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Possibilities of Earthquake and Disaster Preparedness for Masonry Structures

Introduction

Earthquakes are frequently of short duration, but great forces arise during their action and can cause extensive damages on a structure. We cannot prevent natural disasters from striking, but we can prevent or limit their impact by making structures strong enough to resist their destructive forces[1] and by applying some methods to neutralize their harm. Structural engineers therefore need to learn about what causes an earthquake and what can be done to minimize its impact.

Masonry is a very diverse building material, strong in compression, but virtually without strength in tension. To compensate for this imbalance in masonry's behaviour, reinforcement bars are cast into it to carry the tensile loads. Reinforced masonry behaves similarly to reinforced concrete. The interface between the masonry unit (bricks, blocks, etc.) and the mortar adds additional potential for failure. Unreinforced masonry possesses little ductility and cannot be expected to behave like an elastic material during an earthquake.

This short report is focused on developing methods to prevent adverse seismic effects on masonry structures. The first issue that must be addressed is an evaluation of the characteristics of masonry; the findings can be used to verify the capacity of the structure after earthquake action.

Characteristics of masonry material

In order to understand the characteristics of masonry and scientifically describe and influence its behaviour it is necessary to perform tests to assess its mechanical properties.

Mechanical properties of masonry

Masonry is a composite material made up of units (bricks, blocks etc.) and mortar. Because of the specific characteristics of the composites it is difficult to predict the mechanical behaviour of masonry, and therefore experiments have to be carried out for different types of masonry. To assess the resistance of masonry walls the mechanical properties of the masonry, such as its compressive strength, shear strength, bending strength and stress-strain relationship, need to be determined.

Compressive strength

The behaviour of the composite material »masonry« subjected to compressive stresses is determined by the different lateral deformation behaviour of mortar and block, which results in a triaxial state of stress in mortar and masonry unit.

If the compressive strength of the mortar has a high value, the units are going to crush first under compression. The compression failure is usually determined by the lateral tensile stresses in the blocks. Therefore, the compression strength of masonry is usually lower than the uniaxial compressive strength of the blocks. A greater exploitation of the compressive strength of the blocks can be achieved if the lateral deformations of the mortar joints can be restricted, reducing the lateral tensile stresses in the blocks. Restraint of the lateral deformation of the mortar can be attained by reinforcing the bed-joints that enclose the mortar.

In other cases, the compressive strength of eccentrically loaded masonry usually affects the strength of arches, vaults, pillars and out-of-plane loaded masonry panels. The eccentric loading problem on masonry leads to tensile stresses which cannot transmit the load properly since the masonry is only able to transmit the load to a limited extent.

Shear strength

Shear along masonry unit/mortar interfaces is an important mechanism of resistance in structural masonry. Several test procedures and set-ups have been proposed to characterize this response so that test results can be used for analysis and design of masonry work, as shown in fig. 1.

By analyzing test results it has been established that the ratio between the tensile and compressive strength of any type of masonry varies within the following margins:[2]

0.03 fk <= ftk <= 0.09 fk

1 Usam Ghaidan: Earthquake-Resistant Masonry Building. Basic Guidelines for Designing Schools in Iran, Paris 2002, p. 4.

2 Kuldeep S. Virdi/Rossen D. Rashkoff, Pell Frischmann Consulting Engineers, Low-rise residential construction detailing to resist earth-

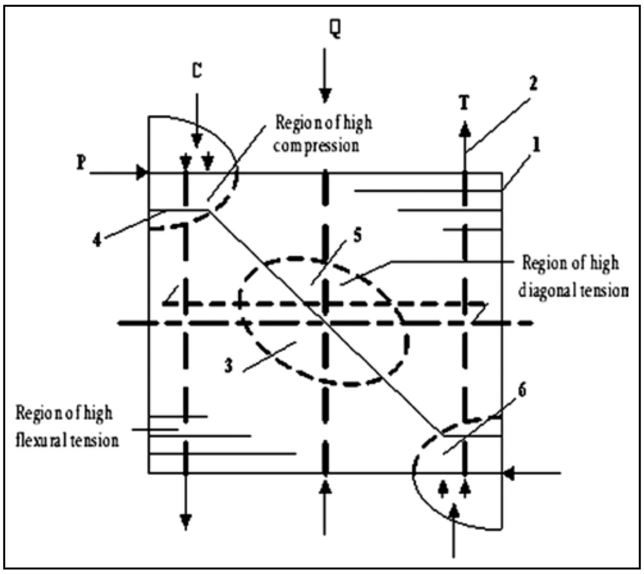

Fig. 1 Six major events in the response of reinforced masonry shear walls

ftk - characteristic tensile strength of masonry
fk - characteristic compressive strength of masonry

If the tensile strength is lower than the compressive strength, it cannot be considered in calculations.

Bending strength

In cases where masonry needs to be verified for out-of-plane loads, the bending strength is the governing factor. According to EuroCode 6, the value of the bending strength parallel to bed joints should be taken as zero when evaluating seismic resistance.[3]

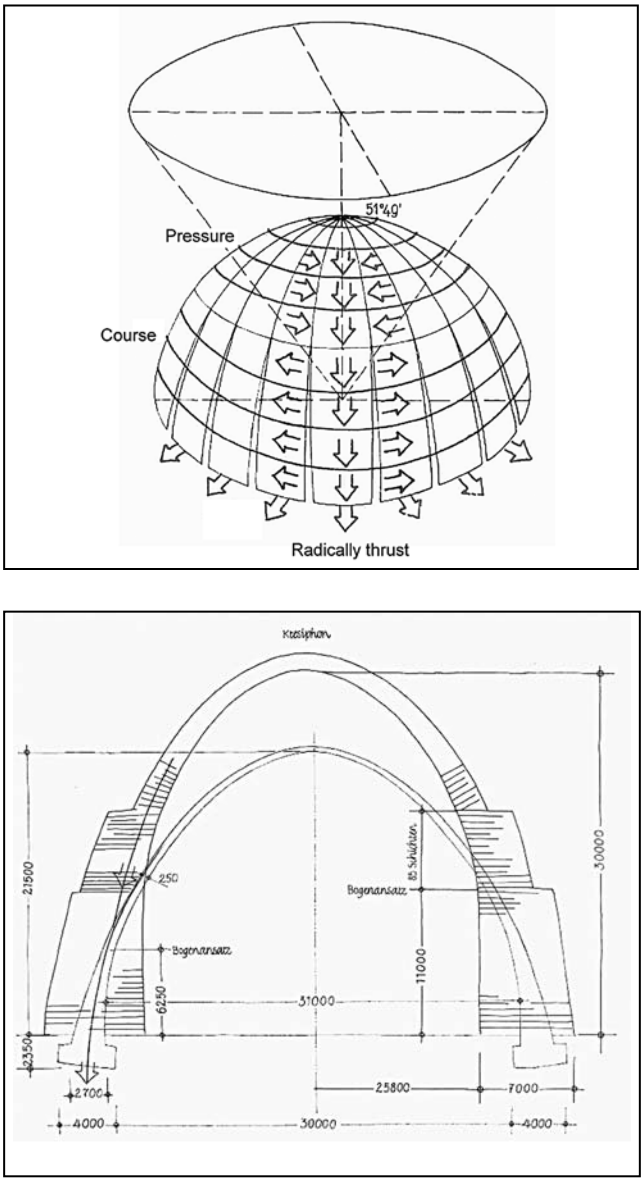

Fig. 2 Sketch of a dome: (a) distribution load and (b) dimensions

Characteristics of historic masonry structures

The main loads most historic masonry structures have to resist are their own dead weights and those imposed by wind and earthquakes. The structural resistance depends primarily on two factors: the geometry of the structure and the characteristic strength and stiffness of the material used.

Historic buildings made of masonry

The use of masonry in structures goes back about 10,000 years. Early examples of masonry structures were mud-brick dwellings. Structurally, they were not very durable and were defined by simple forms, with timber tie beams spanned between the walls. When the need for larger interior spaces arose, mostly for religious buildings, stone was usually used as the masonry unit.[4]

The most successful examples of stone masonry structures of the early period are Egyptian pyramids. Even though they have no large spaces, they have a perfect structural form for withstanding environmental effects. This perfect structure is achieved by stacking varying masses of blocks in such a way that their angles relate to the shapes of the individual blocks.

The famous lost city of Machu Picchu is the best surviving example in South America. The Inca were sophisticated stone cutters who did not use mortar for their masonry

quakes, http://www.staff.city.ac.uk/earthquakes/Repairstrengthening/RSStoneMasonry.htm

3 Ibid.

4 Ali Ishan Unay: Structural Wisdom of Architectural Heritage. Middle East Technical University, Ankara, Turkey, in: http://www.unesco.org./archi2000/pdf.unay.pdf

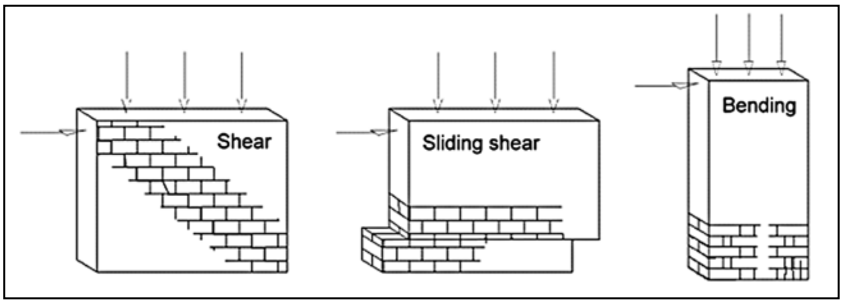

Fig. 3 Failure modes for masonry walls subject to in-plane loads

(»dry-stone walls«). Usually the walls of Incan buildings were slightly inclined inside and the corners were rounded. This, in combination with the thoroughness of the masonry work, led Incan buildings to have a peerless seismic resistance. During an earthquake of small or moderate magnitude the masonry was stable, and during a severe earthquake stone blocks would »dance« near their normal positions and remain exactly in the right order after an earthquake.[5]

Another example is the Bam Citadel, which was the largest adobe building in the world, located in Kerman Province in south-eastern Iran. Like most medieval fortresses, Bam has a wide moat outside the crenulated walls. The area within the walls is over 200,000 square metres; the outer walls are eight metres high and five metres thick (at the base).[6]

Behaviour of structural elements

The inability of masonry structures such as arches, vaults, domes and walls to resist tensile stresses required widening of their cross-sections so that compression would reduce the effect of potential bending. A substantial thickness was directed by the coarseness of their constituent materials: stone, brick and mortar joints were often intuitively necessary to prevent buckling.

For example, the dome is the structural form which distributes loads to supports through a doubly curved plane. The dome must be designed to resist compressive stresses along the meridian lines and to resolve circumferential tensile forces in the lower portion of hemispherical domes. The compressive forces within the dome are similar to those developed within an arch and must be resisted in a similar manner. The dome will spread at its base if it is not restrained by either mass or ties. The thrust at the base of the dome is continuous and traditional methods of obtaining stability rely upon massive buttressing. The dome is an extremely stable structural form and resists lateral deformation through its geometry (fig. 2).[7]

Structural damages caused by natural disasters

A natural disaster is the consequence of a combination of natural hazards (a physical event, for example hurricanes, floods, landslides, earthquakes) and human activities. A natural hazard is an event that has an effect on people and results from natural processes in the environment.

Damages and failures caused by earthquakes

In the event of an earthquake, in addition to the existing gravity loads horizontal racking loads are imposed on walls. Unreinforced masonry behaves like a brittle material. When the state of stress within the wall exceeds the masonry strength, brittle failure occurs, followed by the possible collapse of the wall and the building. Therefore unreinforced masonry walls are vulnerable to earthquakes and should be confined and/or reinforced whenever possible.

Masonry walls resisting in-plane loads usually exhibit the following three modes of failure (fig. 3).[8]

- *Shear:* a wall loaded with a significant vertical load as well as horizontal forces can fail in shear. This is the most common mode of failure.
- *Sliding shear:* a wall with poor shear strength, loaded predominantly with horizontal forces, can exhibit this failure mechanism.
- *Bending*: this type of failure can occur if walls have improved shear resistance.

The lateral resistance and ductility of plain masonry walls can be improved by reinforcing the masonry with steel. Vertical reinforcing bars can be placed in hollow block masonry channels. The contribution of vertical and horizontal reinforcement to the resistance of the wall, failing in shear, is shown in fig. 4.

5 http://en.wikipedia.org/wiki/Machu_picchu, redirected from Machu Picchu, Historic Sanctuary of Machu Picchu, UNESCO World Heritage Sites.

6 Asad Mahbub: Bam-Citadelo, in: Irana Esperantisto (Iranian Esperantist), no. 4, vol. 2, Summer 2003, pp. 5–7; Engl. translation in: http://en.wikipedia.org/wiki/Bam_Citadel.

7 Unay (note 4).

8 See note 2

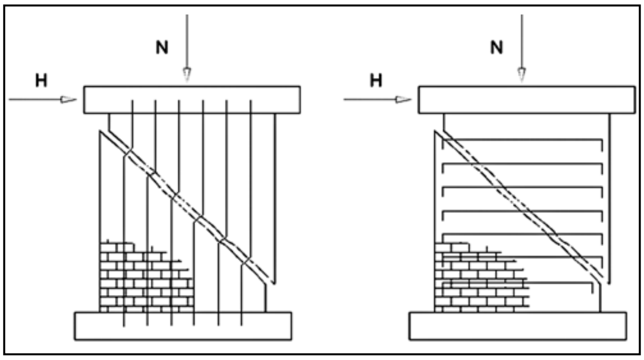

Fig. 4 Mechanism of action of vertical and horizontal reinforcement in a masonry wall failing in shear

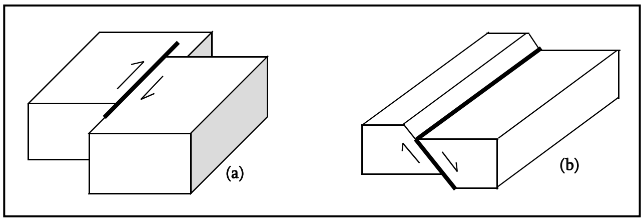

Fig. 5 Different types of faults: (a) left lateral fault/strike-slip fault and (b) dip-slip fault/normal fault

Earthquakes and typical damages

Most of the stresses that cause earthquakes can be explained by the theory of plate tectonics. The typical damages to a structure depend on the amplitude and the duration of shaking during an earthquake in the context of the structure's design and the materials used in its construction.

Characteristics of earthquakes

In general, during an earthquake there are usually one or more major peaks of magnitude of motion. These peaks represent the maximum effect of the earthquake. Although the intensity of the earthquake is measured in terms of the energy release at the location of the ground fault, the critical effect on the given structure is determined by the ground movements at the location of the structure. The effect of these movements is determined mostly by the distance of the structure from the epicentre, but it is also influenced by the geological conditions directly beneath the structure and by the nature of the entire earth mass between the epicentre and the structure.

One of the most common and modern methods for recording earthquakes is to plot the acceleration of the ground in one horizontal direction as a function of elapsed time. Thus a typical acceleration record of an earthquake allows us to simulate the effects of major earthquakes.[9]

Focus and epicentres

The point along the rupturing geological fault inside the earth where an earthquake originates is called the focus, or hypocentre. The point on the earth's surface directly above the focus is called the epicentre. Earthquake waves begin to radiate from the focus and subsequently to form along the fault rupture. If the focus is near the surface, between 0 and 70 kilometres (between 0 and 40 miles) deep, shallow-focus earthquakes are produced. If it is intermediate or deep below the crust, between 70 and 700 kilometres (between 40 and 400 miles) deep, a deep-focus earthquake will be produced. Shallow-focus earthquakes tend to be larger and therefore more damaging because they are closer to the surface where the rocks are stronger and build up more strain.

Elastic rebound theory

Different types of earthquakes are based on the movement along the fault line. In a normal fault, one side of the fault line moves up and one side moves down as shown in fig. 5a. In a strike-slip earthquake, the movement is horizontal as shown in fig. 5b. A slip is the amount of displacement that adjacent blocks move along the fault.[10]

Effects of earthquakes

The response of a building to an earthquake is dynamic, not static. Earthquake effects that can have an impact on structures include: ground-shaking in three dimensions, soil failures, ground settlement and seismic sea waves.[11]

- *Ground-shaking:* Caused by the passing waves of vibration through the ground, this can result in several types of damaging effects. Some of the major effects include destruction of rigid structures: they either totally collapse or they are knocked off their foundations.
- *Soil failures*: Soil failure, such as liquefaction, is the process by which saturated, non-cohesive soil loses its shear strength during seismic shaking and behaves like a liquid rather than a solid. The effect on structures and buildings can be devastating and is a major contributor to urban seismic risk.
- *Ground settlement*: Buildings can also be damaged when the ground gives way beneath them. This can

9 British Columbia Institute of Technology, Civil and Structural Engineering Technology Program: Earthquake Effects, from http://www.eng.bcit.ca/civil/courses/4167/unit1_01.htm

10 Earthquake Types, from http://library.thinkquest.org/03oct/00795/earthtypes.html

11 T. Weiland: Earthquakes, Introductory Geosciences I, from http://itc.gsw.edu/faculty/tweiland/quake.html

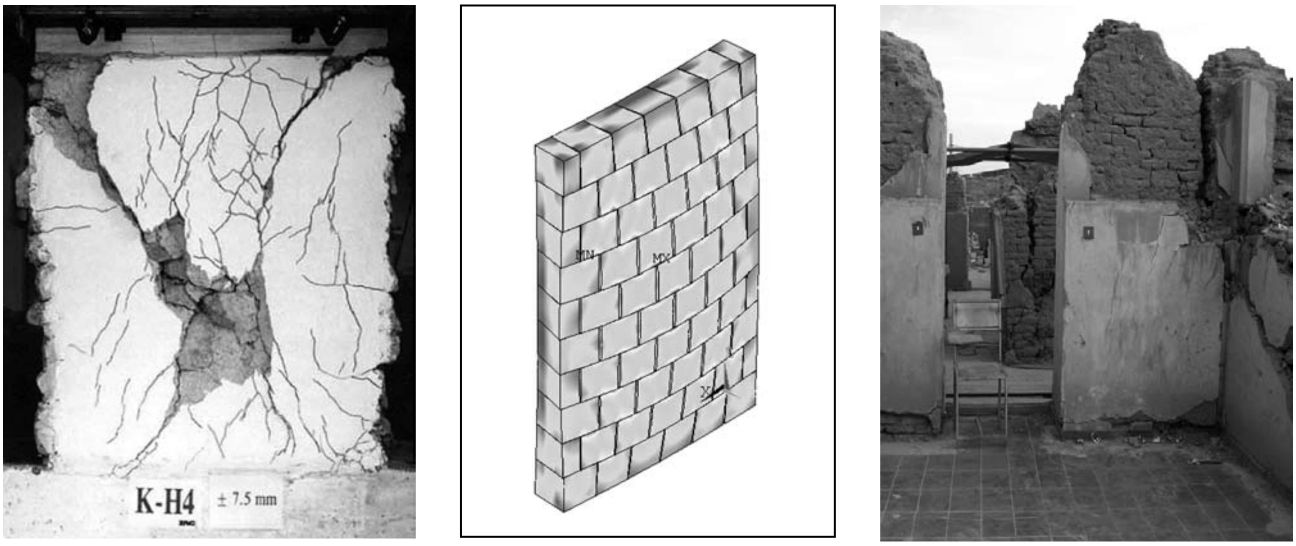

Fig. 6 Typical damages on masonry structures: (a)—X-cracking, (b)—bending, (c)—loss of integrity

happen in the form of a landslide down a hill, which can cause severe settling of the ground.

- *Tsunami*: Tsunamis are the most dangerous effects of an earthquake. They are large destructive ocean waves caused by the sudden displacement of the seafloor and are associated with earthquakes. They have been recorded at heights of up to 20 metres (around 60 feet) and speeds of up to 500 mph.

Typical damages

The following types of damage can be identified through analysis of observed earthquake damage patterns: x-cracking, crushing, bending failure, loss of integrity, cracks between walls and floors, cracks at the corners and at wall intersections, out-of-plane collapse of parametric walls, cracks in spandrel beams and/or parapets, diagonal cracks in structural walls, partial disintegration or collapse of structural walls and partial or complete collapse of the building (fig. 6).

Preservation and retrofitting against earthquakes

In the Preservation Brief »The Seismic Retrofit of Historic Buildings, Keeping Preservation in the Forefront« three important preservation principles have been spelled out for seismic retrofit projects:

- »Historic materials should be preserved and retained to the greatest extent possible and not be replaced wholesale in the process of seismic strengthening;
- New seismic retrofit systems, whether hidden or exposed, should respect the character and integrity of the historic building and be visually compatible with it in design; and
- Seismic work should be »reversible« to the greatest extent possible to allow the removal for the future use of improved systems and the traditional repair of remaining historic materials.«[12]

Base isolation

Base isolation is another technique to reduce earthquake hazards to masonry buildings. It is an energy dissipation method rather than a structural retrofitting. It shifts the fundamental period of vibration of the structure to a range outside the predominant energy content of the earthquake. Its limitations include serious physical disruption and high costs. It can be effective for safeguarding buildings of cultural value.

The concept of base isolation is explained through the example of a building resting on frictionless rollers. When the ground shakes, the rollers move freely, but the building above does not move. Thus, no force is transferred to the building when the ground is shaking, and the building therefore does not experience the earthquake.[13]

12 David W. Look, Terry Wong, Sylvia Rose Augustus, The Seismic Retrofit of Historic Buildings, Keeping Preservation in the Forefront, Preservation Brief 41, Technical Preservation Services, National Park Service, US Department of the Interior, Washington, D.C. 1997, pp.2-3; cited from http://www.oldhousejournal.com/notebook/npsbriefs/index.shtml

13 C. V. R. Murty: Earthquake Tip, Indian Institute of Technology Kanpar, Building Materials and Technology Promotion Council, New Delhi 2003.

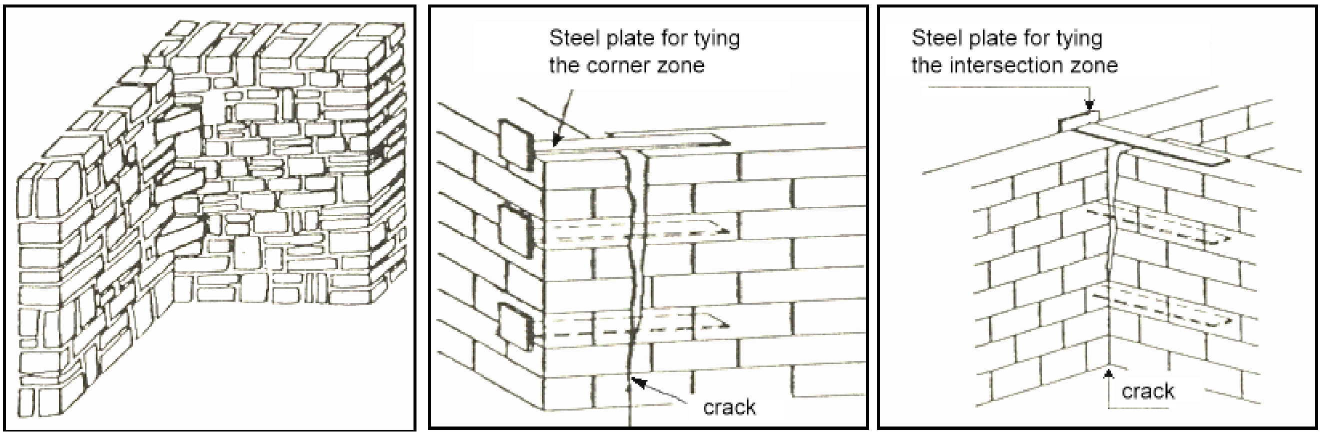

Fig. 7 Methods for improving integrity

Fig. 8a and 8b Results of a shaking table test using a model of a rural stone house with wooden floors; (a) without steel ties, (b) with steel ties

Improvement of integrity[14]

The integrity of masonry can be improved by applying anchors for tying existing building elements together (fig. 7). The forces acting in the anchors will be transmitted by bond, plates, perpendicular bars or other means. Usually the materials used should be compatible with the historic structure. Wooden and/or iron ties have been used to improve the structural integrity of masonry buildings and prevent lateral instability of masonry walls caused by the horizontal action of structural elements. More recently new materials such as glass or carbon fibres have been used.

Methods for improving structural integrity can be classified into the following main groups:

- tying of walls with steel ties;
- replacing, stiffening and anchoring of floors;
- strengthening of corners and wall intersection zones;
- strengthening of walls by construction of vertical confining elements.

14 Miha Tomaževič, Methods of Repair and Strengthening: Methods for Improving Structural Integrity, Retrofitting of Masonry Structures, in: Beate Boekhoff and Annette Lippert (ed.), International Short-Course on Architectural and Structural Design of Masonry with a focus on Retrofitting of Masonry Structures and Earthquake Resistant Design, hosted by Lehrstuhl für Tragwerksplanung, Technische Universität Dresden, 7–18 December 2003, (unpublished conference material) p. 50.

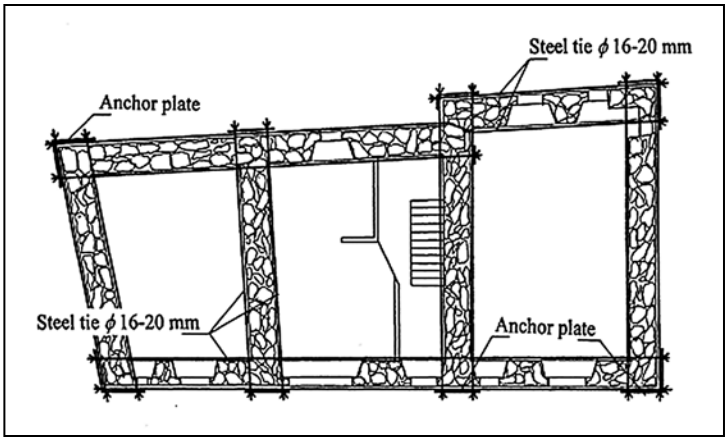

Fig. 9 The position of steel ties on the plan of a rural stone house

Post-tensioning of an existing construction[15]

Unreinforced masonry developing tension owing to either in-plane or out-of-plane bending can be strengthened by using pre-stressing steel to create axial compression in the wall. The additional axial compression increases the bending moment required to produce tension.

On the other hand, reinforced masonry can also be strengthened where the additional axial compression reduces the need for tensile reinforcement. Internal pre-stressing has been used successfully to increase the strength and provide ductility to existing unreinforced masonry structures. If a cavity or cell space is sufficiently opened to permit the placement of post-tensioning strands or bars, wall openings are required to install anchors and bearing plates. If masonry material is strong enough, the anchoring can also be carried out with bonding.

Anchoring and tying[16]

The failure of anchors of floors, roofs and walls limits their stability under lateral out-of-plane loading and limits the ability of the floor or roof system to transmit lateral in-plane loads to the rigid walls to provide overall building stability. On the other hand, walls can have vastly improved strength and stiffness characteristics if an adequate connection can be made at their intersections. Retrofit bolts, expansion anchors, or epoxy sock anchors are typical for mechanical connections.

Anchors may act in shear or tension or both but in general the most critical aspect of the design is to adequately anchor the bolts in the masonry and to ensure adequate stiffness where interconnecting elements may introduce additional displacements along the interface.

For a comparison of the collapse of stone masonry models during a shaking table test with and without ties see fig. 8a and b.

Observations showed that the freely supported wooden floors from the model without ties did not prevent the separation of the walls. As a consequence, the upper storey of the model disintegrated and partially collapsed before the model's final collapse. Severe out-of-plane vibration of transverse walls had been observed before the disintegration of the upper storey. In the case of the model with wall ties, separation and disintegration of the walls were prevented. The model collapsed because of the shear failure of the load-bearing walls in the first storey.

The results of the shaking table test led to design recommendations that should be taken into account if masonry walls are tied with additionally placed steel ties (fig. 9).

Base retrofitting[17]

Several options exist for retrofitting a building's footings and foundation walls, such as capping, replacement and parallel systems.

Capping simply means that concrete is placed over or alongside the existing foundation wall. An engineer or architect has to specify the reinforcing steel, anchor bolts and connections between the existing foundation wall and the new capping. The embedment of anchor bolts and the placement of reinforcing steel generally follow the standards for new construction.

Replacement involves shoring up the building and putting in a complete or partial perimeter footing and stem wall. This method is frequently used if the conditions of the foundation do not allow verification during an earthquake. Shoring can be omitted when replacement is done in small sections at a time. The latter technique is popular for occupied structures.

Parallel systems are systems of new structural elements that create a parallel horizontal force-resisting system at the foundation level. The new structural elements are typically located near the exterior walls.

15 Ahmad A. Hamid, Robert G. Drysdale, Retrofitting of Masonry Structures, in: Boekhoff/Lippert (See note 15), pp. 165 f.

16 Ibid., pp. 156 f.

17 Richard Chylinski/Timothy P. McCormick: Foundations, Seismic Retrofit Training, p. 70, from http://www.abag.ca.gov/bayarea/eqmaps/fixit/manual/PT10-Ch-5.PDF

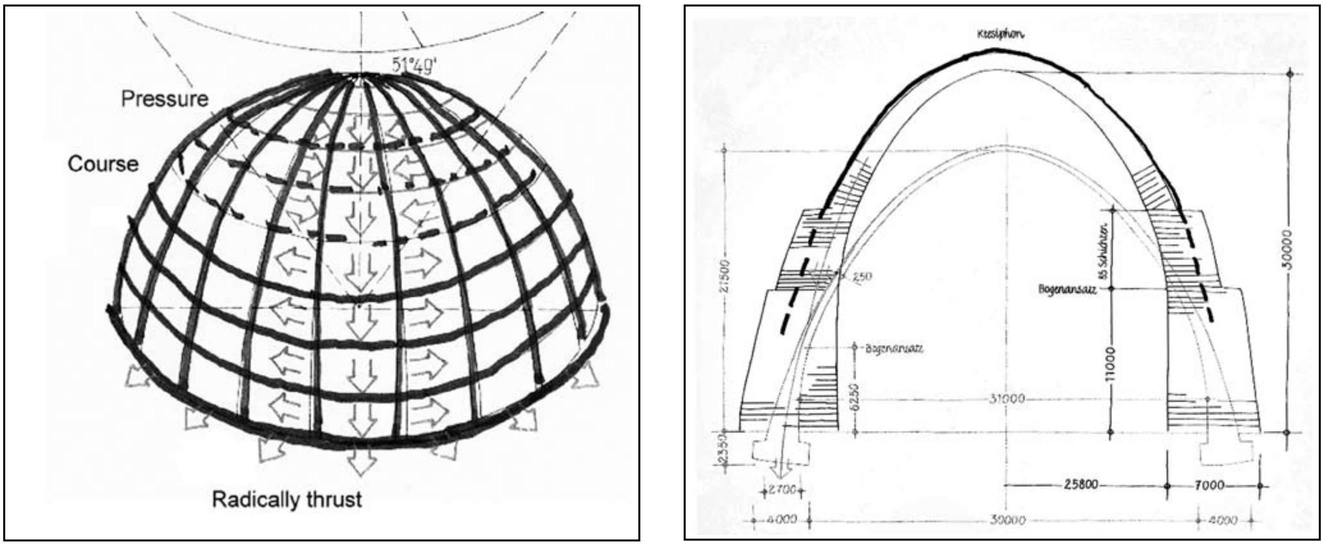

Fig. 10 Placement of reinforcement bars in a dome: (a) reinforcement in both directions, (b) detail of reinforcement

Reinforcement

Tensile failure of the bed joints or the units can be avoided by vertical reinforcing bars, which can carry tensile stresses perpendicular to the bed joints. A sufficient cross-section of reinforcing bars will be determined by flexural or tensile design. Reinforcement also can be helpful for improving the shear capacity of masonry (fig. 10).

Consolidation by injection[18]

This method is usually applied to stone and mixed stone-and-brick masonry which is frequently characterised by two outer leaves of uncoursed stones (or uncoursed stones mixed with bricks) with inner infill of smaller pieces of stones. Lime mortar used as a bonding material is of relatively poor quality. Because of the way in which such walls are constructed, they contain many voids that are uniformly distributed over their entire volume. Therefore, systematically filling the voids by injecting cementitious grout is an obvious and efficient method of strengthening in the hope that after hardening, the injected grout will bond the loose parts of the wall together into a solid structure.

During grouting, the spilling of grout out of the cracks and joints between the stones is prevented by the application of dry fast-binding cement. As indicated by experience, the quantity of the dry part of the grout needed to systematically fill the voids in stone-masonry walls does not exceed 50 to 150 kg per cubic metre of the wall.

Life cycle and historic buildings

Historic buildings are inherently sustainable. Preservation maximises the use of existing materials and infrastructure, reduces waste and preserves the historic character of old towns and cities. The energy embedded in an existing building can be 30 per cent of the energy of maintenance and operations for the entire life of the building. Sustainability begins with preservation.

Historic buildings were traditionally designed with many sustainable features that responded to the climate and site. When effectively restored and reused, these features can bring about substantial energy savings. Taking into account the original climatic adaptations of historic buildings, today's sustainable technology can supplement inherent sustainable features without compromising the unique historic character.

Conclusion

To avoid or minimize earthquake risk on historical masonry consideration should be given to the characteristics of masonry material and the historic building itself. Applying new technology might help prevent damage to the masonry building during natural disasters. Generally, the options for the level of seismic retrofitting depend on the expected seismic activity and the desired level of performance. Several methods are introduced for improving structural integrity and for strengthening masonry structures in order to significantly improve the seismic resistance of existing buildings.

18 Tomaževič (note 14), pp. 54 f.