistance.

(a) (from top to bottom): accurate realization between supports; arch splitting to cover a larger space; destruction by the formation of four hinges.

(b) flat arch.

(c) rigid vertical support: (left) passive state; (right) working state

Reinforcement of stone masonry

Stone masonry buildings not reinforced with anti-seismic beams and columns are very vulnerable to seismic actions. This is particularly pronounced in historical areas as phases of inhomogeneous structural changes due to expansions, opening of walls to connect rooms or additions made with inappropriate joints favor the mechanism of overturning during an earthquake.Inappropriate structural interventions in existing buildings over time can be considered the use of:

- Reinforced concrete elements in the form of rigid diaphragms,
- Reinforced concrete ring beams,
- Columns within the width of the walls

without paying due attention to the effects on increasing the level of mass and stiffness.

The use of the above elements without clear structural criteria favors the mechanism of unforeseen local or global destruction, due to the inconsistency of the deformations of the additional stiffening elements with the original structure.

For this reason, the use of efficient alternatives of reinforcing interventions is a direct dependence of the typology of the masonry and the objective of achieving a certain level of performance that would require the relevant codes that are currently lacking in Albania.

Reinforcing interventions

The seismic performance of buildings in general depends on both the interconnection between the constituent elements and the resistance, stiffness and ductility of the individual elements. When individual elements of the structural system are reinforced, care must be taken to ensure a uniform distribution of stiffness in both directions in the plan.

In the case of reinforcement with additional structural elements, e.g. columns or reinforced concrete walls, attention must be paid to the uniform distribution of stiffness in height, in order to prevent its sudden changes from one floor to the next. Below are some recommendations that must be followed to have an efficient repair of the damaged structure:

- Structural walls must be uniformly distributed in both directions in the plan.
- Structural walls should cooperate during the action of loads through the implementation of rigid diaphragms of the basement.
- The basement floors should be connected to the walls of the structure through tie rods that limit the walls from working out of their plane, during the earthquake.
- The foundations are reinforced to ensure adequate transfer of loads to the foundation.

The purpose of the strengthening intervention is:

- Ensuring the monolithic three-dimensional behavior of the structure after reinforcement, to the action of seismic forces, through the appropriate connection of the walls to each other and of the walls to the floors.
- Ensuring the smoothest possible path of the passage of seismic loads from the roofs and floors of the basement to the stone masonry and further to the foundations.

Three-dimensional behavior is a minimum requirement for the application of analytical methods for seismic analysis of buildings as a whole. This analysis requires the application of the out-of-plane wall work restraint mechanism achieved by:

- Metal ties (Fig. 3)
- Circular bars that create closed and continuous contours.
- Appropriate connection joints
- Ring beams or girders

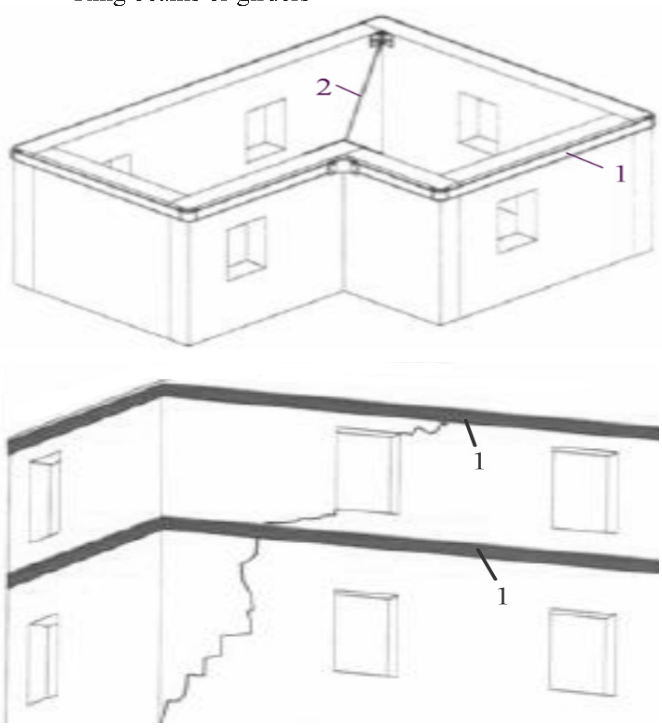
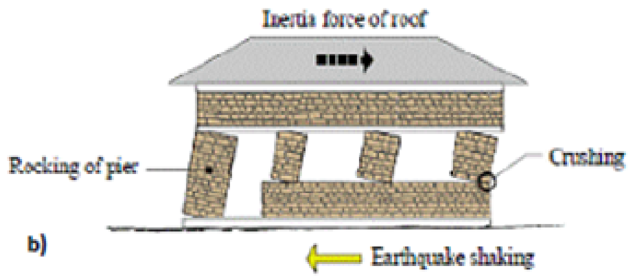


Figure 3. External bracing;

1- metal plate strips t= 8-12mm, height 10-20cm 2-circular rods d=24-32mm.

Pillar reinforcements (masonry between spaces)

The low quality of the pillar masonry is a possible cause, favoring the destruction mechanism. The action of seismic loads leads to the rotation or diagonal cracking of the pillars, most clearly expressed in the perimeter walls of the building, Fig.4.



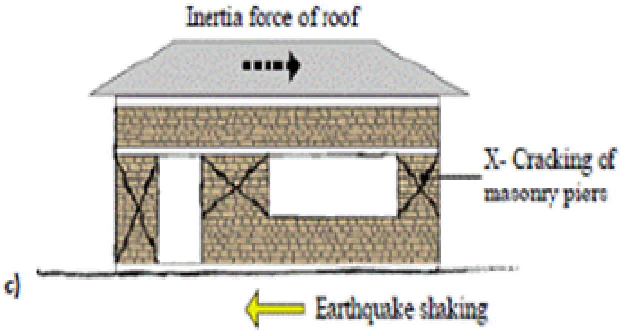


Figure 4. Damage to the masonry plane from earthquake action

(b)rotation of the pillars, (c) diagonal cracks

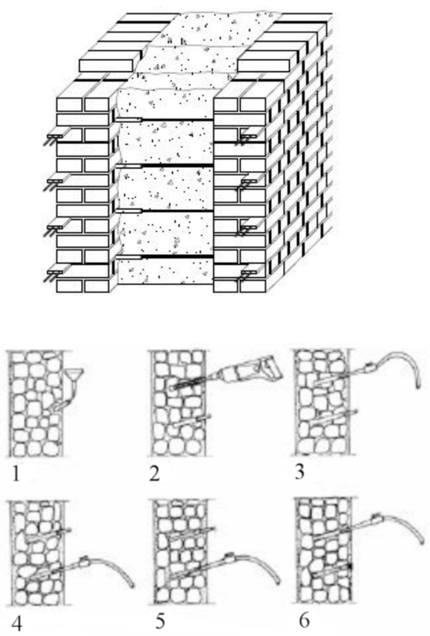
The installation of transverse connectors inside the wall (perpendicular to the cracks, anchored above and below the pillars, i.e. in undamaged areas) is the first but insufficient step of the strengthening intervention. However, the most effective intervention is determined based mainly on the quality of the material and the typology of the object. The typology of the objects of the Gjirokastra bazaar is relatively the same.

Pressure cement mortar injection, Fig.5 (a), is recommended to be used to improve the mechanical characteristics of the wall, as it increases the degree of monolithicity and the resistance of the masonry.

This method should not be used when the amount of voids found is very small. Care should be taken in choosing the injection pressure and the type of mortar for injection.

Reinforcement with transverse iron bars by drilling and cementing holes, Fig.5(b), can be widely used as it does not cause damage during execution. It is particularly suitable for connecting the outer layer to the inner layer of stone masonry.

Small prestressing can be applied to control out-of-plane deformations. This technique can be used for regular masonry typologies and textures, with squared stones etc.



(a) by injection (b)transverse bars fixed with bolts

Figure 5. Reinforcement of pylons

1.4 Details of stone masonry reinforcement

As mentioned above, the methods of strengthening stone masonry depend on the mechanical characteristics of the main constituent elements such as the stones and the mortar used. Some of the basic orientations where the reinforcement of the existing buildings of the Gjirokastra Bazaar should be focused are:

o Repair of cracked walls

o Replacement of damaged mortar to the joint

o Partial reconstruction by replacing stones detached from the masonry, arches, etc.

o Implementation of tie rods

o Reinforcement through the use of concrete sleeves on both sides of the wall, where possible by evaluating in a balanced way the conservation of the existing solution.

Repair of cracked walls

Depending on the size of the cracks, different materials and techniques can be used.

When the thickness of the stone masonry is small (<50 cm) and the width of the cracks within the limits of 5÷10mm, filling with cement mortar is recommended.

In cases where the wall has a greater thickness, the injection of cement mortar with anti-shrinkage additives is recommended.

For microcracks of the order of 1.0÷3.0 mm, the use of cement mortar or epoxy resin injection is recommended. The use of resins becomes necessary if the microcracks are smaller than 1mm.

When the cracks are over 10mm wide, from a purely structural point of view, the solution with reinforced concrete sleeves placed on both sides of the wall is preferred.

Reinforcement through the use of concrete sleeves is shown in Fig.6,

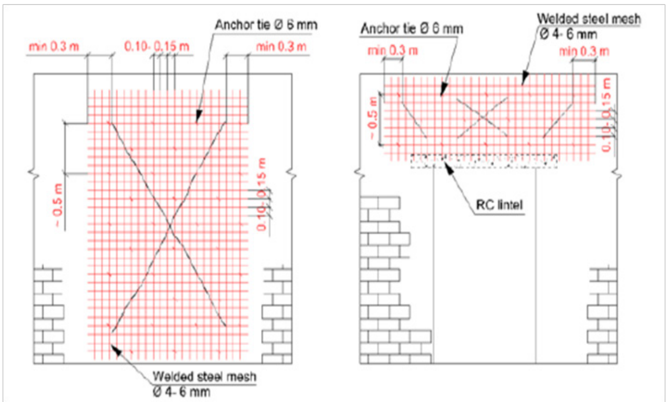


Figure 6. Repair cracked brick masonry wall with reinforced concrete coating

Replacing the mortar in the areas of the wall where it is missing prevents the masonry from continuing to be exposed to atmospheric agents.

In cases where joints with poor mortar are found, it is replaced, taking into account that the replacement is not done simultaneously on both sides of the wall, Fig.7. Existing mortar with poor mechanical parameters is recommended to be removed with water at a pressure of ≈40bar. The depth of the mortar to be removed should not exceed 1/3 of the wall thickness, due to the eccentricity created by vertical compressive loads in the masonry.

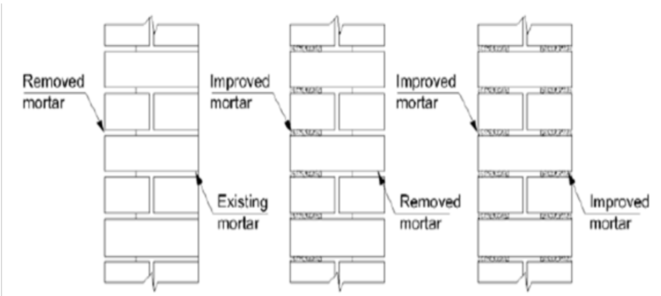


Figure 7. Repair and strengthening masonry by replacing mortar in horizontal joints

Reinforcement details to increase the structural integrity of masonry buildings

The main techniques for increasing structural integrity are:

- Connecting walls with metal ties
- Connecting walls with ring beams at floor level
- Anchoring floor and roof slabs to walls
- Increasing the stiffness of floor and roof slabs in their plane
- Reinforcement at masonry intersection joints
- Connecting walls with transverse reinforcement (perpendicular to their plane)

Metal ties are used to prevent the loss of stability of perimeter walls and to improve the behavior of masonry corners to the horizontal action of seismic loads. The placement of ties in the plane is done as in Fig. 8.

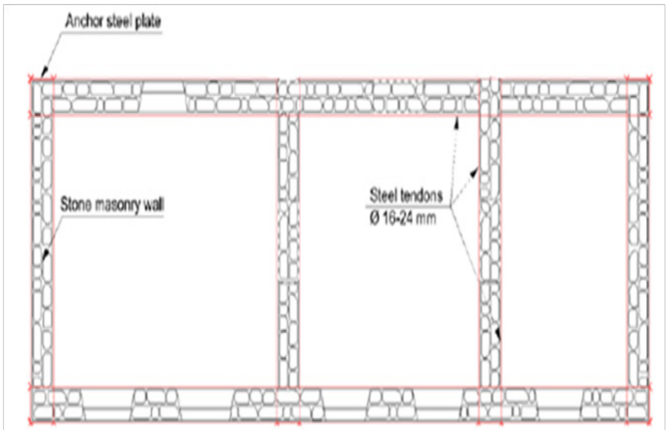


Figure 8. Distribution of horizontal ties in the plan for reinforcing stone masonry

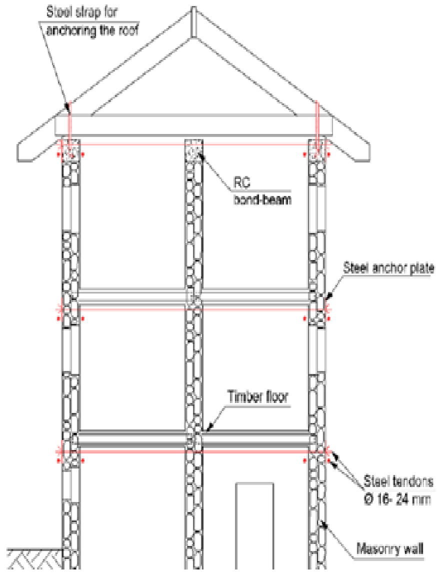


Figure 9. Height distribution of horizontal ties for reinforcing stone masonry

The recommended steel ties are 500C. The fastening can be done with bolts at both ends and with metal plates or with wedges and welding (identical to the original fastening method). When the walls have a considerable length (L≥6.0m) the tie must be fixed to the length of the wall every (2.5÷3.0)m to maintain horizontality. The metal anchor plates, in addition to the structural dimensioning, must be adapted to the existing original anchors.

For better performance, it is recommended that the ties be placed on both sides of the wall, directly under the floor (made of wood or reinforced concrete) and threaded with the anchor plates. In plastered walls, the tie can be placed inside after cutting a horizontal channel with a depth of 5cm. After installation, all steel elements must be protected from corrosion. Details of the fastening of the tie rods at the wall intersections and corners are shown in Fig. 10 and Fig. 11, respectively.

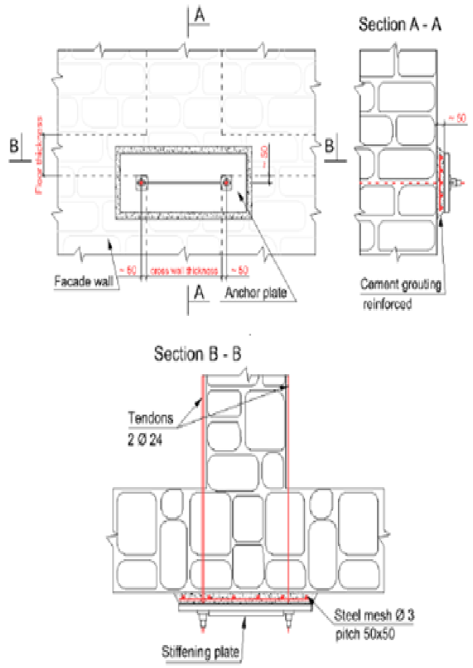


Figure 10. Detail for tying of walls at T junction using steel ties

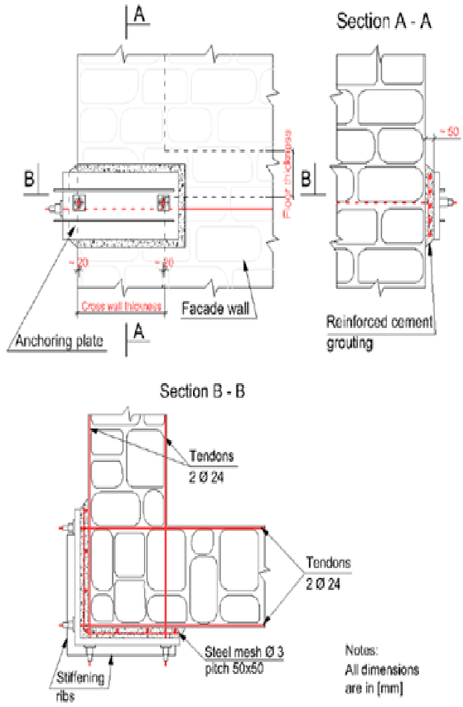


Figure 11. Detail of fixing the tie rods to the corners of the walls

The above details reflect these two basic principles:

o Ties placed along the walls perpendicular to the direction of seismic loads, create together with a part of these walls above them the necessary connecting beam. The ties together with the wall work in bending perpendicular to the plane of the wall. According to this principle, both ties should be identical and calculated as the longitudinal reinforcement of the connecting beam.

o Ties placed along the walls in the direction of seismic loads, participate in the global reaction of the structure by forming elements that work in tension. A global system equivalent to the truss is thus created where the compressive loads are balanced by the stone masonry. In the global truss system, the forces from the compressed diagonals of the stone masonry are transmitted down, floor by floor, through horizontal ties. The forces acting on the tie rods in the ultimate limit state are very close to the seismic shear load values of the floor.

The determination of the minimum diameter Dmin of the tie rod is made by the expression:

$$D_{min} = \sqrt{\frac{4 \cdot H_{u,seg} \cdot \gamma_s}{\pi \cdot n \cdot f_y}} \qquad (1)$$

D_{min}- minimum diameter

$H_{u,seg}$- the limit seismic resistance of the part (floor or segment) of the building where the tie rods are placed

f_y- yield strength of tie steel

γ_s-partial safety factor of steel

n-number of braces

The largest diameter determined by the calculations for all parts (floors or segments) is the one that should be applied to all the tie rods of the building. For buildings with stone masonry of the Gjirokastra bazaar blocks, the tie rod diameters are recommended within the limitsD_{min}=(16÷32)mm.

Connecting walls with reinforced concrete bandages at the basement level

Placing a reinforced concrete layer (slab) at the basement level on the outer side of the perimeter walls, Fig.12, is a simple solution that can be applied to increase the performance of stone masonry buildings. The iron grid of the layer is fixed to the masonry with anchor rods every 40cm in plan and height. The anchor rods are fixed after the holes have been drilled in the existing masonry, Fig.13. At the top of the wall, the first layer of 1.5cm thick cement mortar 1:2.5 is sprayed. Before it hardens, the iron grid is fixed φ(5÷6), 5/5cm on the anchor rods. The second layer of cement mortar, about 1.5cm thick, is placed after the grate has been fixed and the first layer has hardened.

1. Foundation
2. Plinth mansory
3. First layer of mortar for the bottom reinforcing band
4. Second layer of mortar for the bottom reinforcing band
5. First layer of mortar for the top reinforcing band
6. Bond beam
7. Anchor rod
8. Reinforcing mesh
9. Top reinforcing band

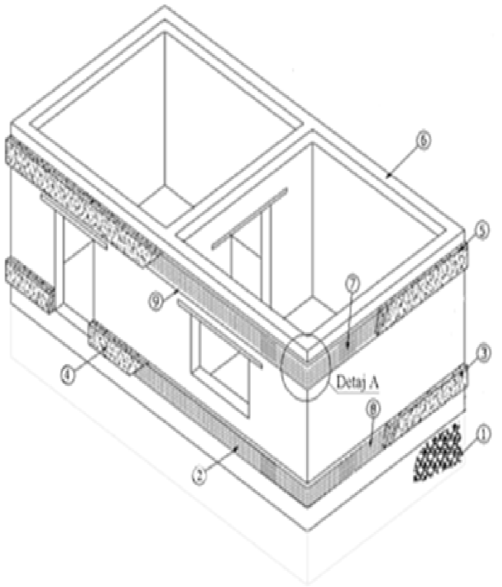
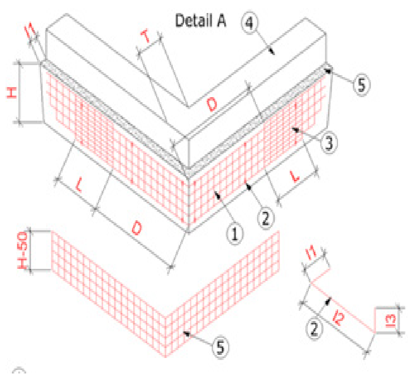


Figure 12. Tying of walls with steel reinforced



1. Cold bent galvanized steel wire mesh 50x50 with d=2
2. Steel cross ties – 400 apart with d=2-4
3. Steel mesh splice
4. Roof bond beam
5. Layer of mortar to provide base for the reinforcement

Figure 13. Wall connection with reinforced concrete bandages; Reinforcement detail

The recommended dimensions for reinforced concrete bandages are:

L≥50cm, I1≥5.0cm, I2≥T+1.5cm, I3=5.0cm, T≥25.0cm, D≥T+60.0cm, H=40cm

Anchoring floors and roofs

In buildings with stone masonry and wooden floors, the horizontal and vertical wall bracings are not sufficient to ensure monolithic behavior, causing significant out-of-plane bending of the walls, Fig.14, especially in cases where the distance between the transverse walls is considerable (L≥7.0m). To ensure monolithic behavior (interaction) of the walls and their possible destruction from out-of-plane bending, their anchoring to the floors and roofs is necessary.

Anchoring can be done with metal plates, Fig.15, on both sides of the floor beam or only on one side of it when the plate strip (anchoring length) is greater, Fig.16.

In addition to anchoring the walls with wooden floors with metal plates, in cases where:

o the distance between the transverse walls is considerable (L≥7.0m),

o anchoring with the existing wooden beams is difficult due to their depreciation or damage,

the full truss with metal profiles remains the preferred solution, Fig.17. The truss belts are made with profiles while the diagonals are steel bars with circular section.

It should be placed at the upper elevation of the existing beams under the wooden floor. The truss placed in the horizontal plane should be anchored to at least three existing walls, to ensure their interaction against the action of the seismic load. The anchoring of the truss to the walls is done with metal anchors fixed with bolts.

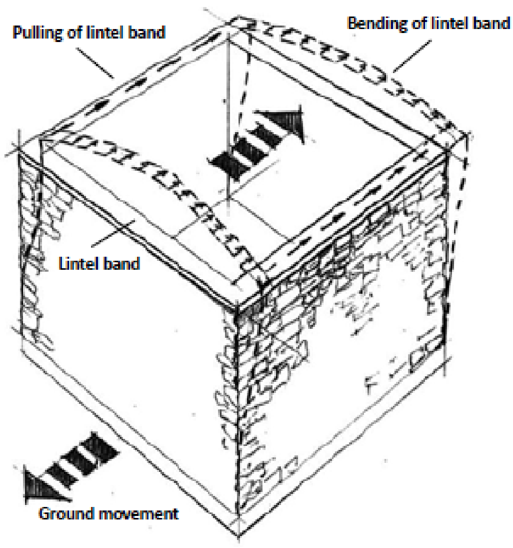


Figure 15. 14. Bending of walls

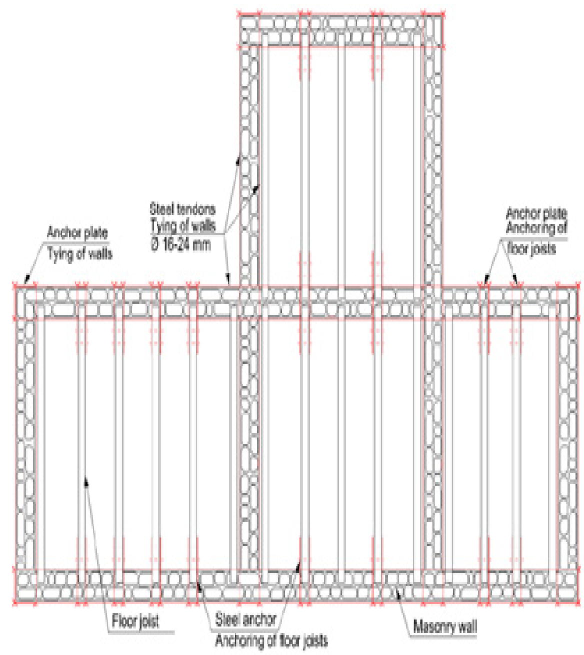


Figure 15. Distribution of horizontal ties in the plan and anchoring outside the planof floors with stone masonry

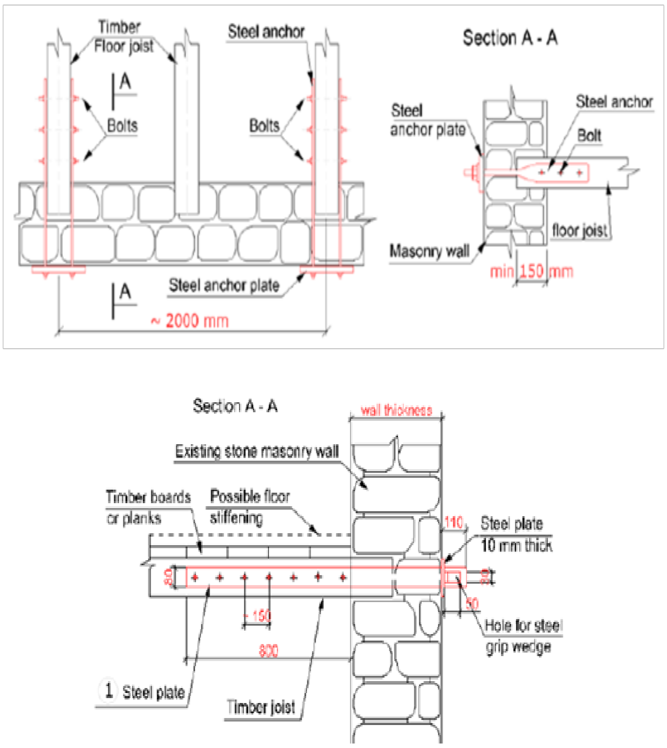


Figure16. Details of anchoring floors to stone masonry

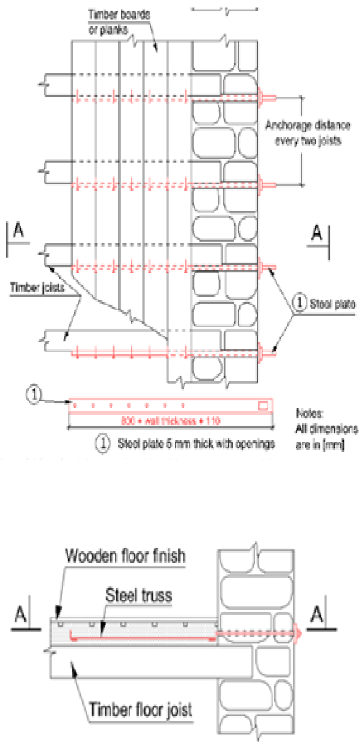


Figure 17. Stiffening large interfloor spaces with steel trusses and anchoring them to the walls.

Stiffening floors and roofs in their plan

To distribute seismic forces in the walls, the floors of the floors and the roofs must be rigid in their plan. Fulfilling the rigidity condition makes them behave as rigid diaphragms. Floors/ roofs that are semi-flexible or flexible in their plan distribute seismic loads based on the floor/wall stiffness ratios.

o To achieve reinforcement, especially in cases where the floor structures of the floors of the floors or roofs are damaged, the best solution is to replace them with monolithic reinforced concrete slabs. At the same time, reinforced concrete connecting strips are also made at the height of the slab, inside the wall at no less than 1/3 of its width and no less than 15cm. From a structural point of view, the width of the anti-seismic connecting strip is preferably the same as the width of the wall. If it is not possible to make the strip across the entire width of the wall, the slab is anchored to the wall with concrete wedges as in Fig.18.

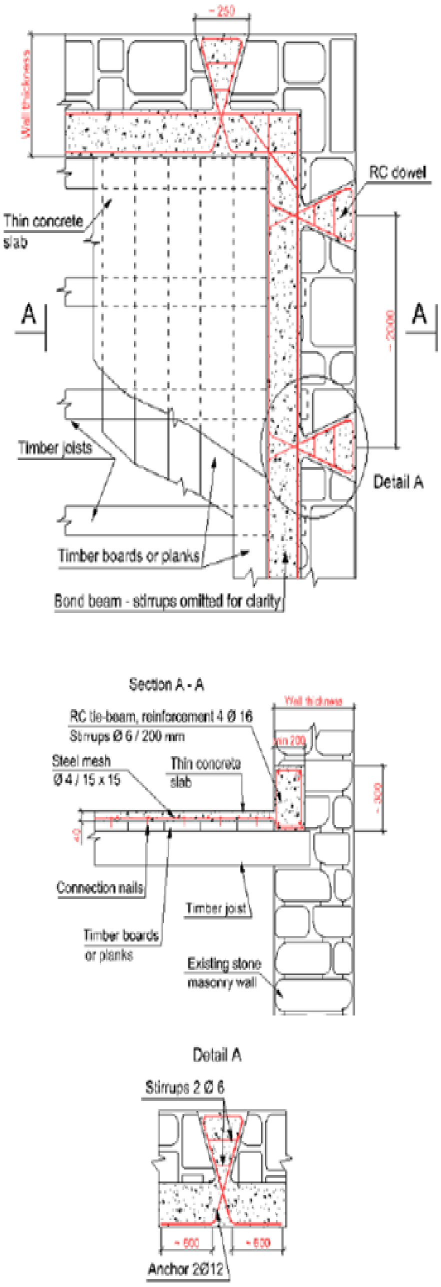


Figure 18. New reinforced concrete slab stiffening the subfloor structure and anchoring to the existing walls with reinforced concrete wedges.

CONCLUSIONS

The heritage buildings in the Old Bazaar of Gjirokastra represent a certain technique and craftsmanship of building traditional structures with local limestone masonry, with good resistance characteristics, high durability and affordable costs for the time.

Over time, earthquakes have significantly threatened these structures, taking into account the morphology of the hill where the buildings were built, which cannot be considered suitable for seismic vibrations.

On the other hand, the seismic vulnerability of stone masonry buildings is high due to the great weight of stone as the main construction material with which they were built and the limitations of the craftsmanship of the time for protecting buildings from earthquakes. Taking into account the relatively low performance of stone masonry buildings against earthquakes, some simple repair and reinforcement methods have been presented above, which aim to increase their performance.

The increase in their performance level is based on these basic criteria:

- Improving the quality of the damaged material and the technique used where possible.
- Ensuring the structural integrity of the buildings by creating a “boxing effect” during seismic vibrations.
- Realization of stiffening bands connecting according to three orthogonal directions in space.

However, it is now known that the methods of reinforcement must be fully compatible with the mechanism of realization of the original structure in order not to violate the character and historical values of these buildings.

In this regard, the compromise between the structural engineer and the architect or restorer must be based on the principle that if the building is not solid and stable, its architectural or historical values are at risk.

The laws of gravity, Newton or structural mechanics apply equally to all buildings, regardless of whether they are of architectural, historical, etc. importance.

On the other hand, the structural engineer in his solutions must respect the unique characteristics of these buildings determined by the time in which they were built, in order to have efficient and successful interventions.

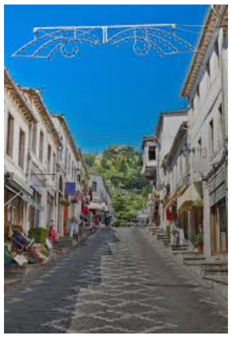


Figure 1. After restauration of Old Bazaar of Gjirokastra, Albania

Aknowlegment

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