International Symposium on
SEISMIC RETROFIT of UNREINFORCED MASONRY
HERITAGE CHURCHES IN THE PHILIPPINES
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Components and Damage Mechanisms of Unreinforced Heritage

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Typology of Heritage Structures

Architectural Heritage structures have diverse construction material & geometrical typology,

Traditionally, as construction material, the local predominance materials as *stone*, *earth* or *wood* were used in monumental or vernacular buildings.

Masonry Construction

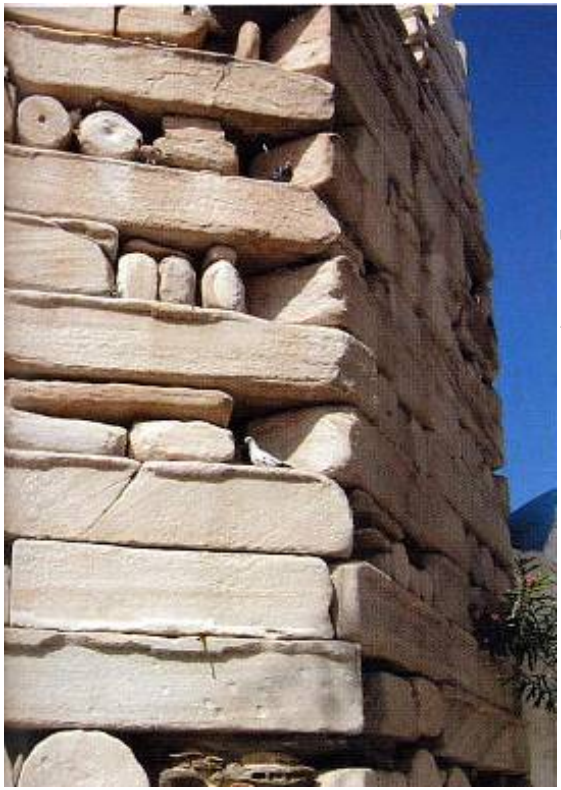
Masonry structures are constructed of

- Placing
  - *stone,
  - * brick: fired clay
  - *adobe: sun-dried clay,
  - *concrete block

  units one over another

- Pouring moist
  - *earth
  - *concrete

  into a formwork in layers

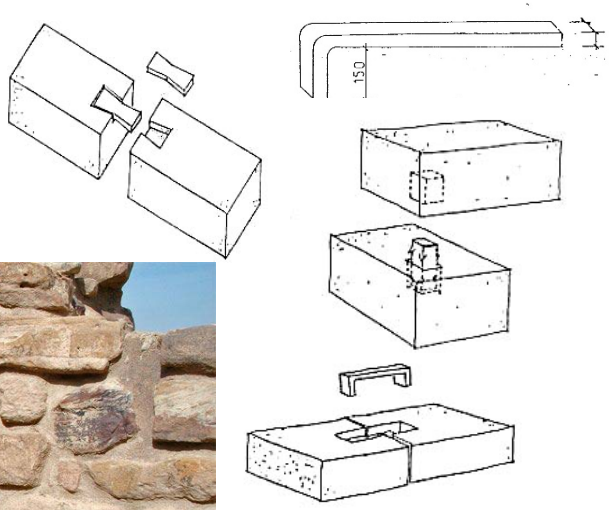


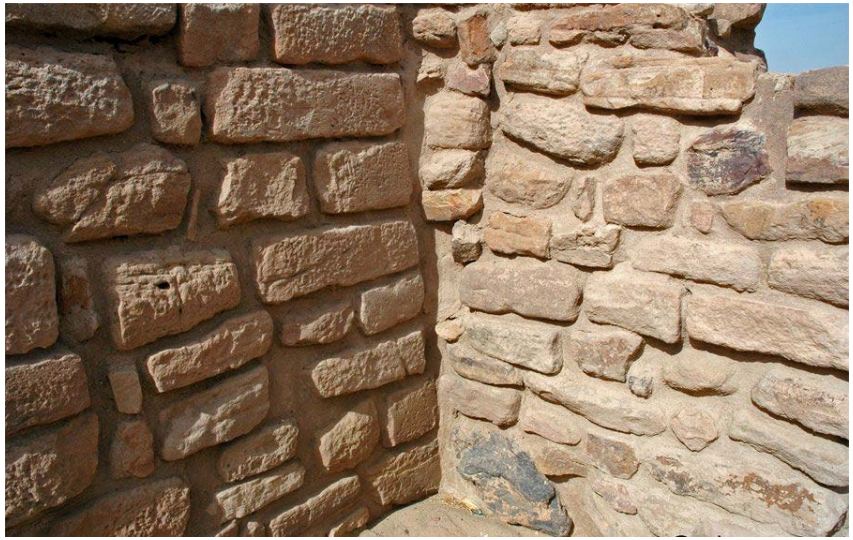
Masonry Construction

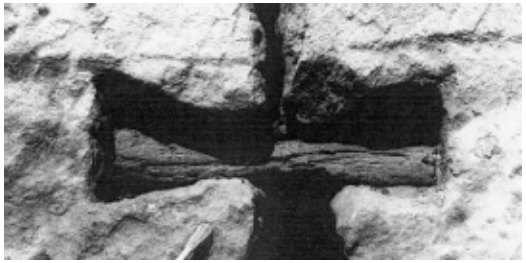
Unit Connection

To make structural elements,
***blocks* are joined together;**

- ***dry**
- ***by metal / timber connectors**
- ***laid in mortar, coursed or un-coursed.**







Masonry Construction

The units constituting the masonry components are;

- **resistant to actions,**
- **non-ductile**
- **brittle**
- **good in compression**
- **weak in tension**

Masonry buildings rely on the compressive strength of its units.

Stone: 20 - 500 N/mm^2.
Clay bricks: 5-10 N/mm^2

Masonry structures *withstand tensile stresses* with

- **the material's *high compressive strength* and**
- **the *friction resistance* between the units in compressive action**

Masonry Components

Structural components of masonry are:

- **Columns or piers**
- **Walls**
  - **Beams, ties or lintels**
  - **Arches**
  - **Foundations**
- **Floors, vaults and dome**

Masonry Components

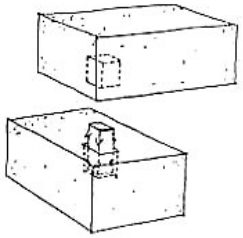
Columns

Columns **are composed of** ***one block*** **of stone in** ***cross-section*****.**

Connection to each other and to other elements:

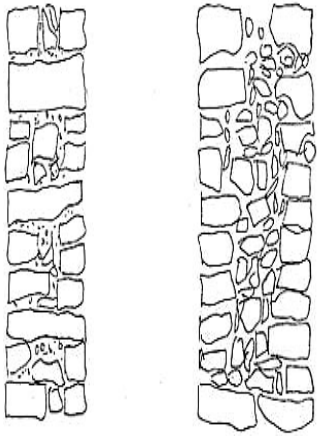
Thick blocks may rest dry laid one over another.

Thin blocks with ***metal connectors*** **laid in lead**



Masonry Components

Piers

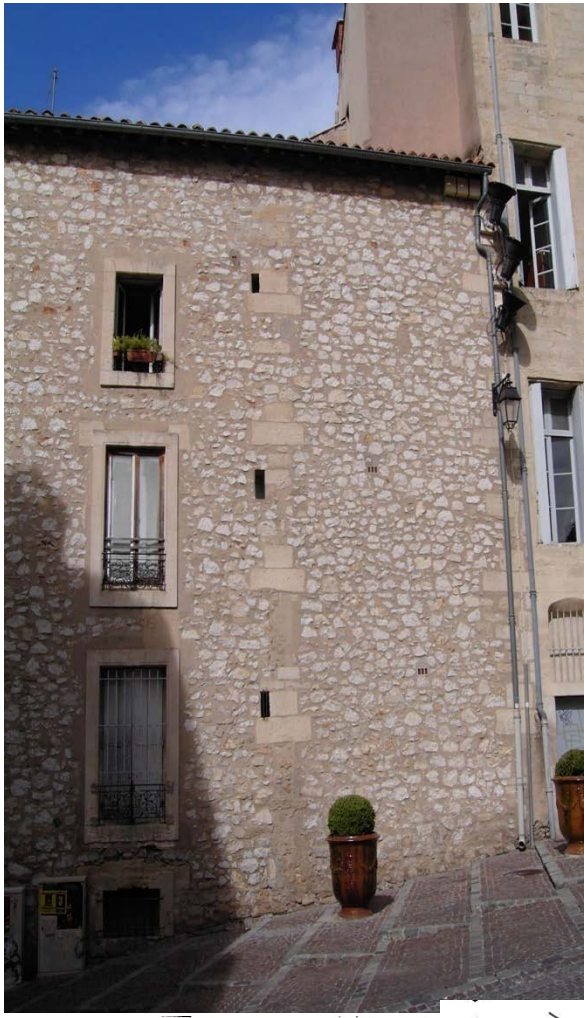


Piers **are wall segments, built of** ***masonry units*** **in rectangular or polygonal cross-section.**

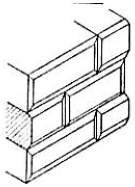
Whatever the form, their behavior is same as a wall.

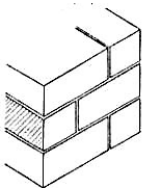
Masonry Components

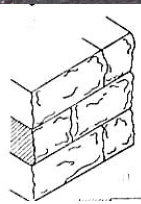
Walls



Masonry walls are constructed from un-coursed rubble, semi-dressed or coursed dressed stones.

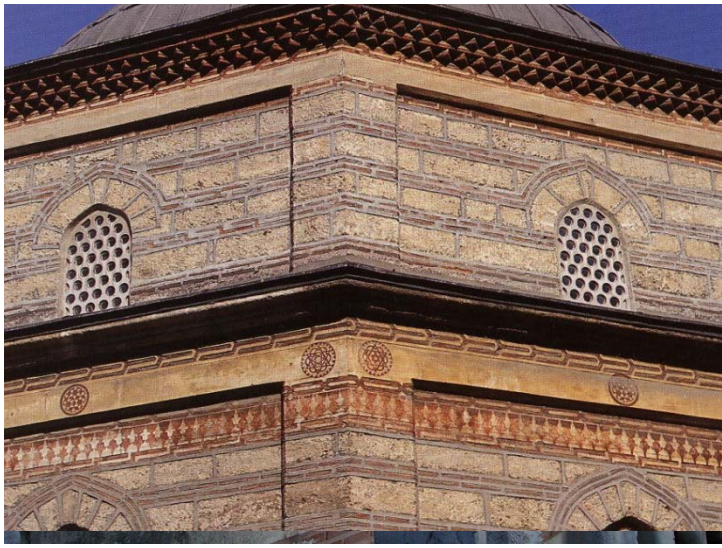






Masonry Components

Walls



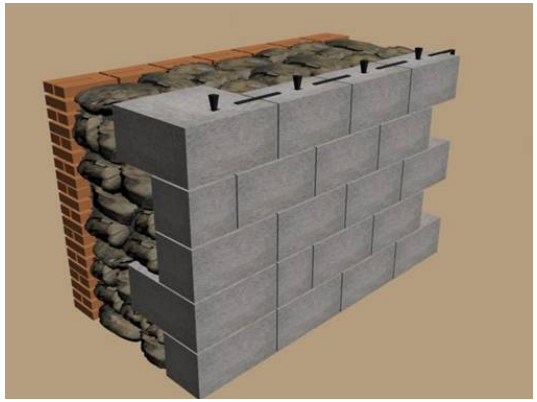
Stone and brick units of **the solid wall** are laid **horizontally.**
When the stone block's strength is weak, the units are laid

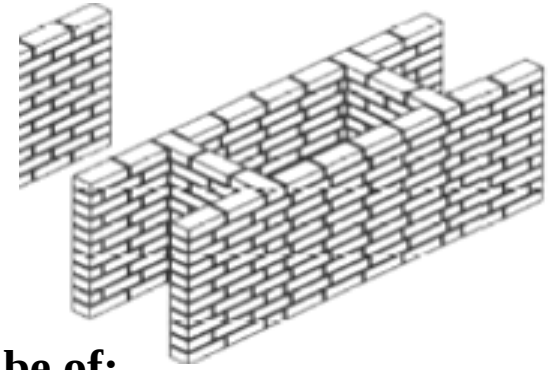
***alternating with brick or**

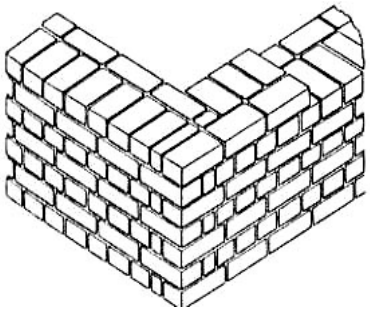
***inclined**

Masonry Components

Walls







A thick masonry wall may be of;

- **Solid wall - one leaf**
- **Cavity wall:**
  - **Leaving the space between the outer faces empty- two leaves**
  - **Filling the space between the outer faces with rubble and mortar- three leaves**

Masonry Components

Walls

The walls of the churches

?

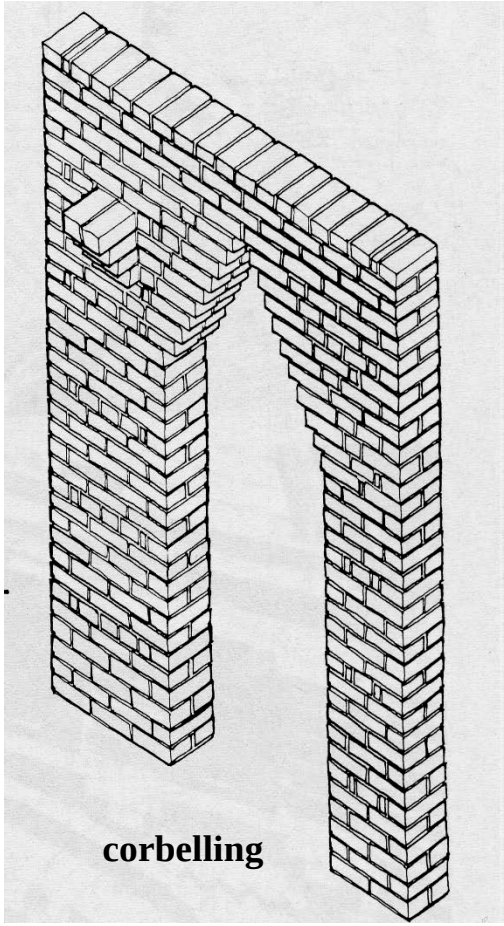
are of three-leaf composed of coral stone facings infilled with rubble and lime mortar

made up of lime concrete veneered by 10 to 15 cm thick coral stone facings

Masonry Components

Walls- Spanning openings

stone lintel



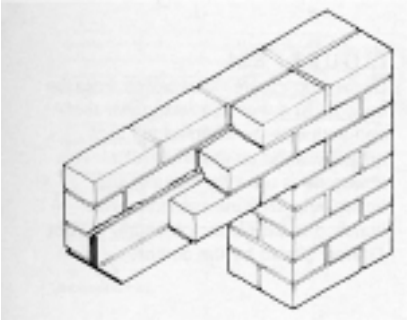
corbelling

arch

In historic masonry construction, the openings for windows and doors were spanned by *lintels* , or *by corbelling*, or by *arches*.

Masonry Components

Walls- Spanning openings



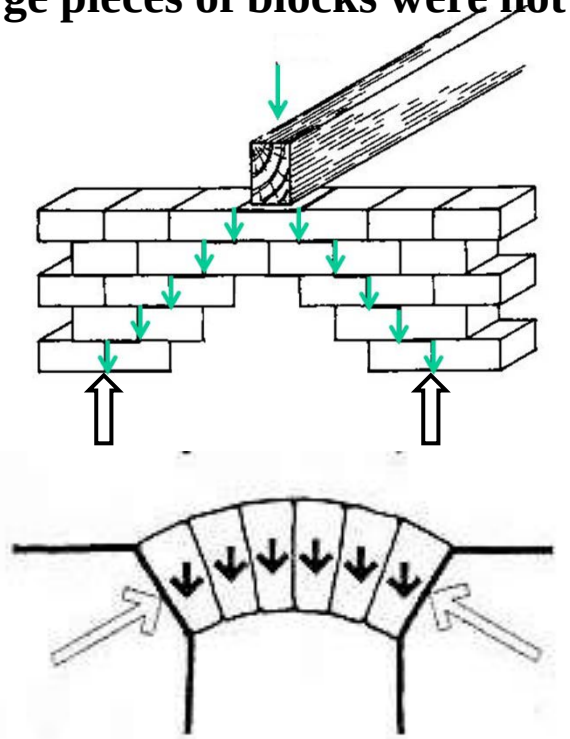
Lintels are horizontal elements of *stone blocks, iron profiles* or *timbe*r that span the door or window openings.

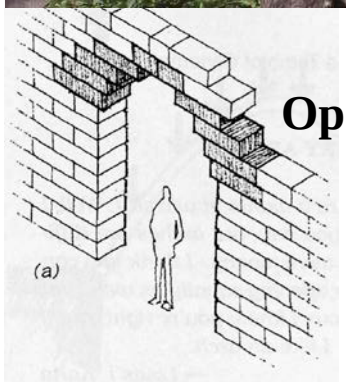
Length of the span depends upon the material's modulus of elasticity.

Masonry Components

Walls- Spanning openings

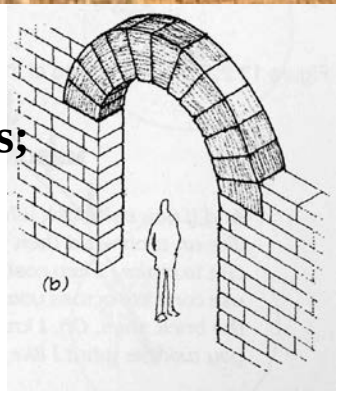
where large pieces of blocks were not obtainable.





Openings are constructed bedding the stone or brick blocks;

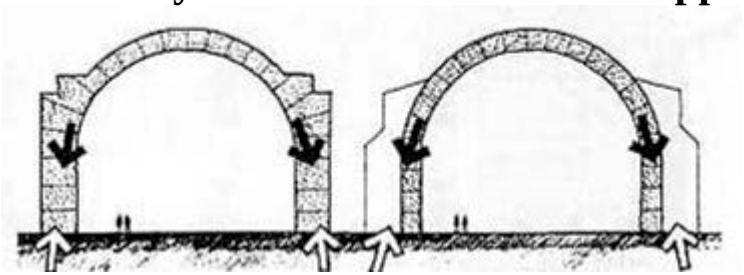
- **horizontally (corbelled/false arch)**
- **radial to the profile curve (free standing/real arch)**

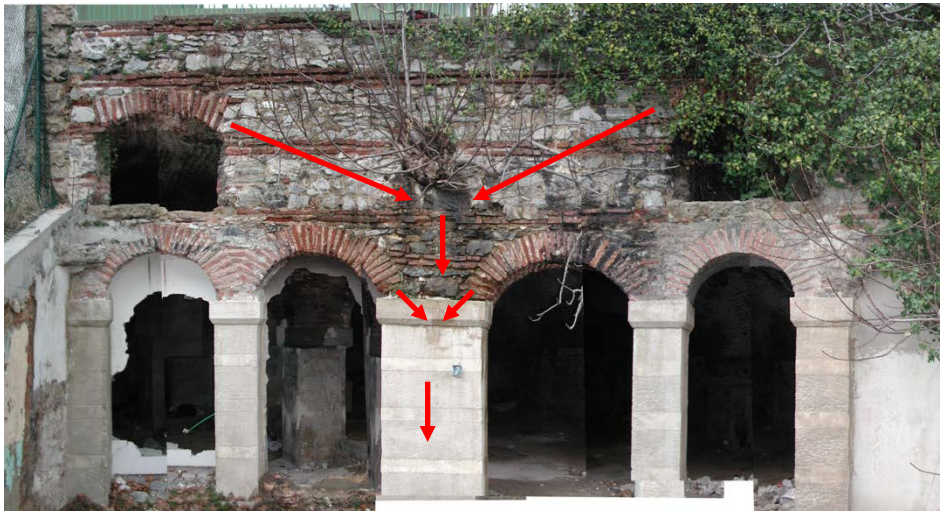


Masonry Components

Walls- Spanning openings

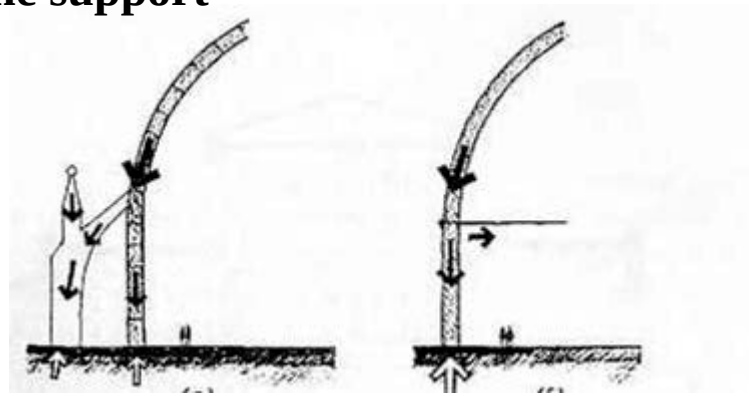
Arch always thrust outwards on its supports.





To take the thrust;

- **an enough *mass of wall* at the supports**
- **an *effective tie* between the supports**
- **another arch with opposing thrust at the support**



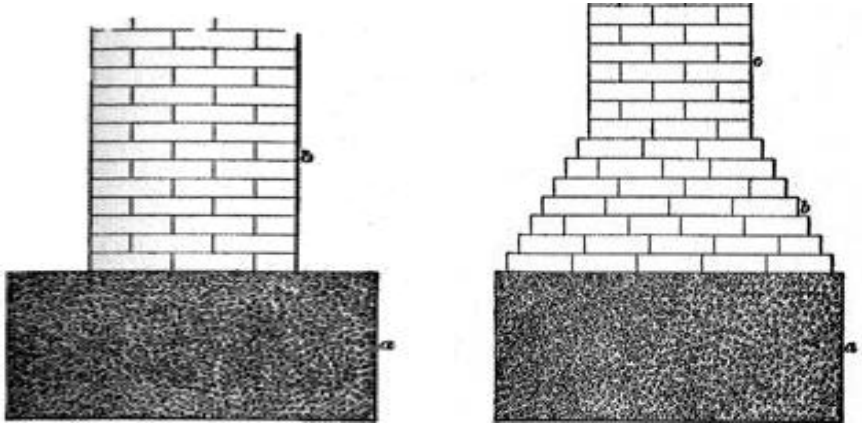
Masonry Components
Foundations

The foundation construction of the walls depended on the type of soil.

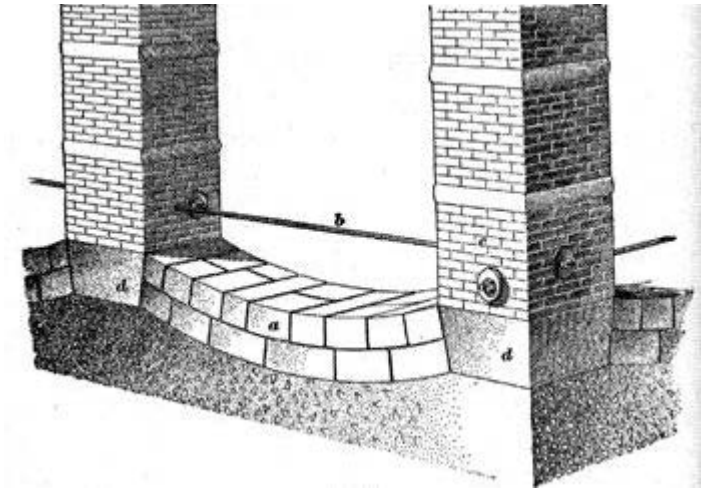
Soft soil needs to be consolidated

Masonry Components
Foundations

The masonry walls are supported by continuous stone foundations;
solid or three leaved.

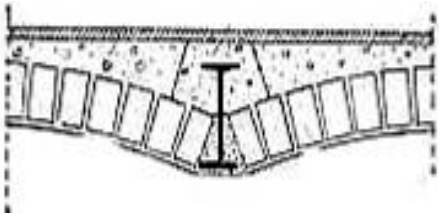


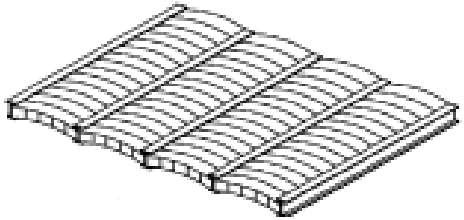
The foundations of **thick walls** → vertical wall
thin walls → widened into a footing
thin walls (closely spaced) → inverted vaults



Masonry Components

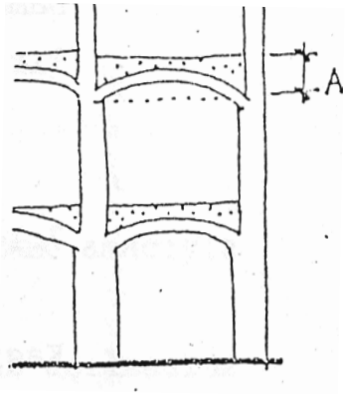
Floors & Roof

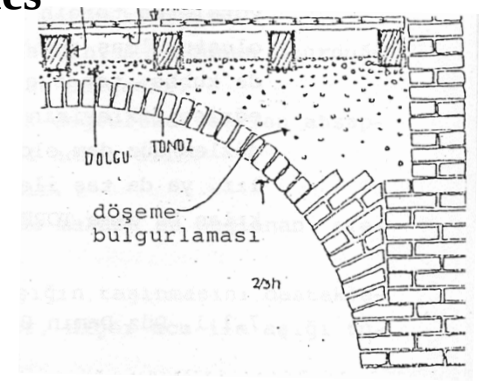




Floors and roof on masonry walls can be framed with;

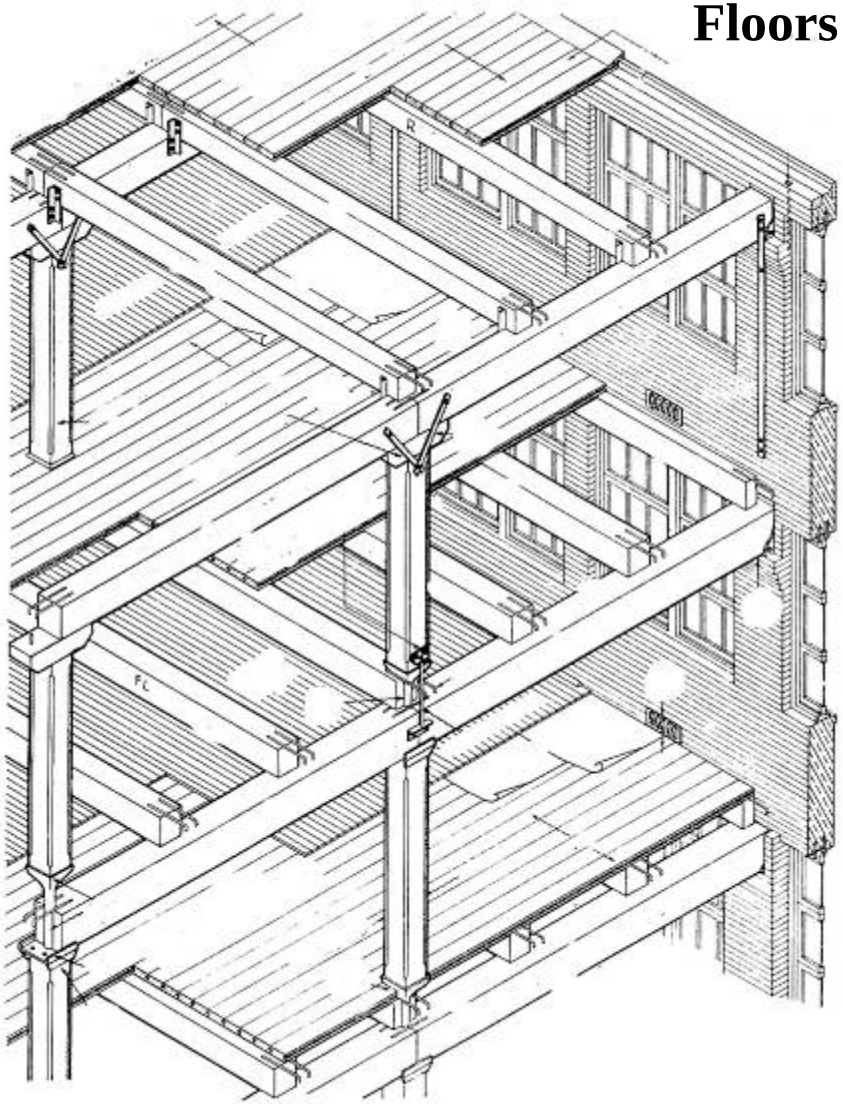
- **wood beams, joists and rafters**
- **timber or steel jack arch**
- **lintel arches**
- **vaults and domes**



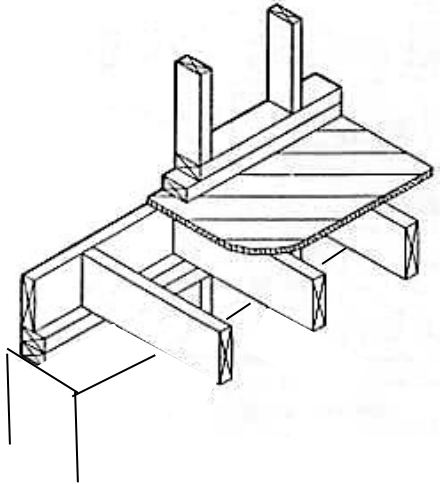


Masonry Components

Floors and Roof



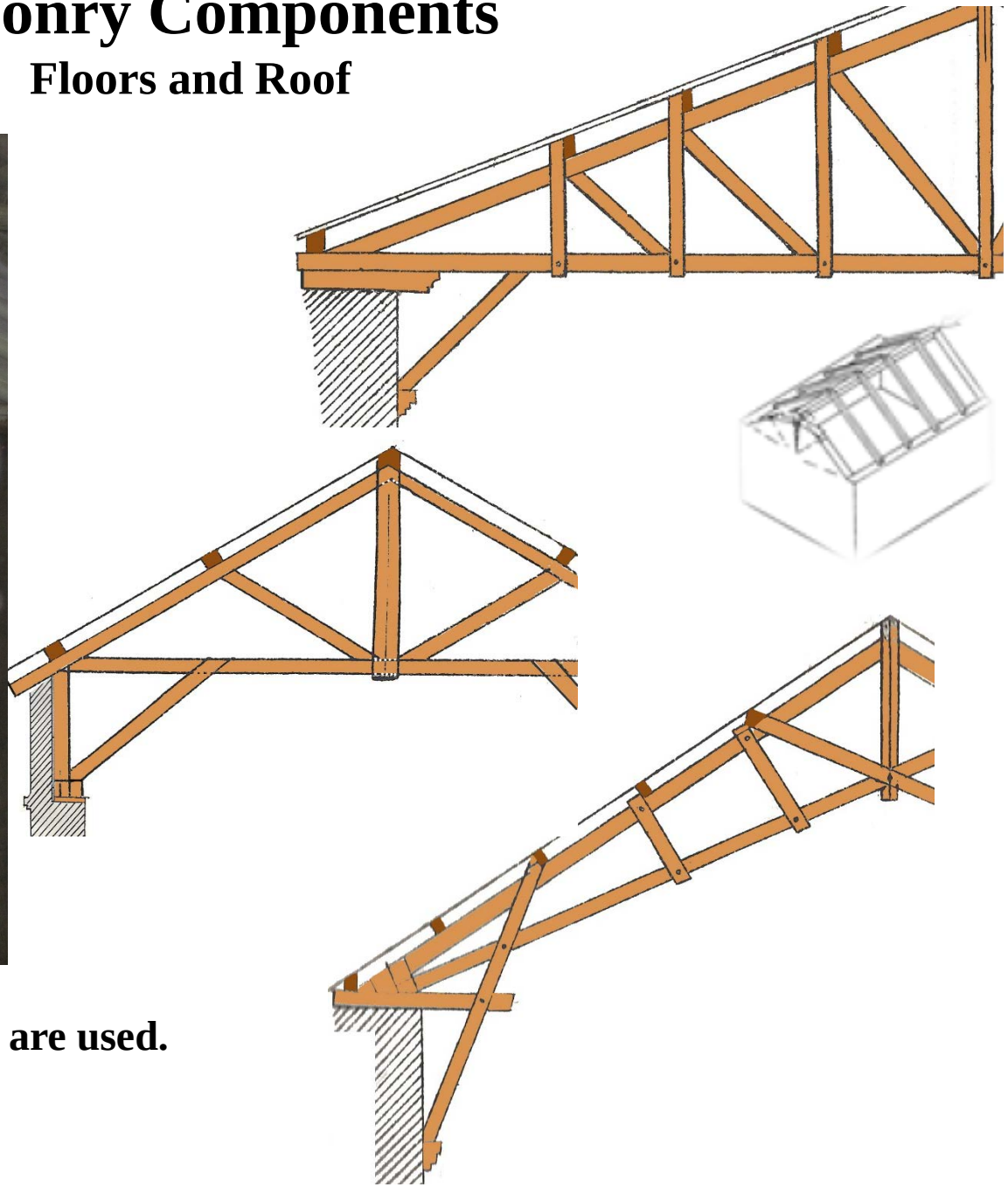
Wood joists and rafters act as a one-way system.



Placing the timber planks diagonally improve its stability

Masonry Components

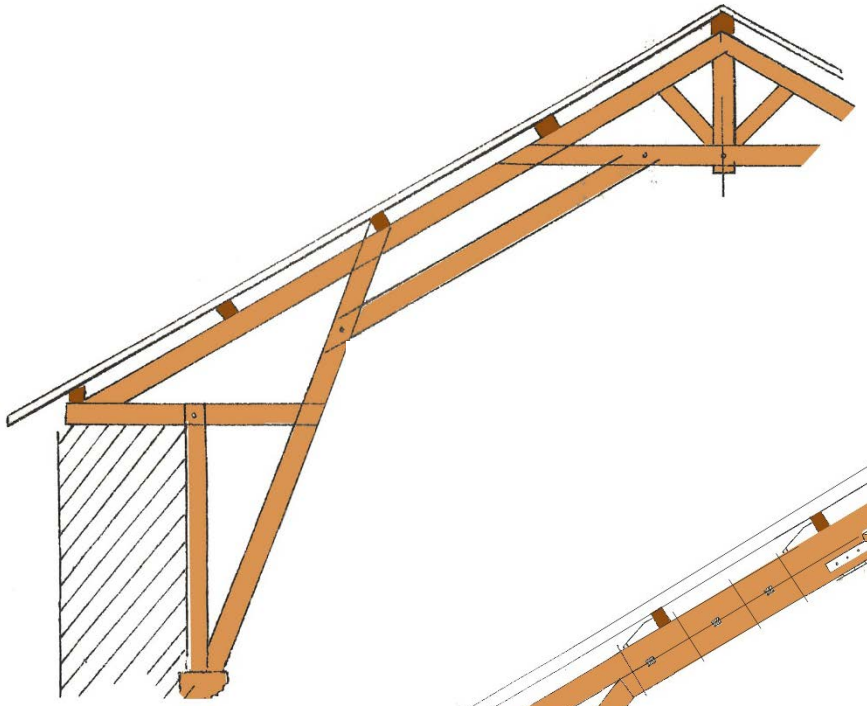
Floors and Roof

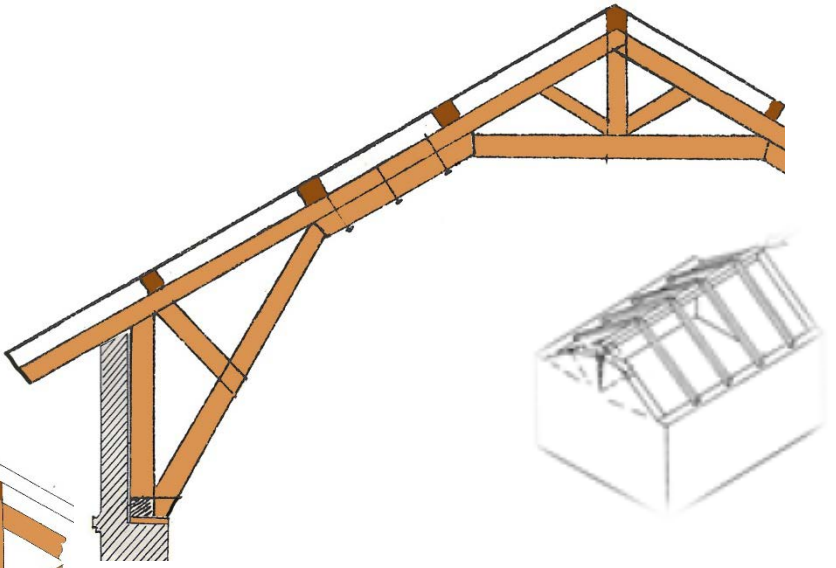


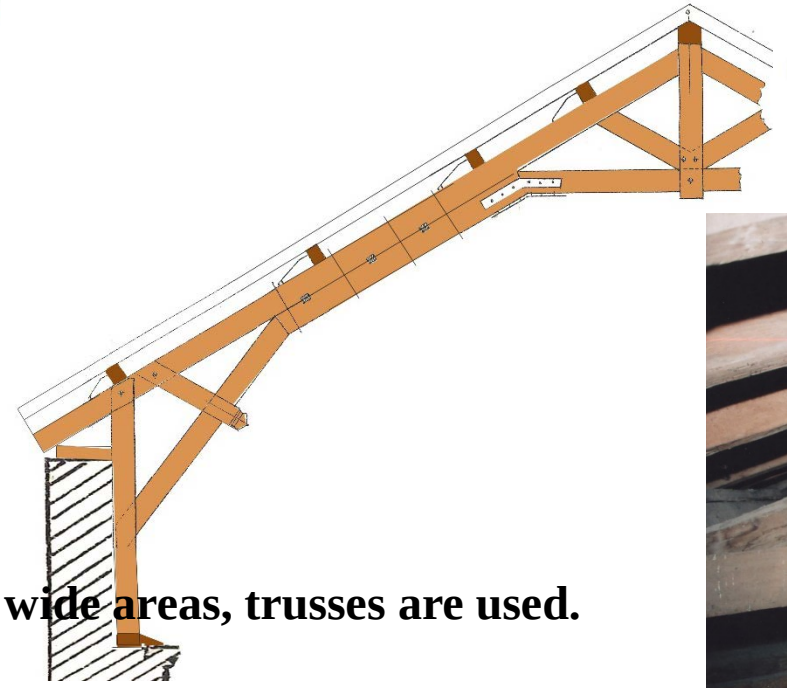
In spanning wide areas, trusses are used.

Masonry Components

Floors and Roof



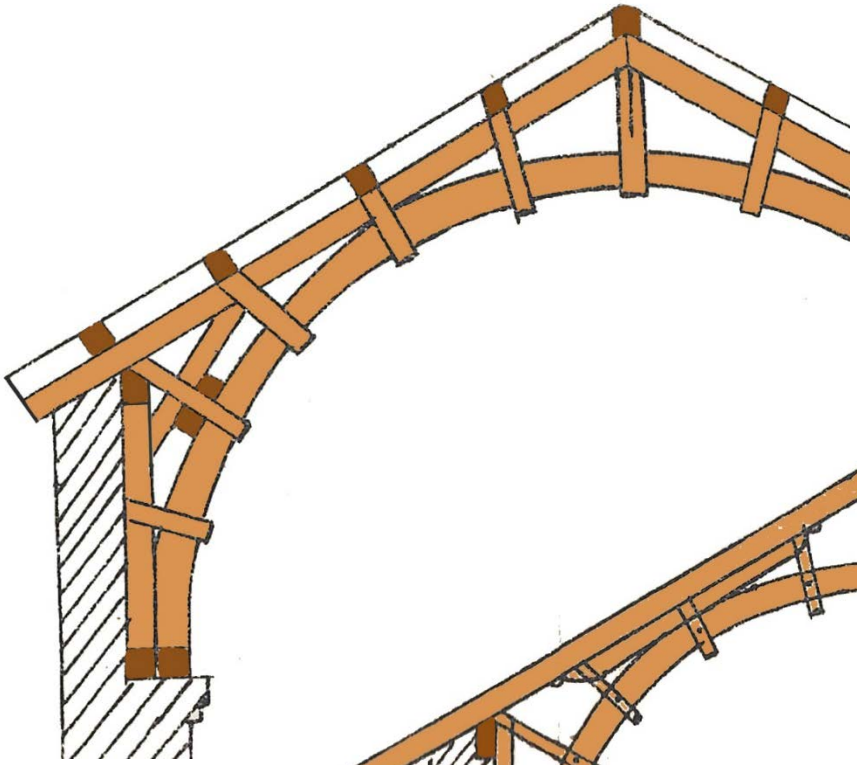


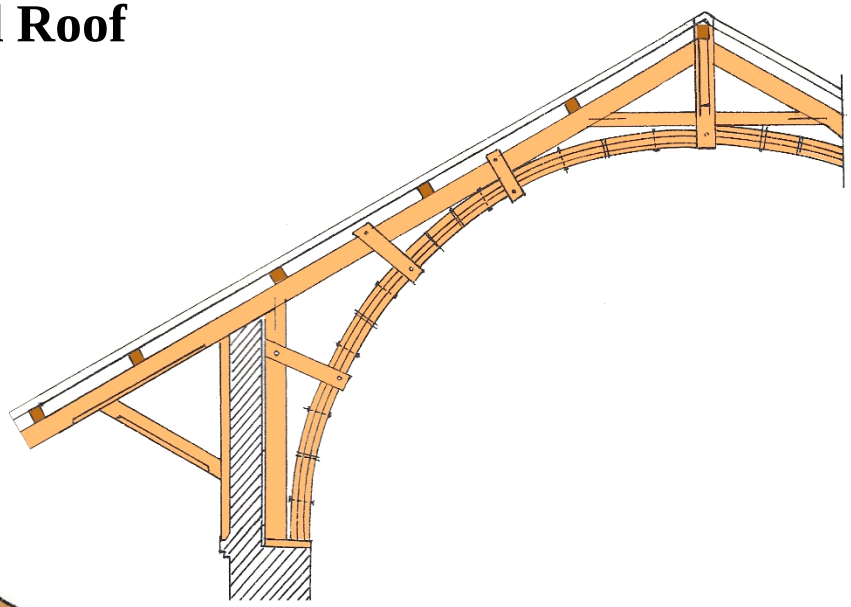


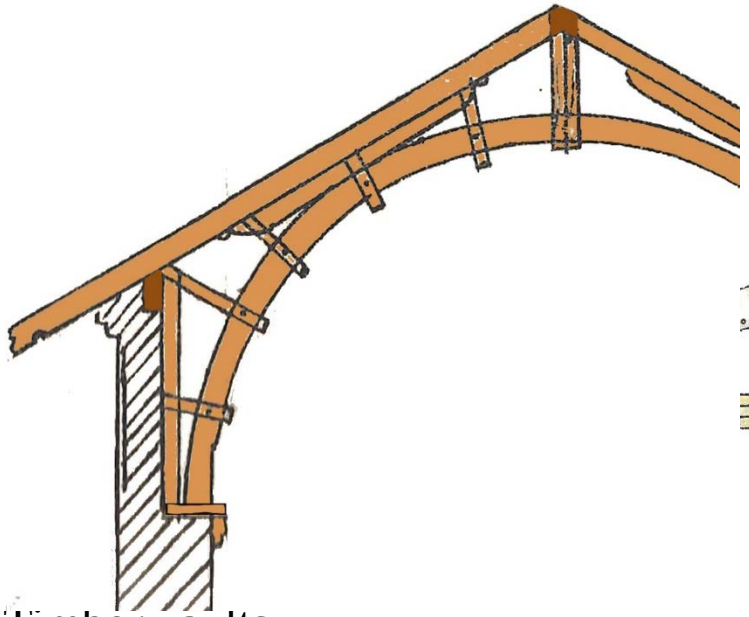
In spanning wide areas, trusses are used.

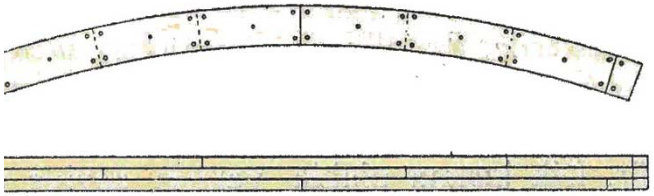
Masonry Components

Floors and Roof









Timber vaults

Masonry Components

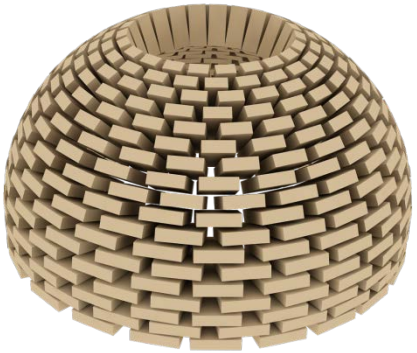
Floors and Roof

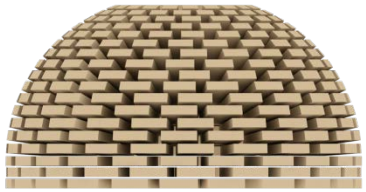
In spanning an area, stone lintels in small spans and brick lintel (flat) arches in large spans formed the rib where the masonry block or a vault could be laid in between.

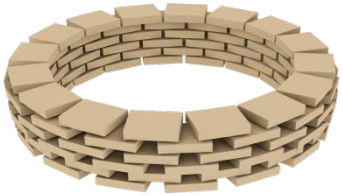
Masonry Components

Vaults & Domes

Radially laid units





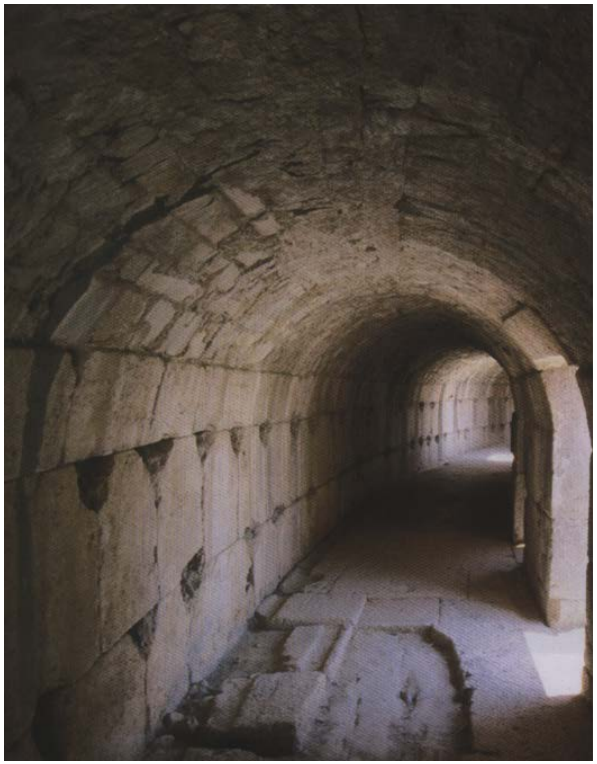


Corbelled units

Masonry Components

Vaults & Domes

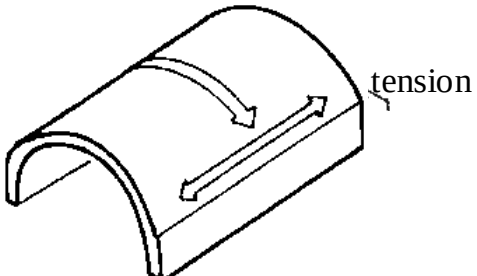
Some doubly curved vaults and domes may contain tension .

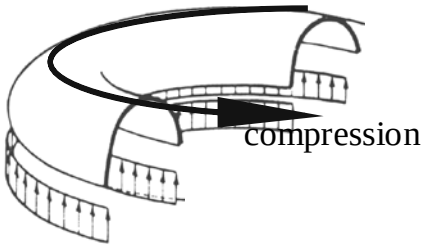


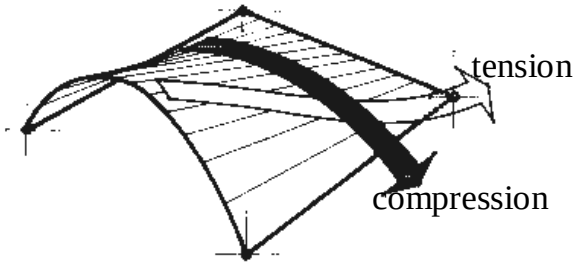
Cylindrical Vault

Torus Vault

Conoid Vault

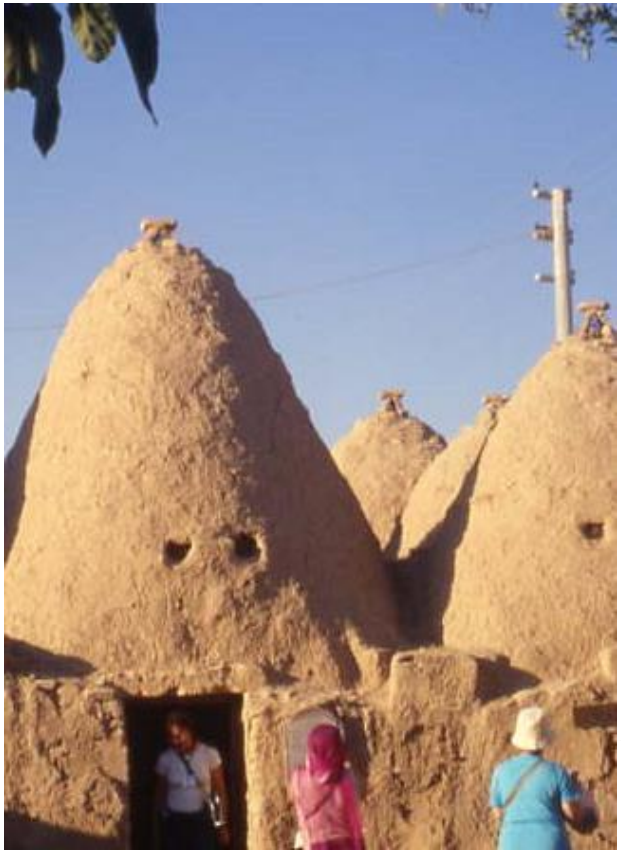


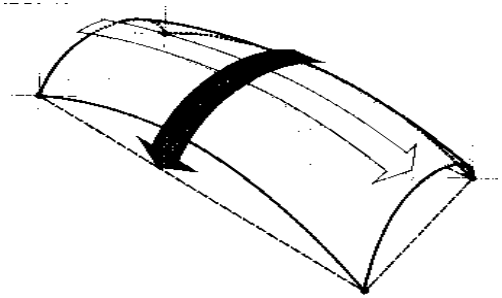




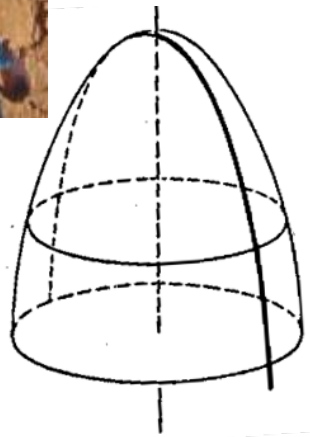
Masonry Components

Vaults & Domes



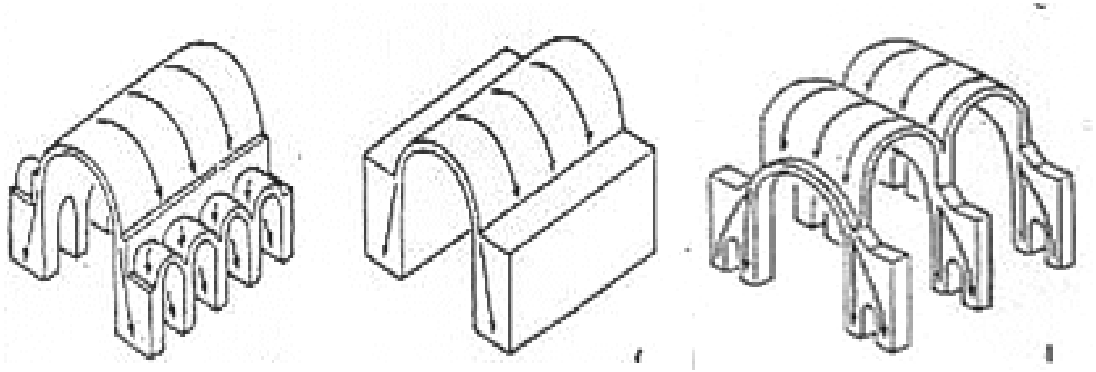


Principle stresses in *elliptic paraboloid vault* and *paraboloid dome* are compression

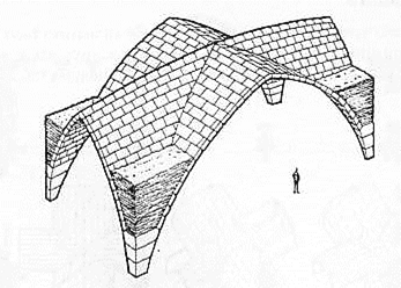


Masonry Components

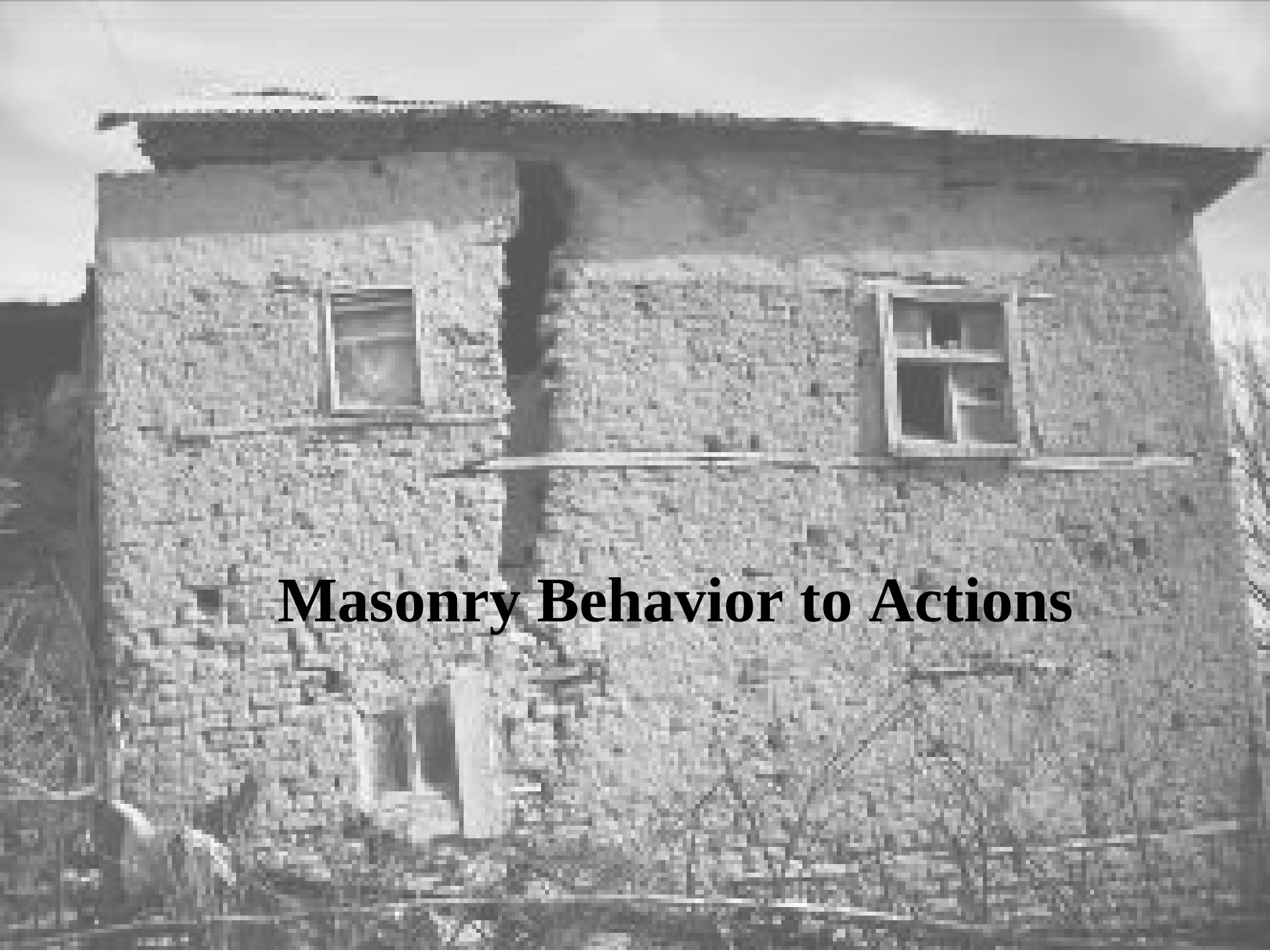
Vaults & Domes



To exterminate the tension in the surface;



- **an enough *mass of wall* at the supports**
- ***vaults perpendicular to the surface***
- ***make an opening* at the surface *with a vault or an arch***
- ***make corbelled transition element***



Masonry Behavior to Actions

Behavior of Masonry Components

Resistance to the imposed loads depends on;

- **the strength and stiffness of the material used**
- **how the masonry units are joined together (dry, metal connectors, mortar)**
- **the geometrical configuration of the structure**

Behavior of Masonry Components

Cracks indicate the presence of possible weak zones

Cracks appear when the imposed loads exceed the tensile capacity of masonry

The cracks;

- **initially perpendicular to the tension lines**
- **then progress slightly different directions**

These defects or imperfections can influence the load bearing capacity and durability

Behavior of Masonry Components

Columns

Columns - primarily carry gravity loads

Horizontal forces

– rocking of the column

– sliding of the blocks

Thick blocks - high friction between the blocks prevents sliding.

Behavior of Masonry Components

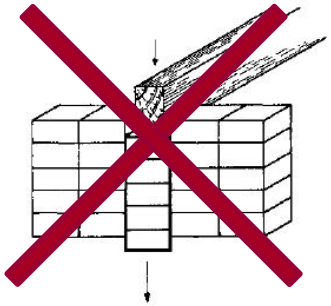
Columns

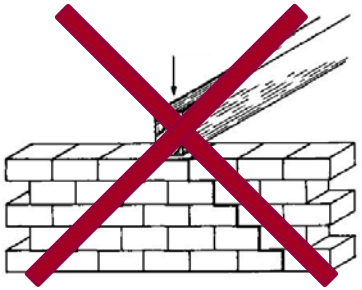
Failure - by relative rotation of the blocks

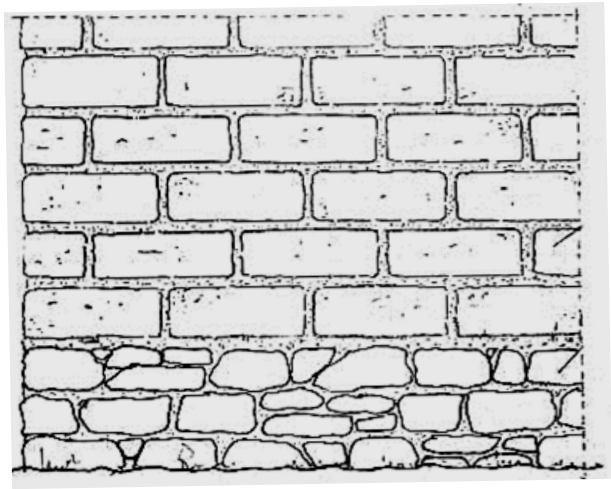
Behavior of Masonry Components

Walls

Behavior of a masonry Wall depends on the configuration of its units. For proper configuration;
*** The joints shouldn't be one over another,**
*** the joints shouldn't be at 45^0 along the Wall height**







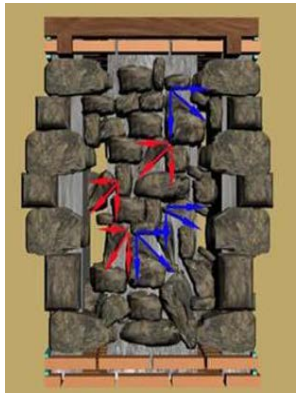
Behavior of Masonry Components

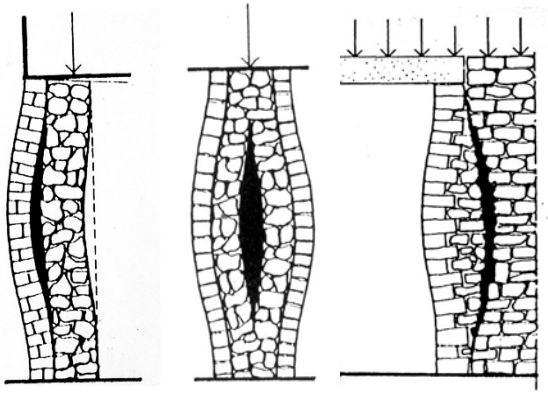
Walls: Delamination of wall wythes

Due to the **different natural frequencies** of the material used, vertical component of EQ ground shaking can cause **internal cracks** delaminating the wall wythes.

In rubble filled walls, the inner core might give thrust to the outer leaves.

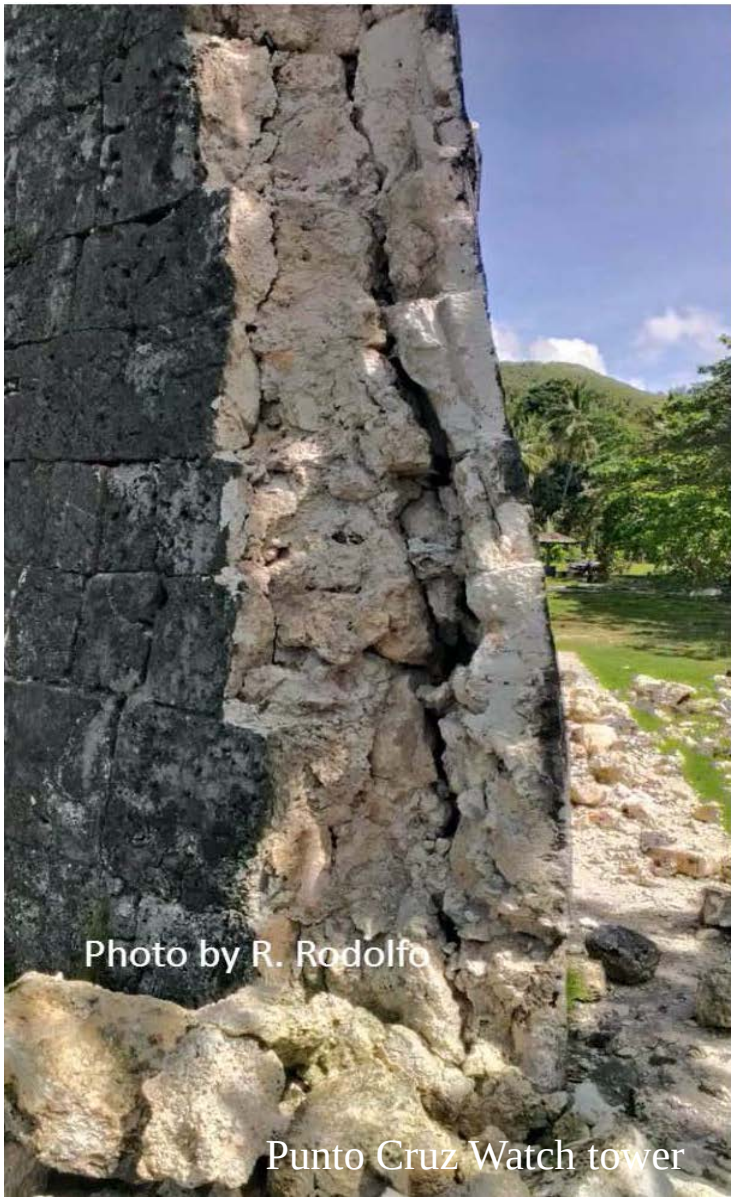
Out-of-plane displacement of a wall may cause **overall collapse of the building.**





Behavior of Masonry Components

Walls: Delamination of wall wythes



Punto Cruz Watch tower

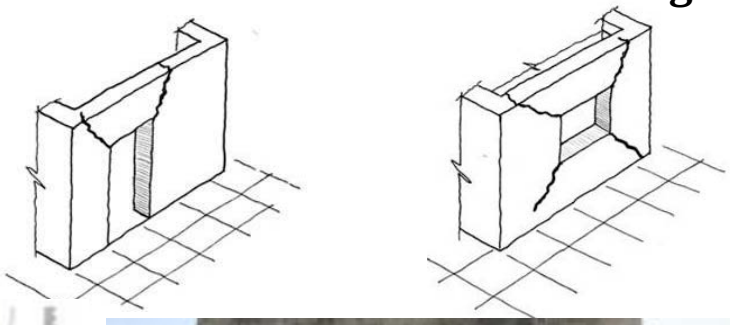
Baclayon church

Photo by Stephen Kelly

Behavior of Masonry Components

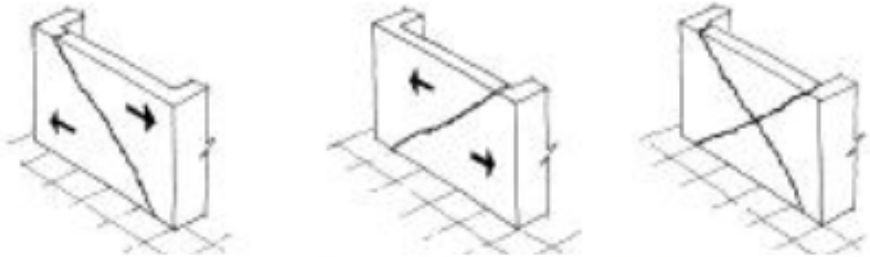
Walls: In-Plane Shear Cracking

In-plane EQ forces generate shear cracks in areas of high stress concentrations



As cracks develop, the dynamic response characteristics change;

- **the fundamental frequency decreases**
- **the Wall displacements increase**



Behavior of Masonry Components

Walls: In-Plane Shear Cracking

As cracks intersect each other, **independent irregularly shaped Wall segments** form on the surface, and **cracks become substantial.**

Broken segments on the *thin walls* are susceptible to slide out

Behavior of Masonry Components

Walls: In-Plane Shear Cracking

Daius Church

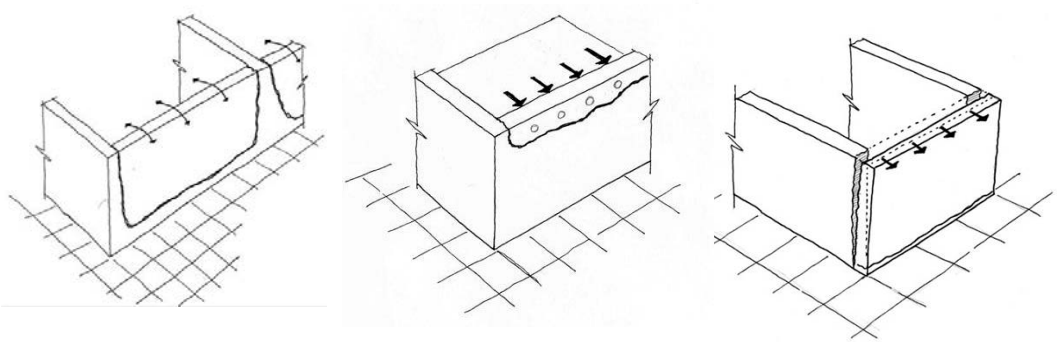
Broken segments on the *thin walls* are susceptible to slide out

Behavior of Masonry Components

Walls: Out-of-Plane Cracking

Out-of-plane displacement of a Wall results with;

- **tilting developing horizontal cracks**
- **separation of the outer leaves of two or three leaved wall**
- **vertical cracks at wall intersections**
- **overturning of the walls**



Behavior of Masonry Components

Walls: Out-of-Plane Cracking

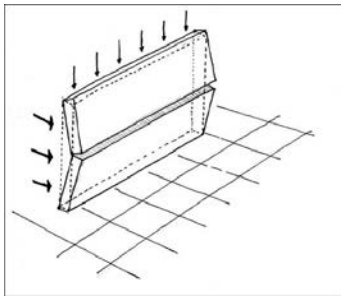
Loay church

Loay church

Loboc church

Behavior of Masonry Components

Walls: Out-of-Plane Cracking

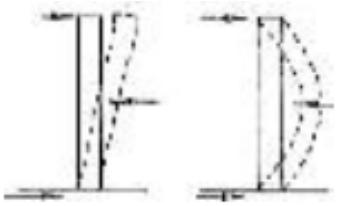


Out-of-plane displacement may lead to collapse when masonry walls are not properly connected to;

- **the floors and roof**
- **The transverse walls** (interior or exterior)

Behavior of Masonry Componen

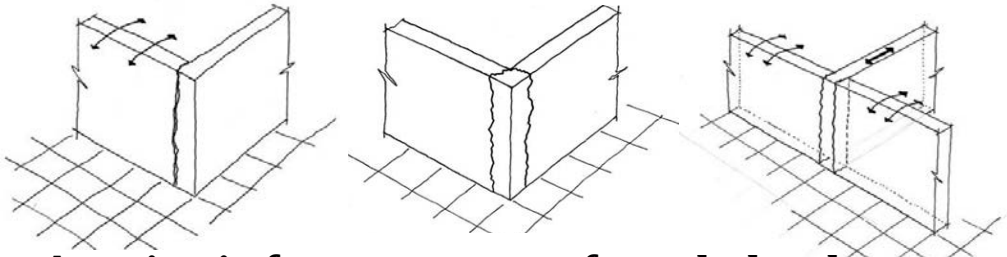
Walls: Out-of-Plane Cracking



Non-load bearing walls, especially gable walls collapse first.

Behavior of Masonry Components

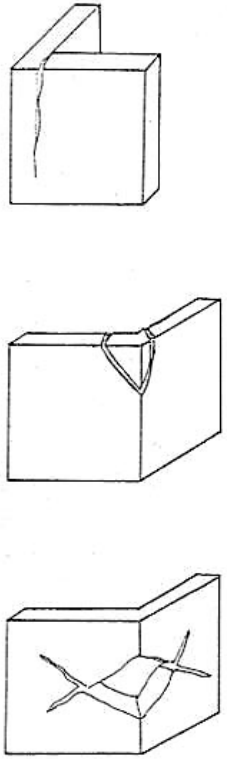
Walls: Separation at the intersections



As seismic forces are transferred, development of tensile and shear stresses make wall intersections vulnerable.

Behavior of Masonry Components

Walls: Separation at the intersections



Walls not properly connected to the transverse walls separate / collapse at the corners.

Behavior of Masonry Components

Floors & Roof

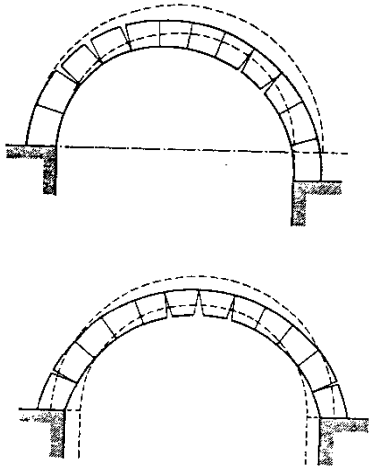
Collapse of floor / roof is a result of separation of the walls

Behavior of Masonry Components

Floors & Roof

Behavior of Masonry Components

Floors & Roof



Arches and vaults collapse when the supporting walls lose the ability to resist exerted loads.

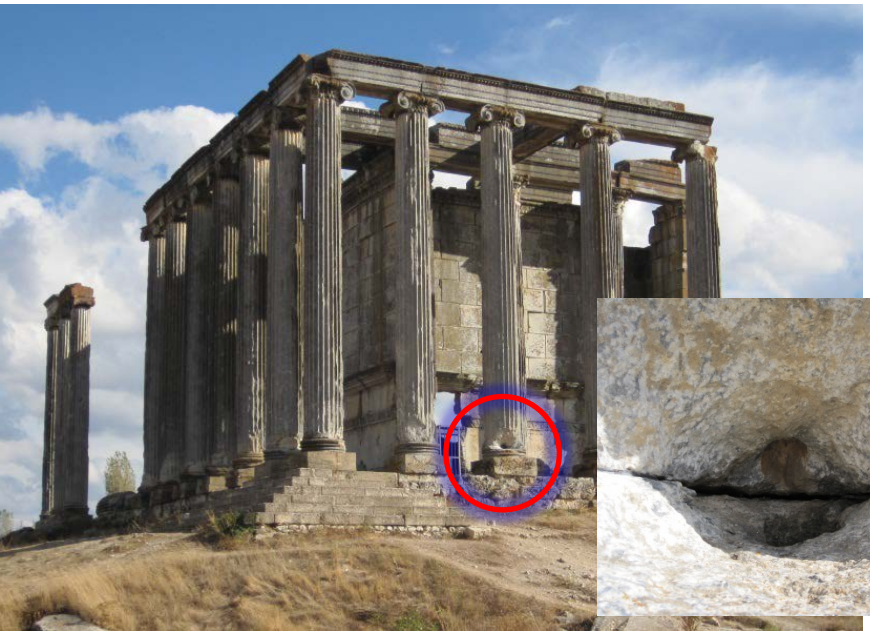
To Improve Earthquake Performance

To Improve Earthquake Performance

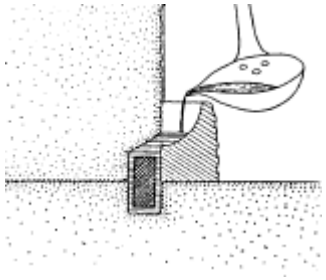
- Avoiding the restriction of unit movement
- Enhancing the integrity of the building
- Providing seismic joints at different weighing parts
- Preventing the Resonance effect
- Avoiding the actions that will weaken the masonry

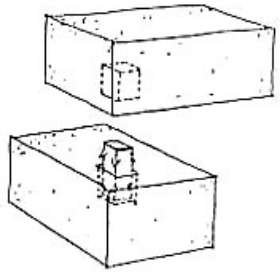
To Improve Earthquake Performance

Avoid restriction of the units' movement



Connection of columns to each other and to other elements with *metal connectors* laid in lead lets the movement of the units.

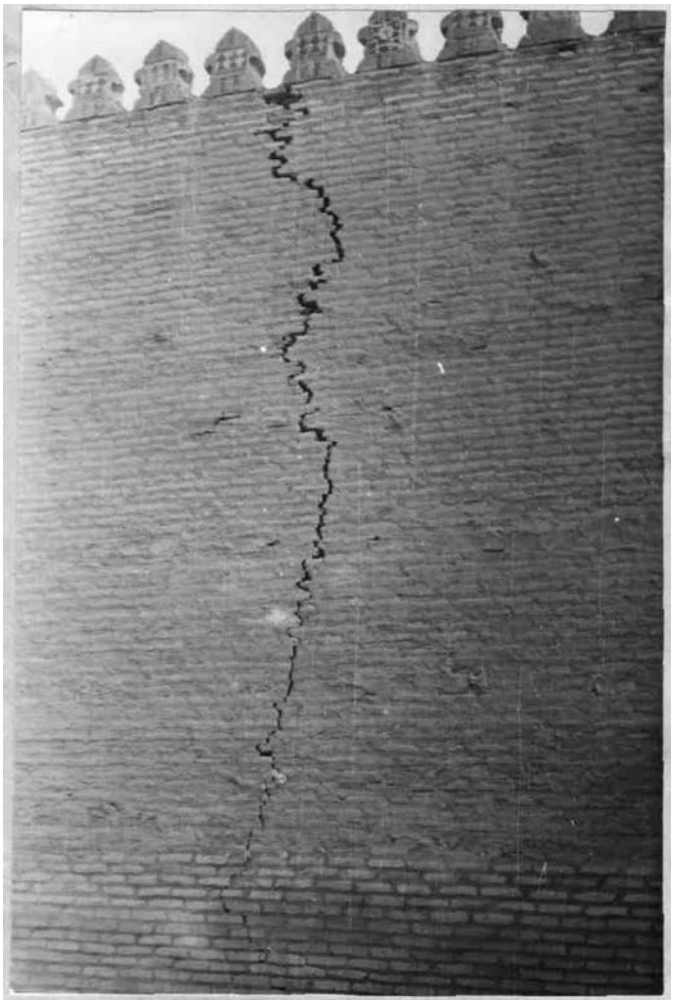


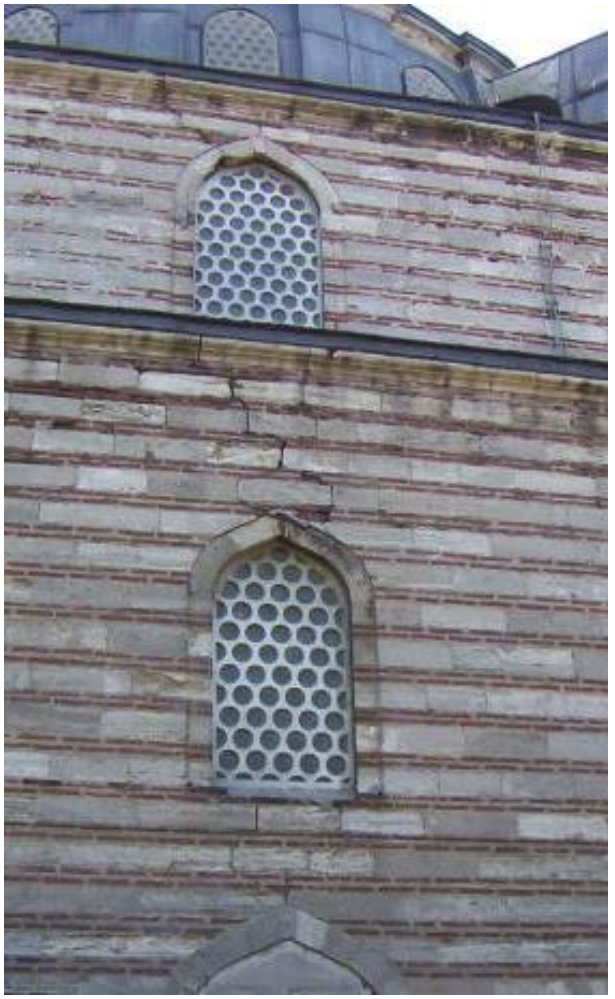


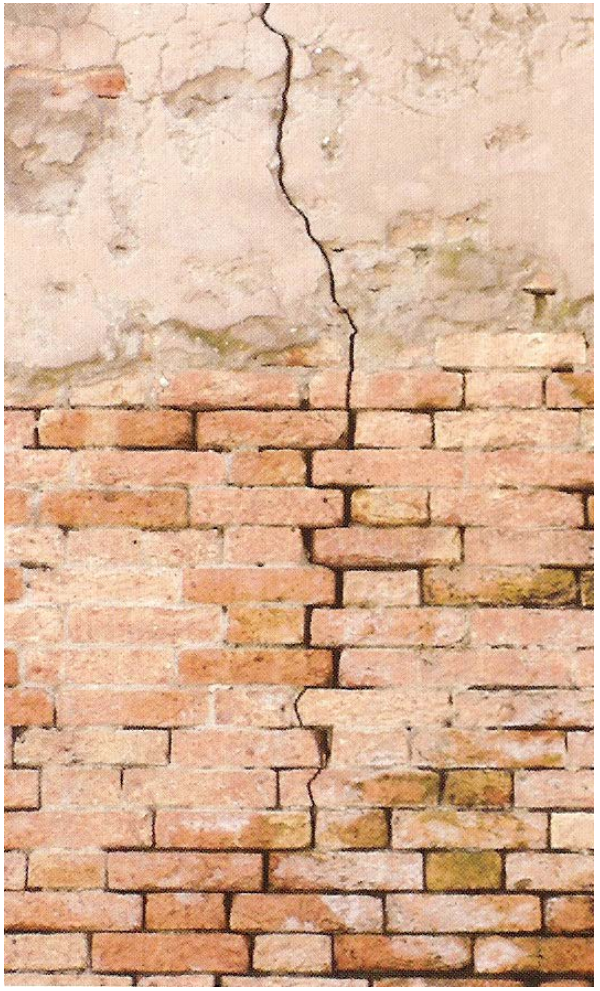
***Metal rings* - prevent sliding and collapse.**

To Improve Earthquake Performance

Avoid restriction of the units' movement







Using weak rather than strong mortar lets sliding along the bed joints dissipating energy.

To Improve Earthquake Performance

Avoid restriction of the units' movement

Restriction of deformations usually appear as a result of wrong interventions.

To Improve Earthquake Performance

Enhancing the integrity of the building

Stability is directly related to the

- **absolute thickness and**
- **slenderness (h/t)ratio**

of the wall.

The studies made by Yildiz Technical University, Turkey and Tabriz University, Iran after several EQs show that

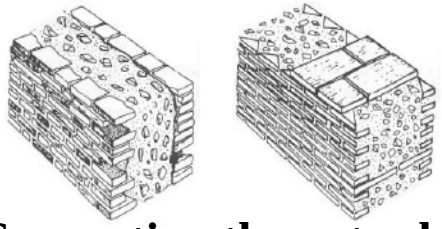
Slenderness ratio not exceeding;

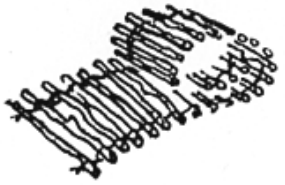
***18 in limestone walls,**
***10 in brick walls**
***5 in adobe walls**

behaved well to horizontal loads.

Enhancing the integrity of the building

Walls- Lacing (Tie bands)





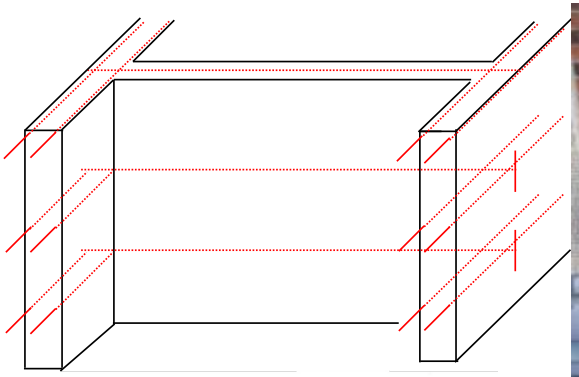
Connecting the outer leaves of the Wall
by suitable lacing (tie bands) at certain intervals,

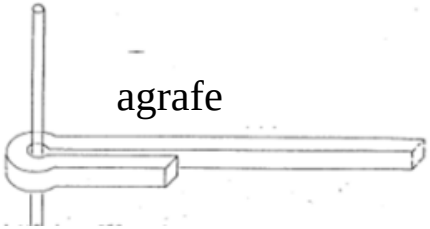
- **limits the support movements**
- **prevents wall bulging under gravity loads**
- **reduces the slenderness ratio of the wall**
- **prevents crack initiation at another location**

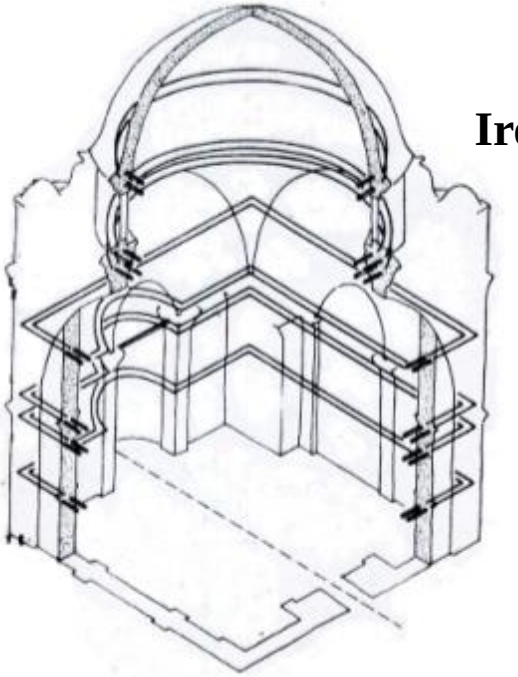
is very effective in enhancing the integrity of the building

Enhancing the integrity of the building

Walls- Lacing (Tie bands)

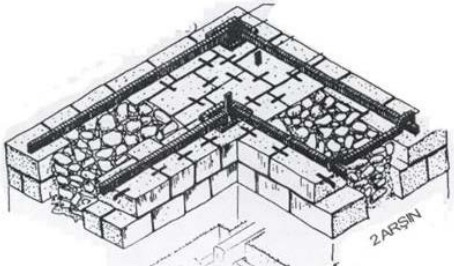






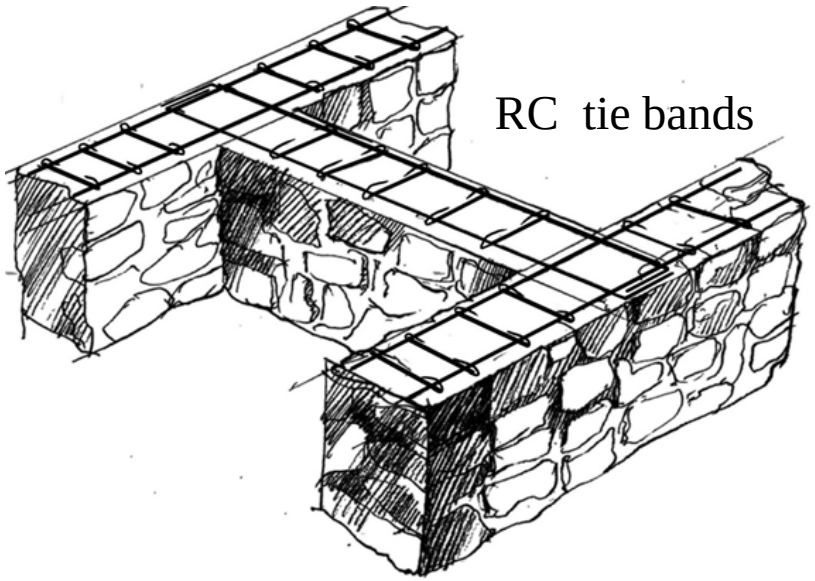
Iron or Copper tie bands in the form of

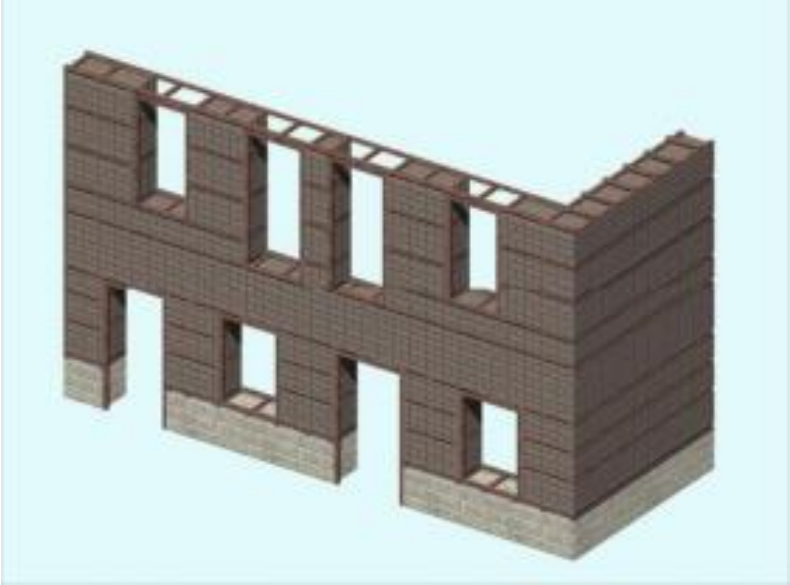
- **Agrafe or**
- **Clevis anchored in lead**



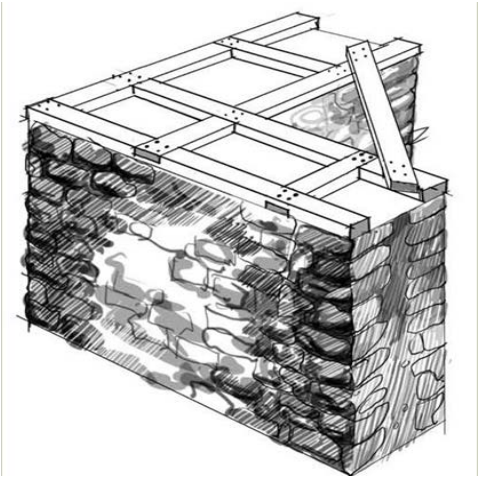
Enhancing the integrity of the building

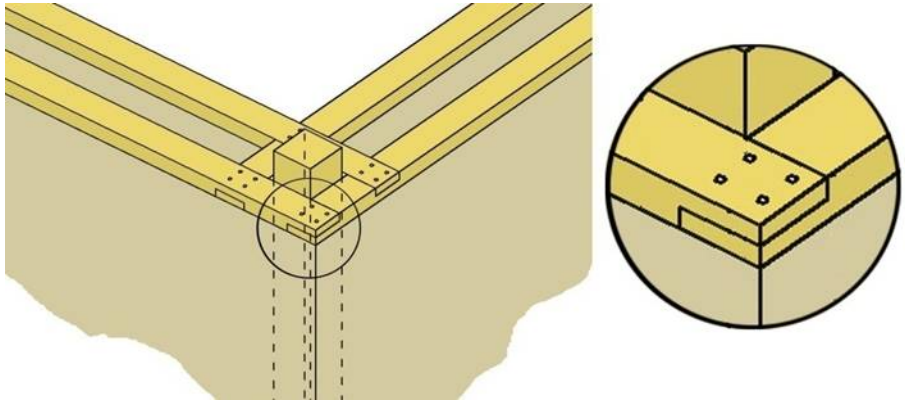
Walls- Lacing (Tie bands)





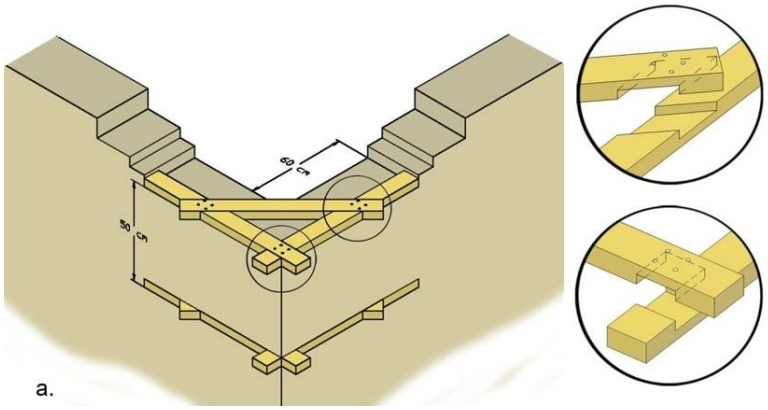
Timber tie bands



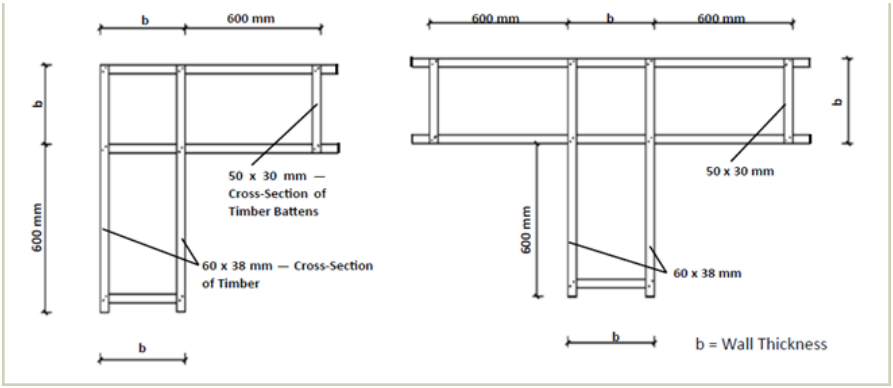


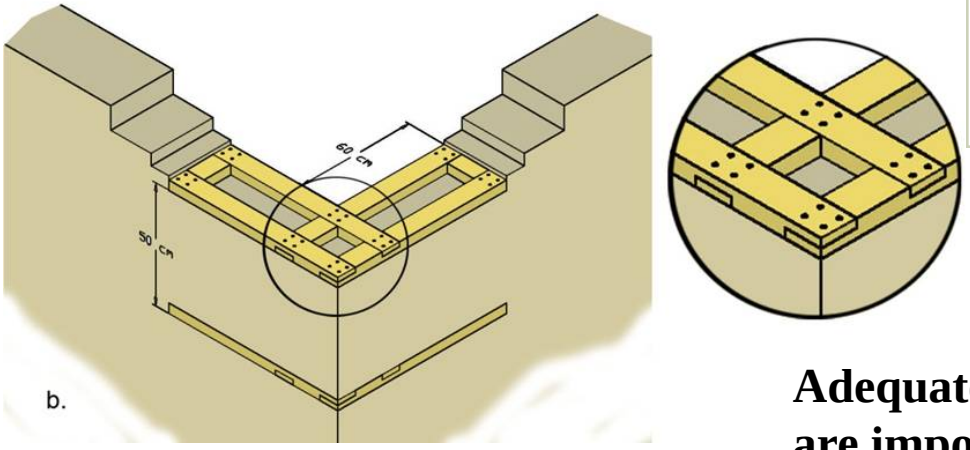
Enhancing the integrity of the building

Walls- Strengthening the intersections



Intersections of the wall has to be strengthened to ensure the integrity of the building.

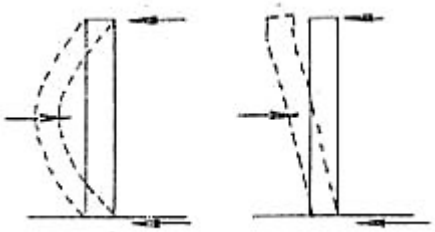




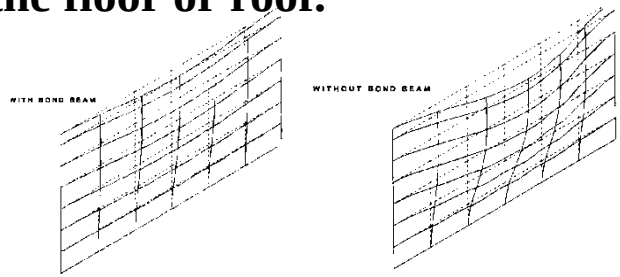
Adequate connections between intersecting walls are important to prevent wall separation.

Enhancing the integrity of the building

Walls- Bond beams



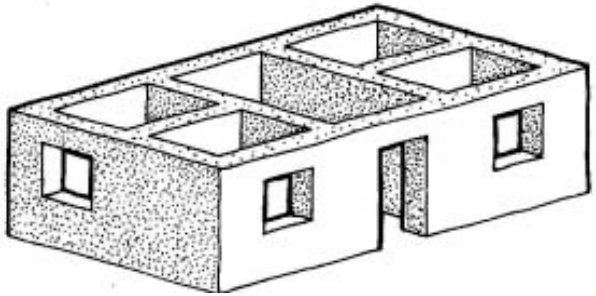
Seismic Performance of URM depends on how well the walls are tied together and anchored to the floor or roof.



Providing restraints as bond beam at the top of the walls will be very effective in enhancing structural integrity.

Enhancing the integrity of the building

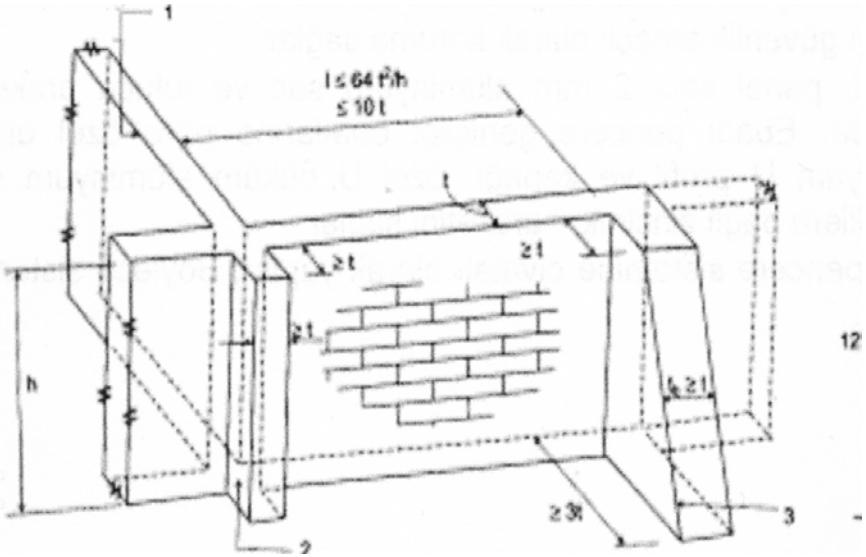
Walls- Vertical Supports



To provide vertical supports to long walls;

- **cross walls and intersecting walls**
- **vertical ties as timber or stone**
- **buttresses**

at regular intervals.



Enhancing the integrity of the building

Walls- Vertical Supports

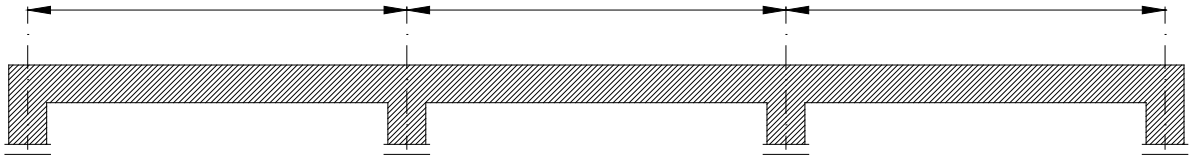
Walls having unsupported wall length:

- $\ell \leq 9t$ in adobe construction
- $\ell \leq 18t$ in brick construction
- $\ell \leq 30t$ in limestone construction

&

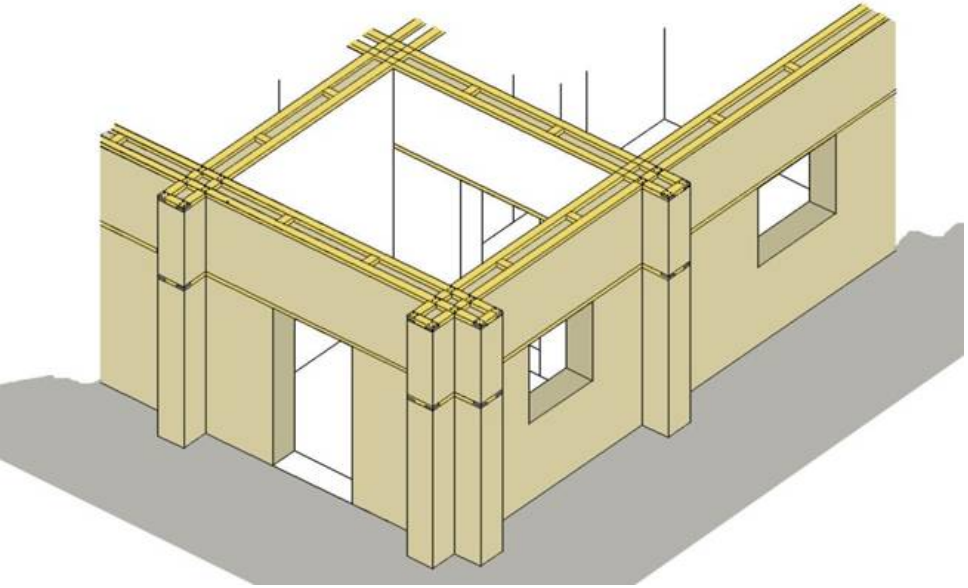
$$\ell \leq f_c\, t^2/h$$

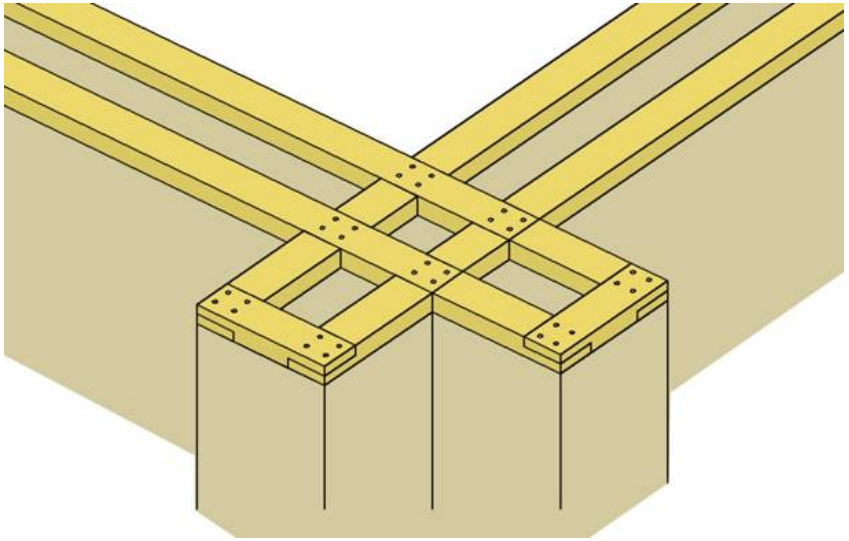
observed to behave well under seismic actions.



Enhancing the integrity of the building

Walls- Vertical Supports

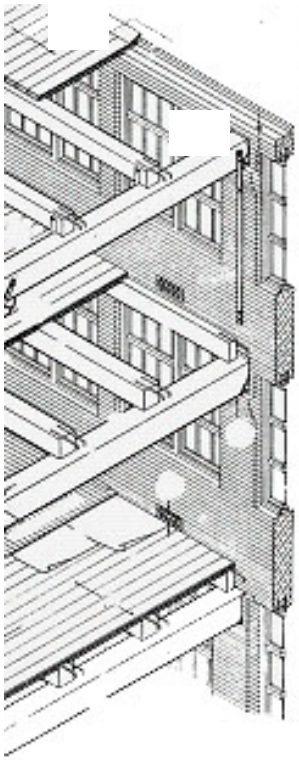


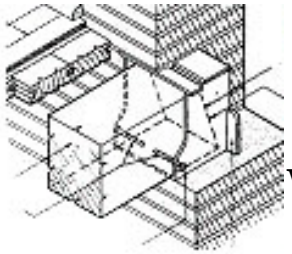


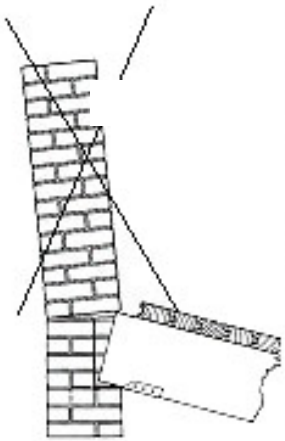
Adequate connections between the walls and vertical supports are important for seismic safety

Enhancing the integrity of the building

Floors & Roof

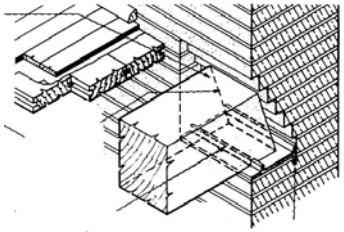


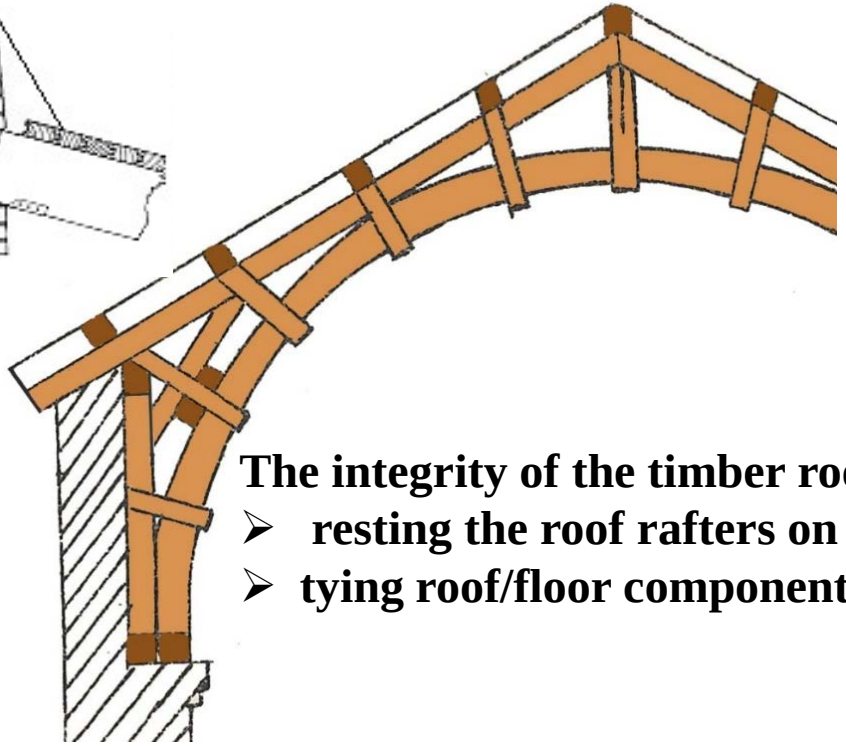




Wooden beams, joists and rafters on masonry walls need to be;

- **protected from the moisture of masonry,**
- **fixed properly to the wall,**
- **rotate without damaging the wall.**





The integrity of the timber roof/floor can be improved by

- **resting the roof rafters on bond beams of the Wall**
- **tying roof/floor components properly**

Masonry Components

Vaults & Domes

It is important to identify

Geometry:

- *cylinderical, conical, eliptic paraboloidal, torus or konoidal*
- *groin vault, cross vault,* or *ribbed vaulted dome*
- *spherical, paraboloidal or elipsoidal dome*

Lay of the units:

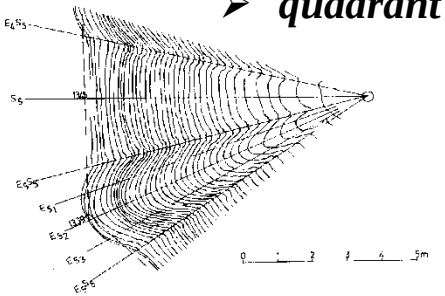
- *corbelled*
- *radial*

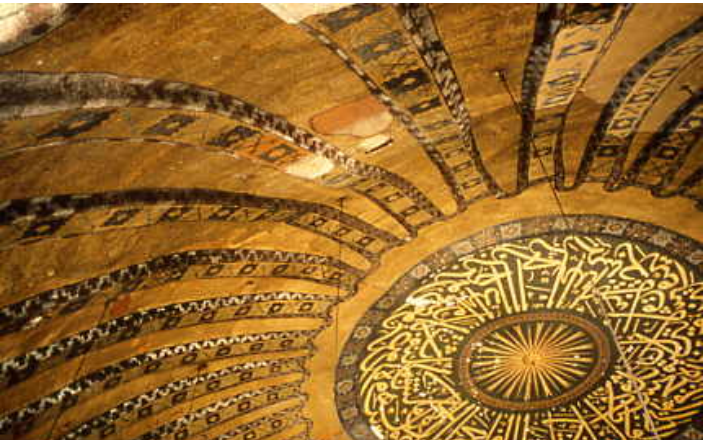
Supporting System:

- *arches*
- *vaults*
- *quadrant*

Transition elements:

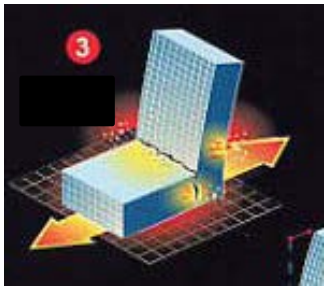
- *squinch*
- *pendantive*
- *corbelled triangle*
- *corbelled band*





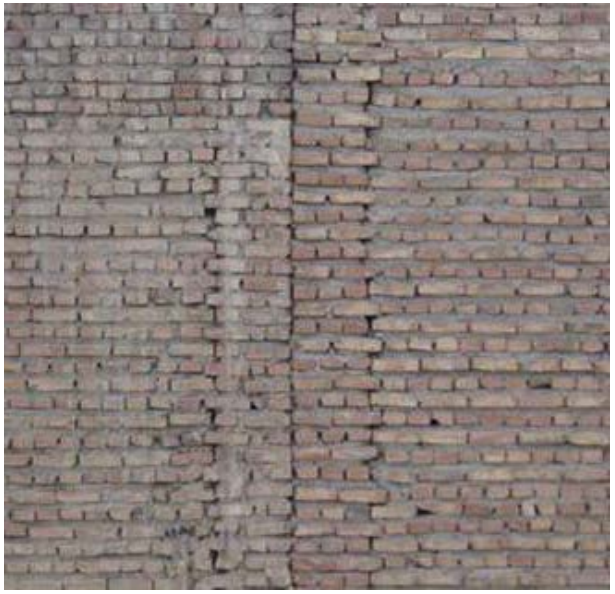
To Improve Earthquake Performance

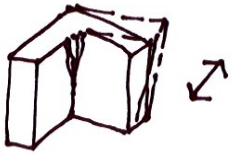
Providing seismic joints at different weighing parts



Providing seismic joints by not connecting the

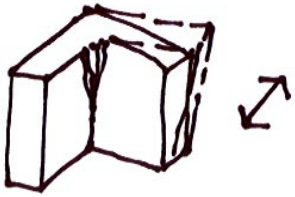
- **long projecting walls to each other and**
- **different weighing components of a building**





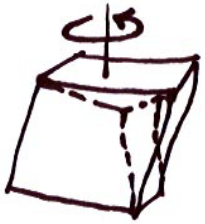
To Improve Earthquake Performance

Providing seismic joints at different weighing parts



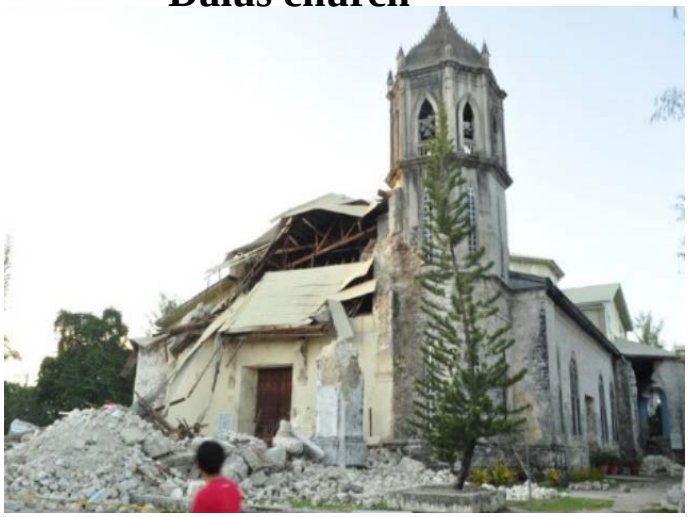
To Improve Earthquake Performance

Separating the different weighing parts of the building



Loboc church

Daius church

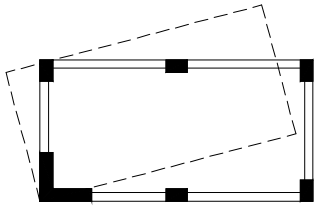


To Improve Earthquake Performance

Separating the different weighing parts of the building

Baclayon church

Loay church



To Improve Earthquake Performance

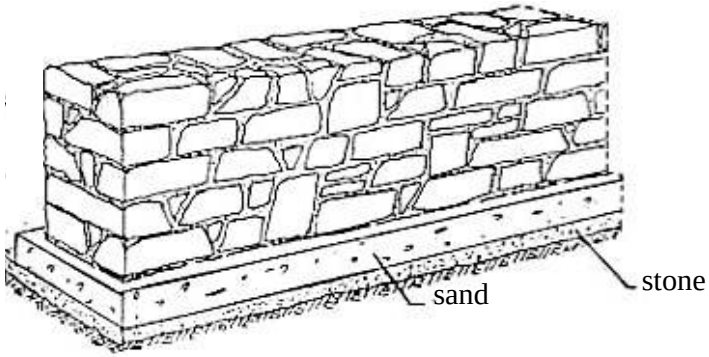
Preventing the Resonance effect

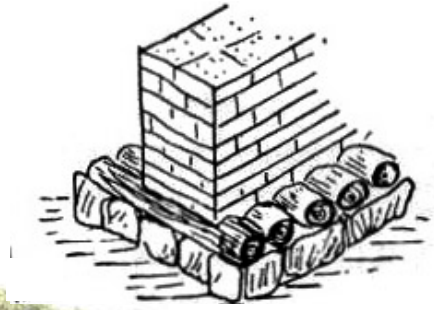
Resonance occurs when

$$T_{building} = T_{soil}$$

Generally rigid buildings on rigid soil suffer resonance

Changing the natural frequency of soil by providing flexible base may improve soil-structure interaction.





To Improve Earthquake Performance

Avoiding the actions that will weaken the masonry

Water ⟶ non-seismic threat to masonry buildings

Depending on

- **the porosity of foundation construction material**
- **soil characteristics,**

Water can damage the wall and soil

- **eroding away portions**
- **reducing the strength.**

Designing an effective underground drainage system is necessary

To Improve Earthquake Performance

Avoiding the actions that will weaken the masonry

Sirkeci

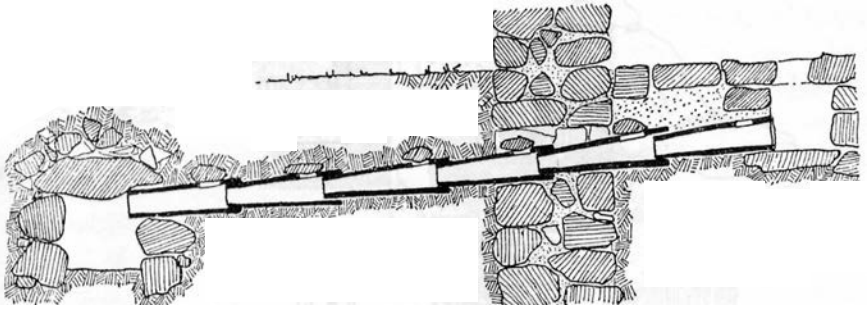
Drainage system: Wells
to control the underground water

Discharge to a fountain tank

Silahhane- Topkapı Palace

Major components of the system:

- wells or cistern
- galleries or channels
- gates



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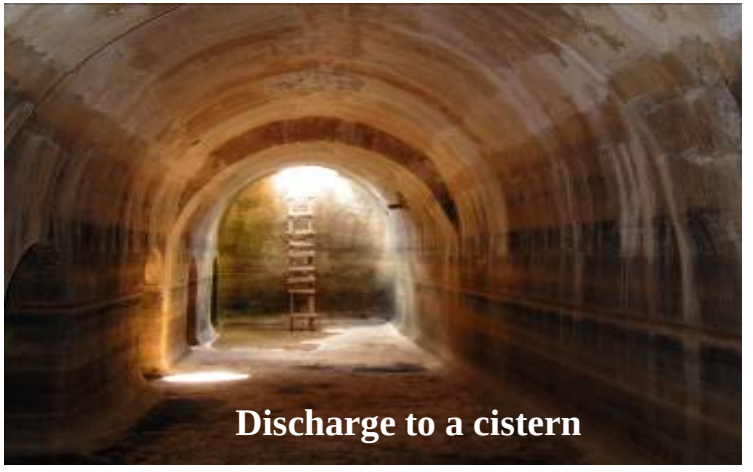
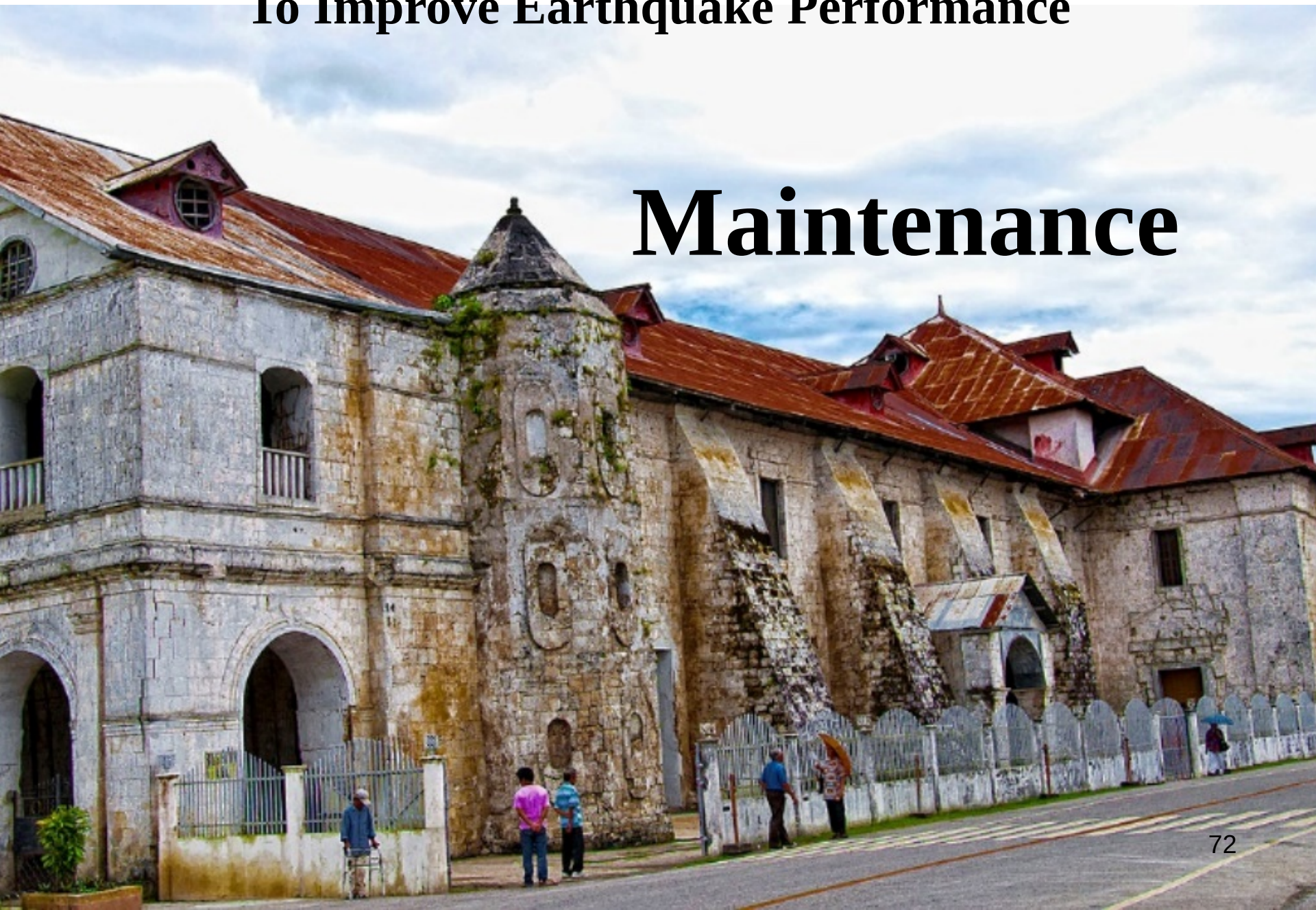


Discharge to a cistern

To Improve Earthquake Performance



Maintenance