Seismic Resistance and Retrofitting of Unreinforced Masonry Buildings

Seizmička nosivost i ojačanje konstrukcija zgrada od nearmirane zidarije

Dr. Svetlana Brzev, P.Eng.
Adjunct Professor, Department of Civil Engineering
University of British Columbia, Vancouver, Canada

President
Serbian Association for Earthquake Engineering (SUZI-SAEE)

Topics

- ✓Unreinforced masonry (URM) buildings: behaviour and failure modes
- ✓Seismic retrofitting techniques: overview and challenges

Unreinforced Masonry Buildings (URM): Seismic Behaviour and Failure Mechanisms

Types of Earthquake Damage in Masonry Buildings

- Wall damage

  Causes: limited capacity of individual walls to sustain in-plane and out-of-plane earthquake effects

- "Non-wall" damage

  Causes: inadequate wall-to-floor or wall-to-roof connections, untied parapets, ceilings, ornaments, etc.

In-Plane and Out-of-Plane Earthquake Damage

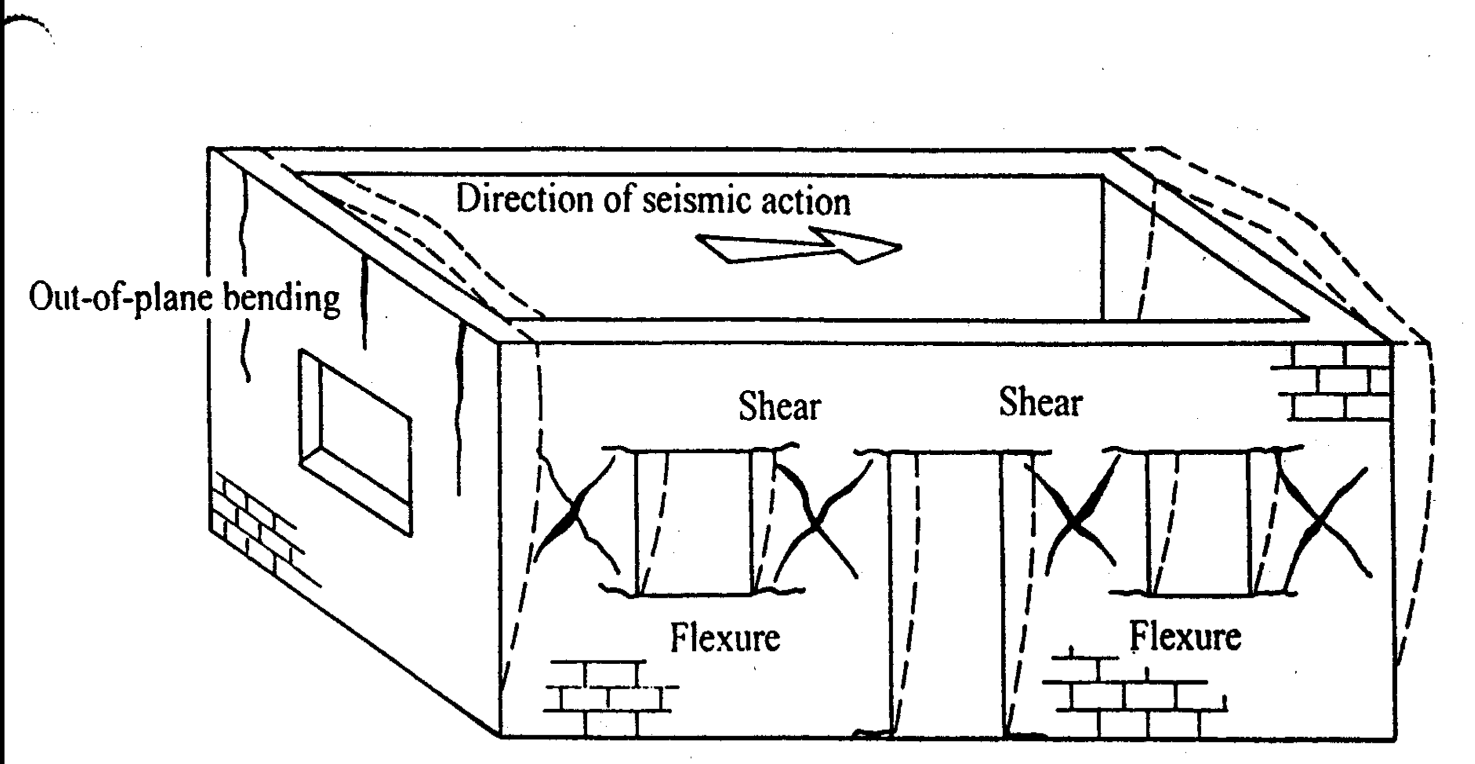


Figure 2.19. Deformation of the building and typical damage to structural wall.

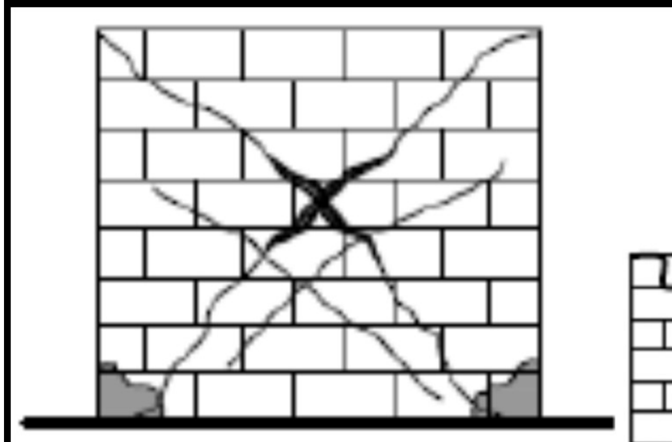
Source: Tomaževič (1999)

In-Plane Failure Mechanisms for URM Shear Walls

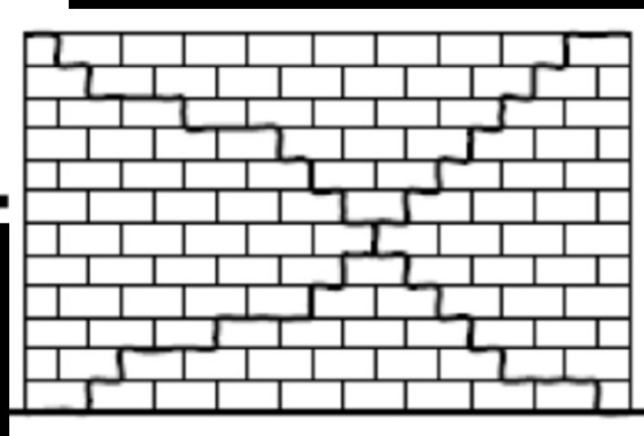
- Most common damage patterns are due to the shear failure mechanisms (to be discussed in this presentation)

- Other failure mechanisms include pier rocking and flexural failure (not covered in this presentation)

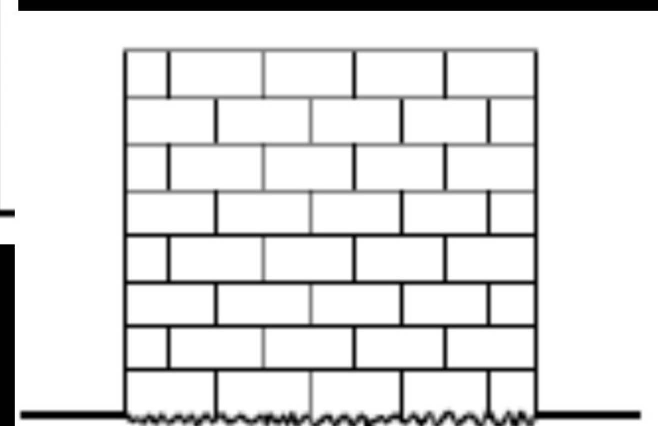
Unreinforced Masonry Walls: In-Plane Shear Failure Mechanisms



1. Diagonal tension shear failure



2. Stair-stepped joint shear failure



3. Sliding shear failure

Diagonal tension shear failure: evidence from past earthquakes

1979 Budva, Montenegro eq. (M7.0)

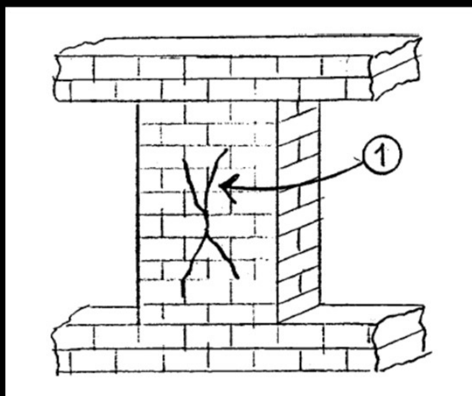
Source: M. Fischinger

Diagonal Tension Failure: Background

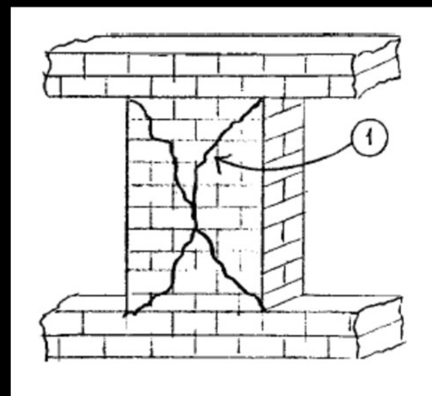
- Diagonal cracks initially develop in the middle portion of the wall once the diagonal tensile strength f_t is exceeded.

- Cracks propagate towards the compressed corners, and may result in local crushing of compressed corners due to excessive normal and shear stresses.

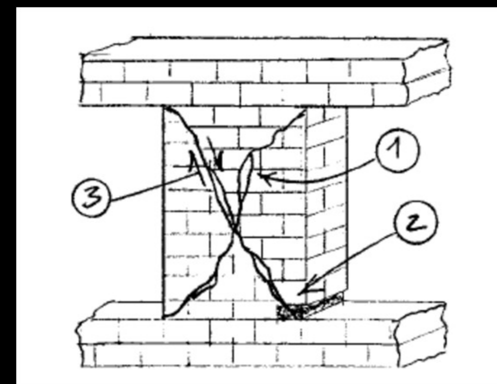
Diagonal Tension: Damage Levels



Insignificant



Moderate

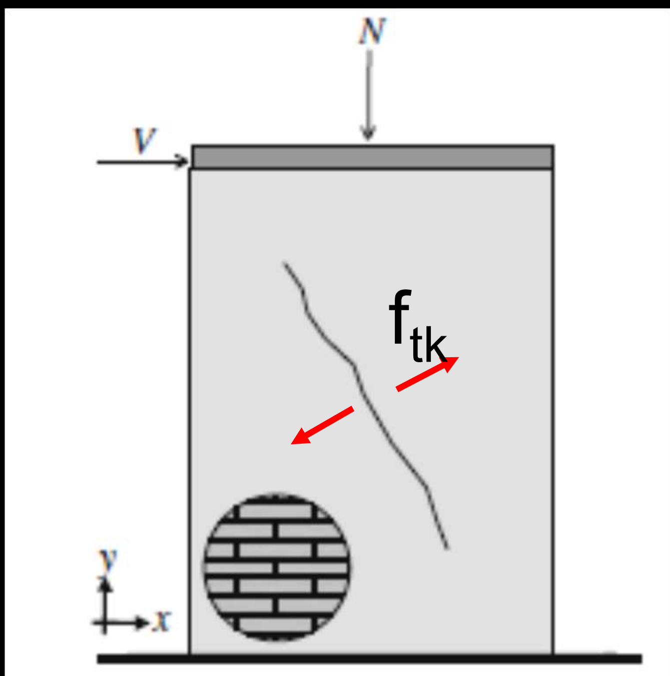


Heavy

1. Diagonal cracks in pier, many of which go through masonry units, with crack widths over 1/4”. Damage may also include:
2. Some minor crushing/spalling of pier corners and/or
3. Minor movement along or across crack plane.

Source: FEMA 306 (1998)

Diagonal Tension Failure: Shear Strength



Source: Tomaževič (2008)

Equivalent tensile strength

$$f'_{tk} = \sqrt{\left(\frac{\sigma_d}{2}\right)^2 + (bf_{vk})^2} - \frac{\sigma_d}{2}$$

$$\sigma_d = \frac{N}{A} \qquad f_{vk} = \tau_{max} = \frac{V}{A}$$

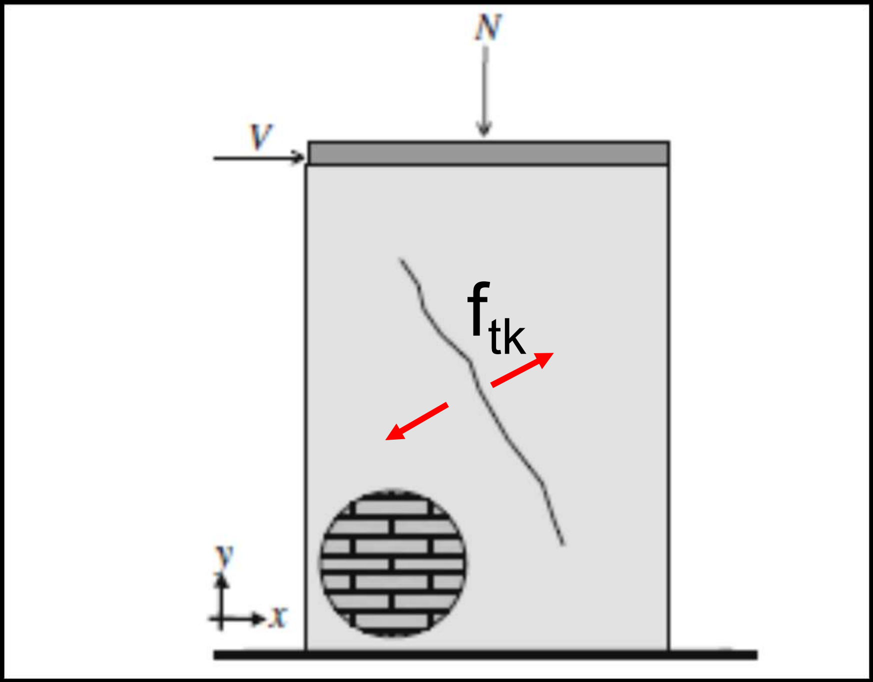
Masonry shear strength (HRN EN 1998-1:2011)

$$f_{vd} = \frac{f_{tk}}{\gamma_M} \frac{1}{b} \sqrt{\frac{\gamma_M}{f_{tk}} \sigma_d + 1}$$

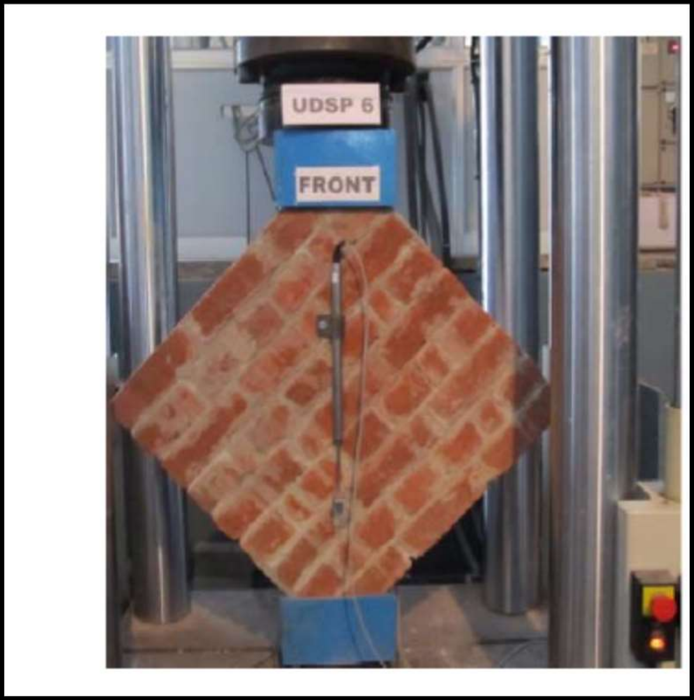
Diagonal Tension Strength: Testing

Diagonal compression test used to determine tensile strength at the onset of diagonal cracking in URM walls

Testing standard: ASTM E 519



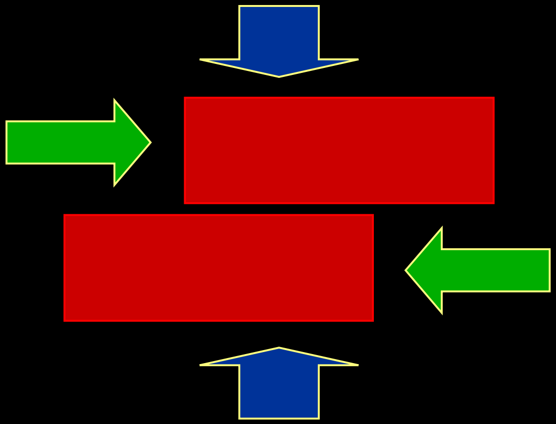
Actual wall



Test specimen: wallette

Stair-Stepped Joint Shear Failure

- Stair-stepped cracks - pass through vertical and horizontal mortar joints
- Also known as bed joint sliding failure (USA and Canada)



Stair-stepped joint shear failure

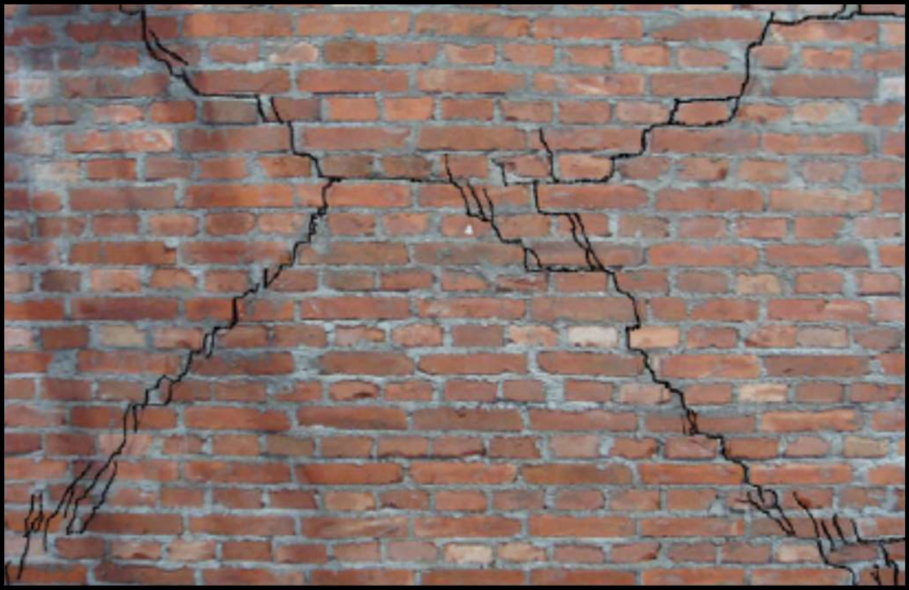
- Due to low axial stresses+ high shear stresses
- Occurs when shear stresses exceed adhesion and shear friction resistance between the mortar and the bricks/blocks
- According to Canadian masonry code CSA S304-14 Cl. 7.10.5.1:

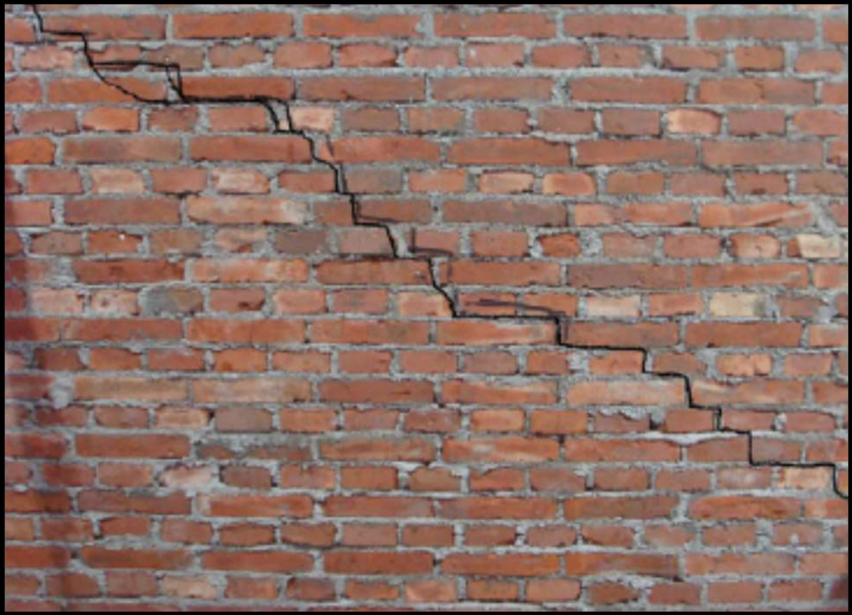
$$V_r = 0.16\phi_m \sqrt{f'_m} A_{uc} + \phi_m \mu P_1$$

Initial shear strength

Due to axial compression

Stair-Stepped Joint Shear Failure: Experimental Studies



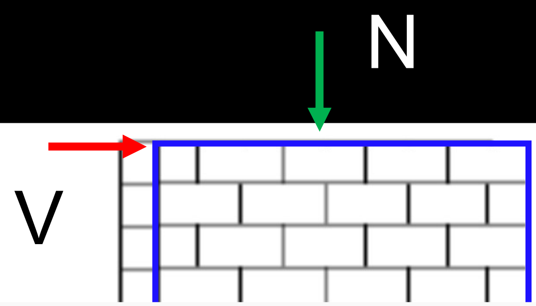


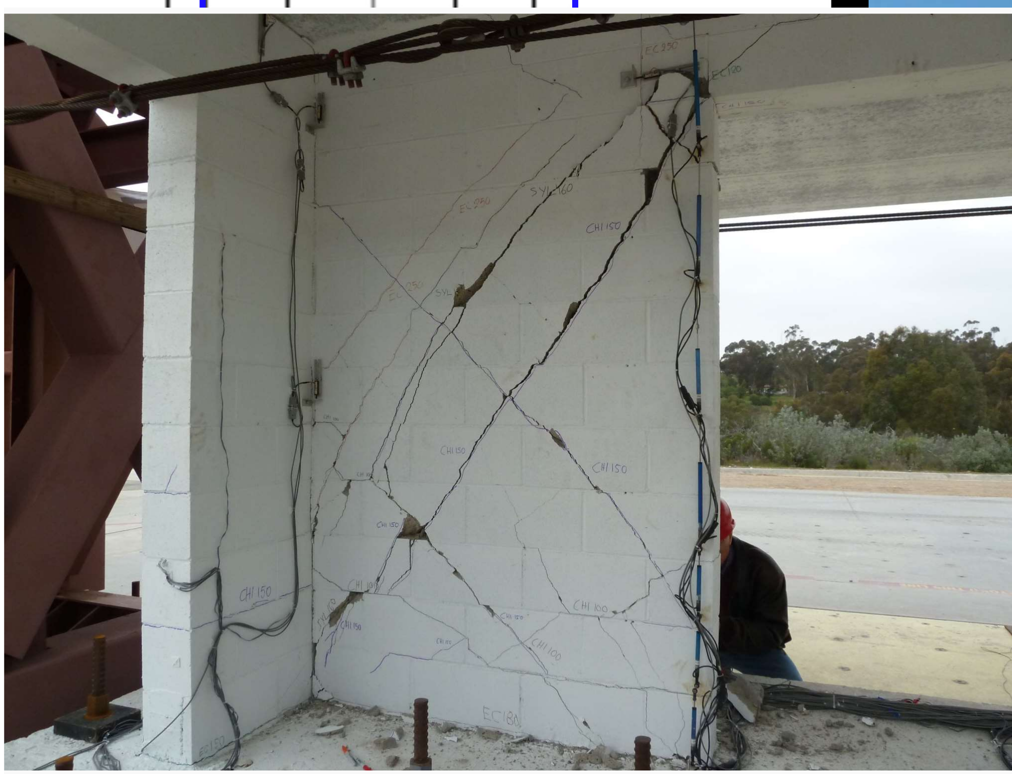
Source: Zhou, Lei & Wang (2013)

Sliding shear mechanism

- Due to low axial compression, usually occurs in low-rise buildings
- Develops along a horizontal crack after flexural-tensile cracking occurs along a mortar bed joint
- Characterized by significant lateral displacements, minimal visible damage

Sliding shear failure





Shaking table testing of a reinforced masonry building by Stavridis, Klingner, Shing, Ahmadi (University of California San Diego, 2011)

Shaking Table Testing at the University of California San Diego, USA

Shear resistance of unreinforced masonry walls HRN EN 1996-1-1:2012 (Eurocode 6)

- Characteristic shear strength of masonry f_{vk} (3.6.2.3)
- Two components:

1) initial (bond) shear strength (f_{vko}) at zero compressive stress, and

2) contribution of the design compressive stress at the section under consideration ($0.4\sigma_d$)

$$f_{vk} = f_{vko} + 0{,}4\,\sigma_d$$

but not greater than $0{,}065 f_b$ or f_{vlt}

f_{vko} is the characteristic initial shear strength, under zero compressive stress;

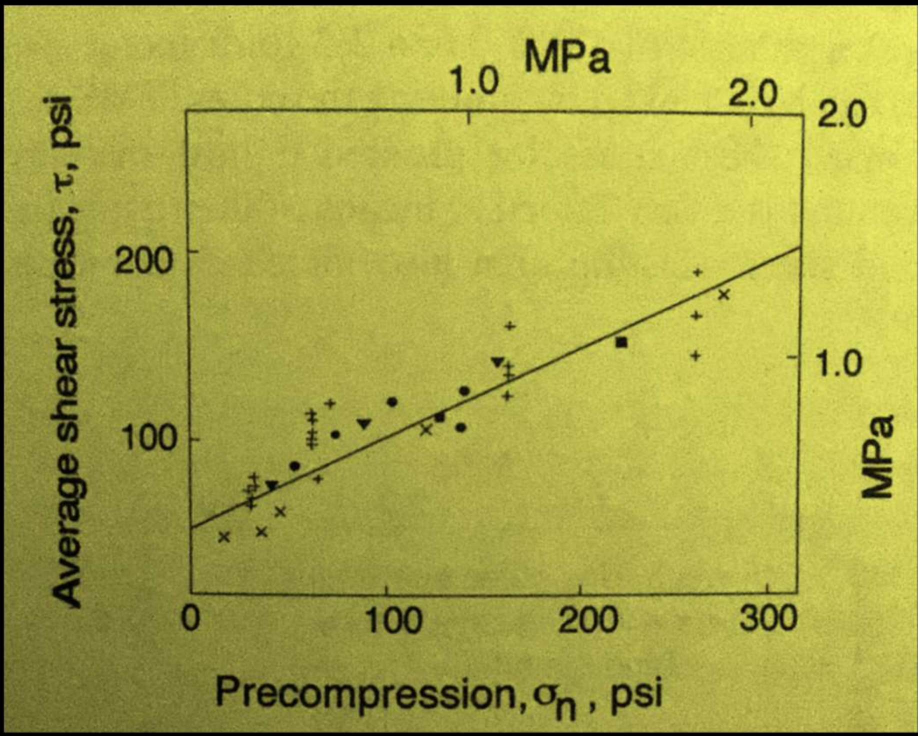
f_{vlt} is a limit to the value of f_{vk};

σ_d is the design compressive stress perpendicular to the shear in the member

f_b is the normalised compressive strength of the masonry units.

Shear resistance of unreinforced masonry walls according to HRN EN 1996-1-1:2012 - Background

- Based on Coulomb friction concept
- Valid at low compressive stresses
- Applies only to failure characterized by slip along the mortar joints (bed joint sliding)
- Supported by experimental studies dating back to 1970s



Source: Hendry (1981)

Shear resistance of unreinforced masonry walls HRN EN 1996-1-1:2012 (Eurocode 6)

Design shear resistance of unreinforced masonry wall (6.7.2)

$$V_{Rd1} = f_{vd}\, t\, l$$

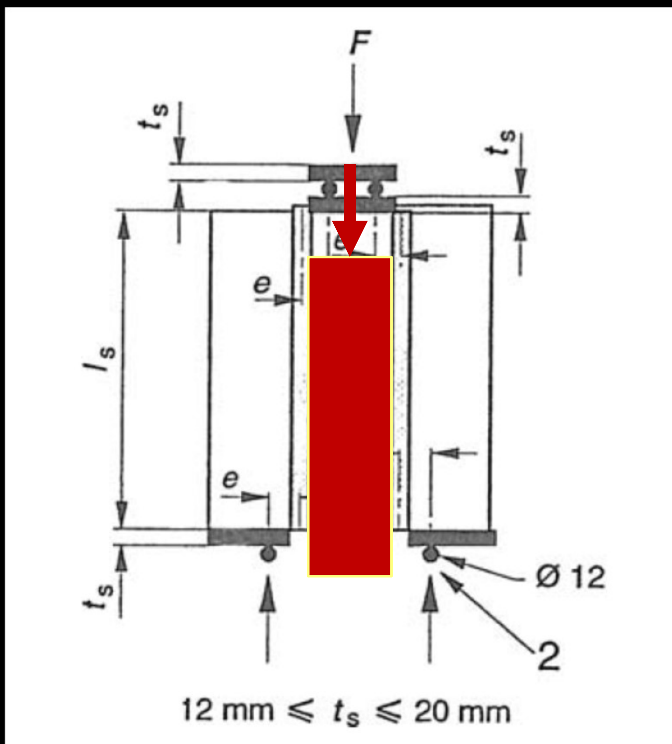
t	is the thickness of the wall;
l	is the length of the wall.

Design shear strength $f_{vd} = f_{vk}/\gamma_m$

$\gamma_m \geq 1.5$ partial safety factor for masonry for seismic design and assessment purposes

Shear resistance V_{Rd1} according to HRN EN 1998-3: 2011 - same underlying equation as HRN EN 1996-1-1: 2012!

Initial shear strength of masonry: triplet tests (testing standard EN 1052-3)



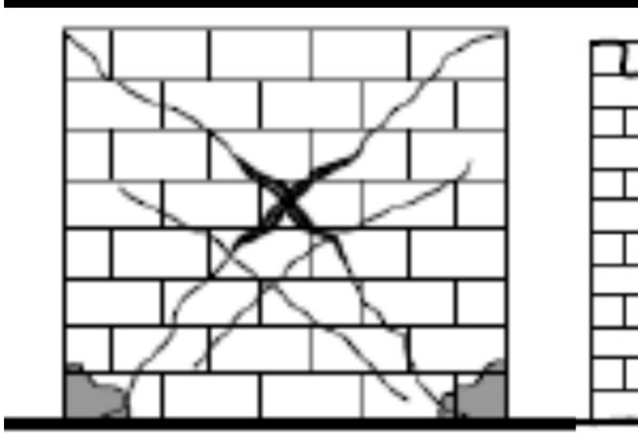
Source: Tomaževič (2008)

Values of the initial shear strength of masonry, f_{vko}

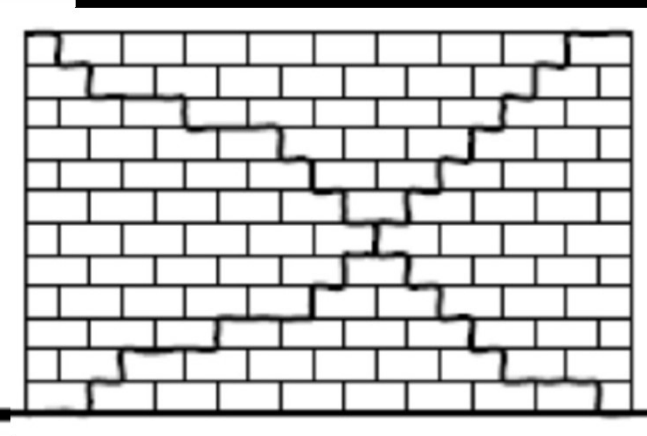
Masonry units	Strength class of general purpose mortar	Initial shear strength f_{vko} (N /mm^2)		
		General purpose mortar	Thin layer mortar (bed joint ≤ 0.5 mm and ≥ 3 mm)	Light-weight mortar
Clay	M12	0.30		
	M4 & M6	0.20	0.30	0.15
	M2	0.10		
Calcium silicate	M12	0.20		
	M4 & M6	0.15	0.40	0.15
	M2	0.10		
Aggregate concrete, autoclaved aerated concrete, manufactured stone and dimensioned natural stone	M12	0.20		
	M4 & M6	0.15	0.30	0.15
	M2	0.10		

Source: HRN EN 1996-1-1:2012

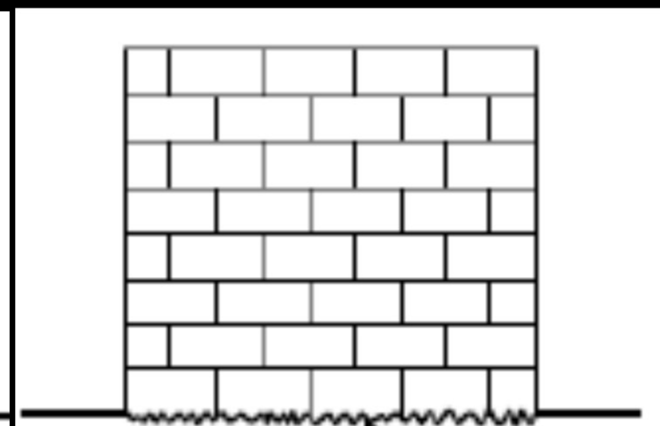
Shear failure mechanisms: which one governs?



A



B



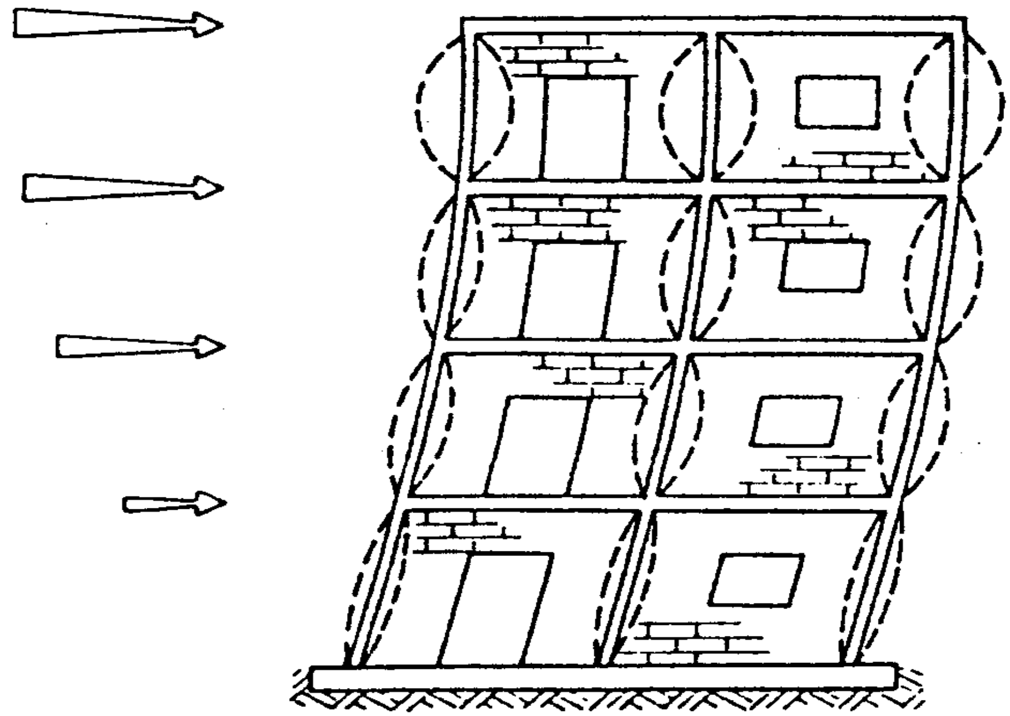
C

$$V_{Rd1} = f_{vd}\, t\, l$$

Is f_{vd} based on the mechanism A? or B? or C?

The smallest value governs!

Out-of-Plane Earthquake Shaking



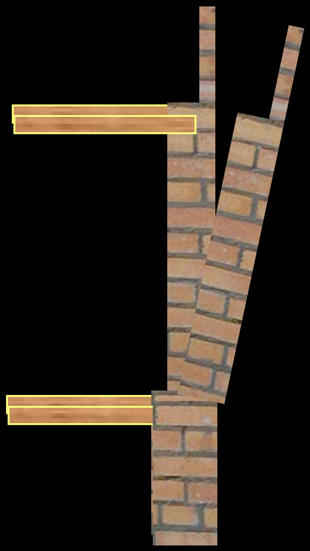
More pronounced response at upper floors

Source: Tomaževič (1999)

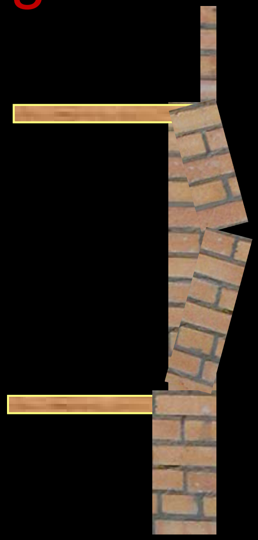
Out-of-plane Failure Mechanisms for URM Walls

Two basic out-of-plane failure modes - depending on the wall-to-floor connections

Cantilever mode
(weak connection)

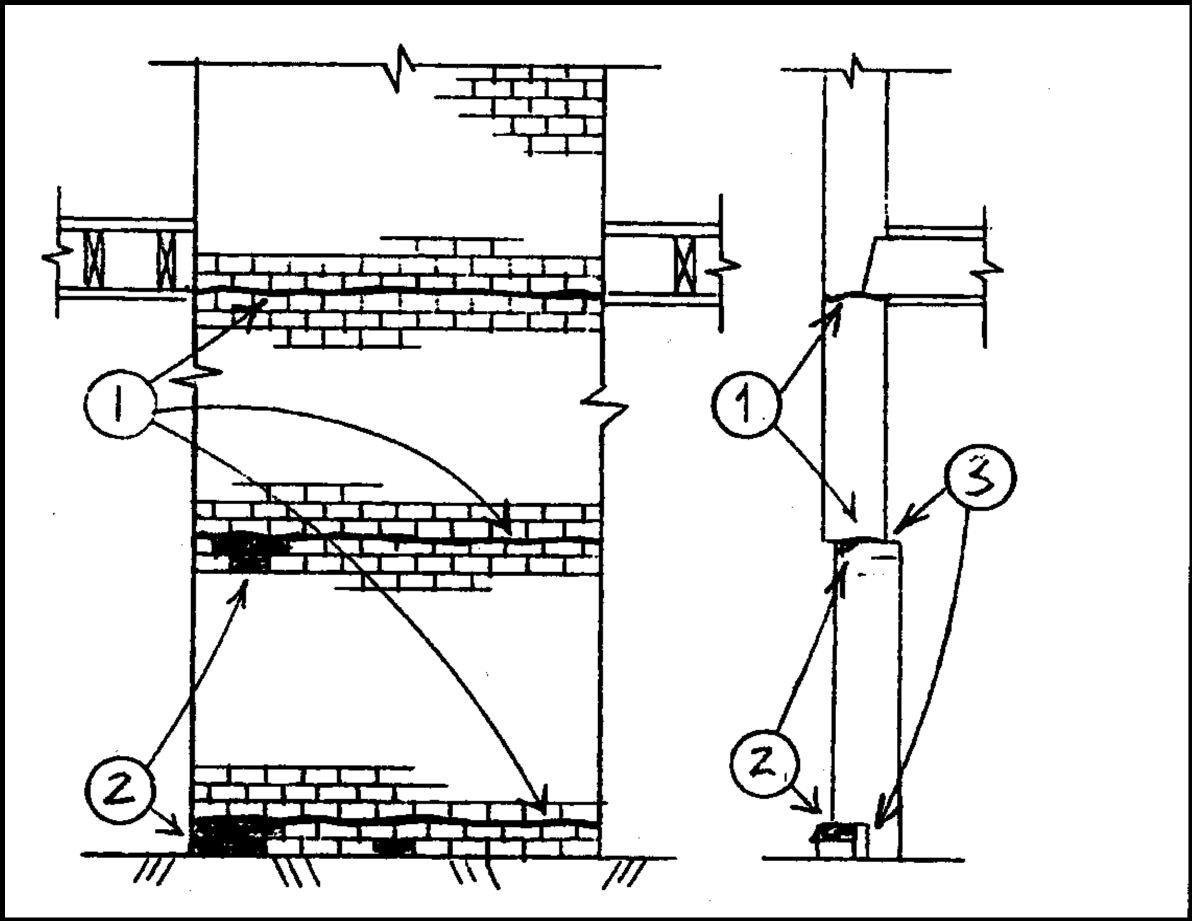


Beam flexural mode
(strong connection)



Source: Ken Elwood (2011)

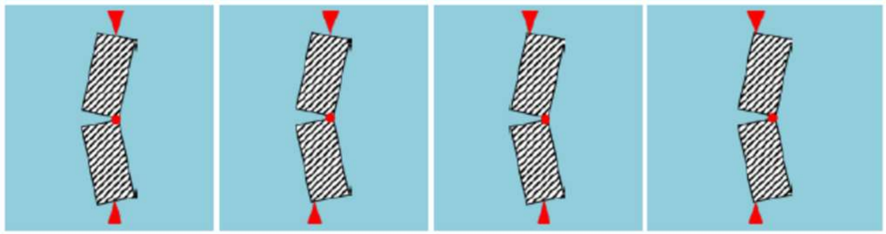
Out-of-Plane Wall Failure: Flexural Mode



Source: FEMA 306 (1998)

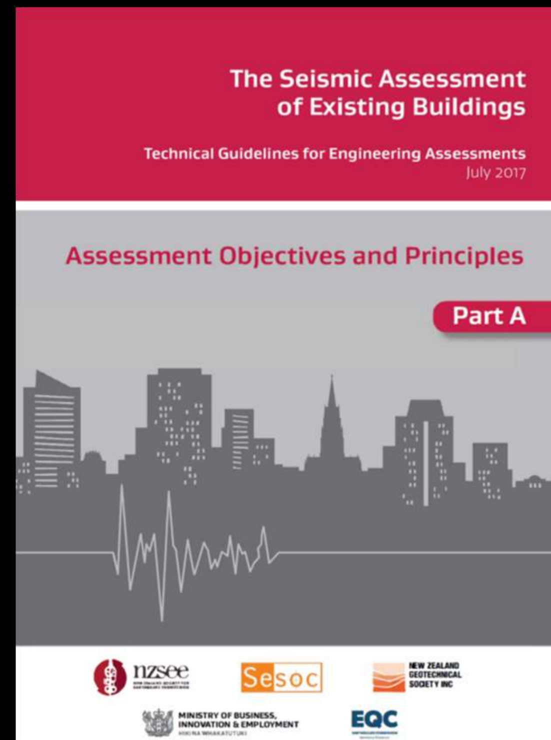
Out-of-Plane Wall Resistance/Capacity: Evaluation Based on the Virtual Work Principle

Table C8B.1: Static instability deflection for uniform walls, various boundary conditions

Boundary condition number	0	1	2	3
				
e_p	0	0	$t/2$	$t/2$
e_b	0	$t/2$	0	$t/2$
b	$(W/2+P)t$	$(W+3P/2)t$	$(W/2+3P/2)t$	$(W+2P)t$
a	$(W/2+P)h$	$(W/2+P)h$	$(W/2+P)h$	$(W/2+P)h$
$\Delta_i = bh/(2a)$	$t/2$	$\frac{(2W+3P)t}{(2W+4P)}$	$\frac{(W+3P)t}{(2W+4P)}$	t
J	$\{(W/12)[h^2+7t^2]+Pt^2\}/g$	$\{\left(\frac{W}{12}\right)[h^2+16t^2]+9Pt^2/4\}/g$	$\{\left(\frac{W}{12}\right)[h^2+7t^2]+9Pt^2/4\}/g$	$\{(W/12)[h^2+16t^2]+4Pt^2\}/g$
C_m	$(2+4P/W)t/h$	$(4+6P/W)t/h$	$(2+6P/W)t/h$	$4(1+2P/W)t/h$

Note:

1. The boundary conditions of the piers shown above are for clockwise potential rocking.
2. The top eccentricity, e_t, is not related to a boundary condition, so is not included in the table. The top eccentricity, e_t, is the horizontal distance from the central pivot point to the centre of mass of the top block which is not related to a boundary condition.
3. The eccentricities shown in the sketches are for the positive sense. Where the top eccentricity is in the other sense e_p should be entered as a negative number.



Source: New Zealand Guidelines (2017)

"Non-Wall" Damage of Masonry Buildings: Inadequate Wall-to-Floor(Roof) Connections

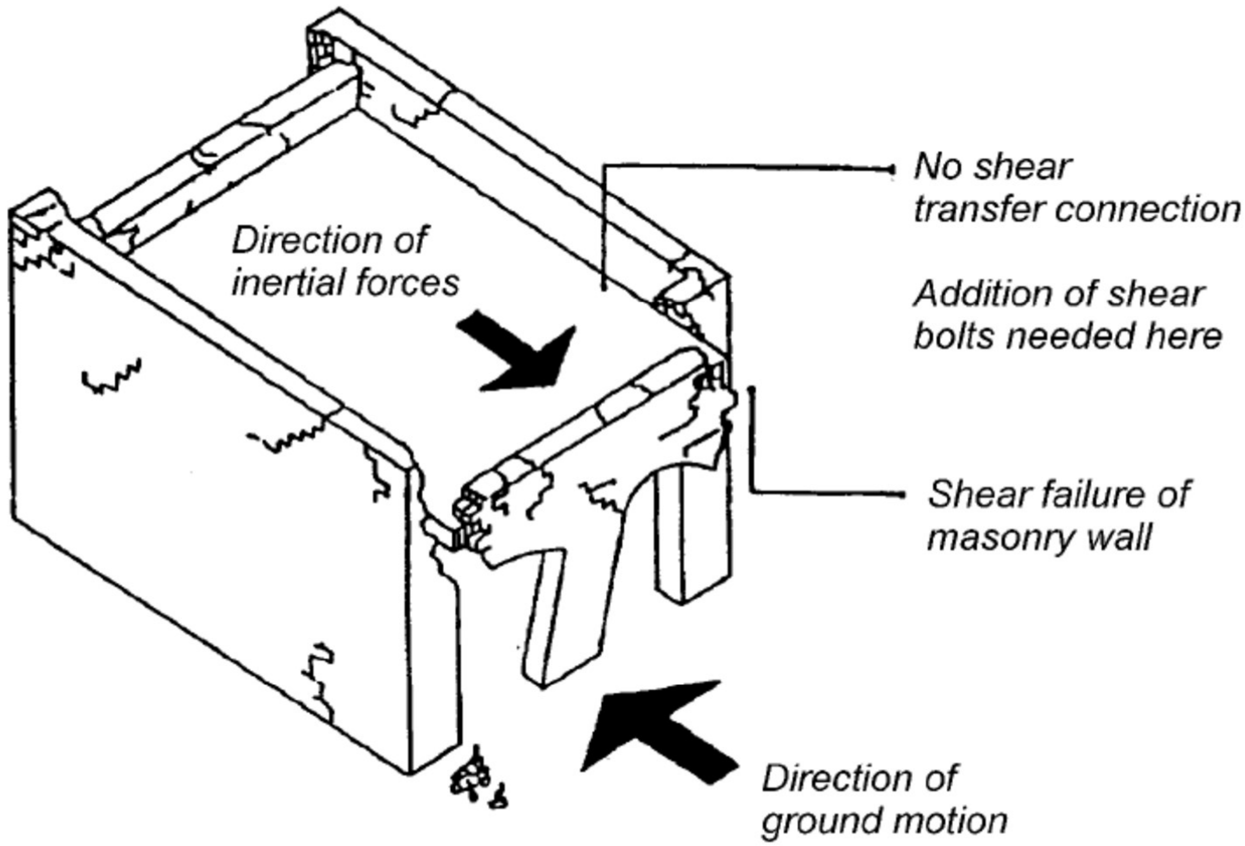
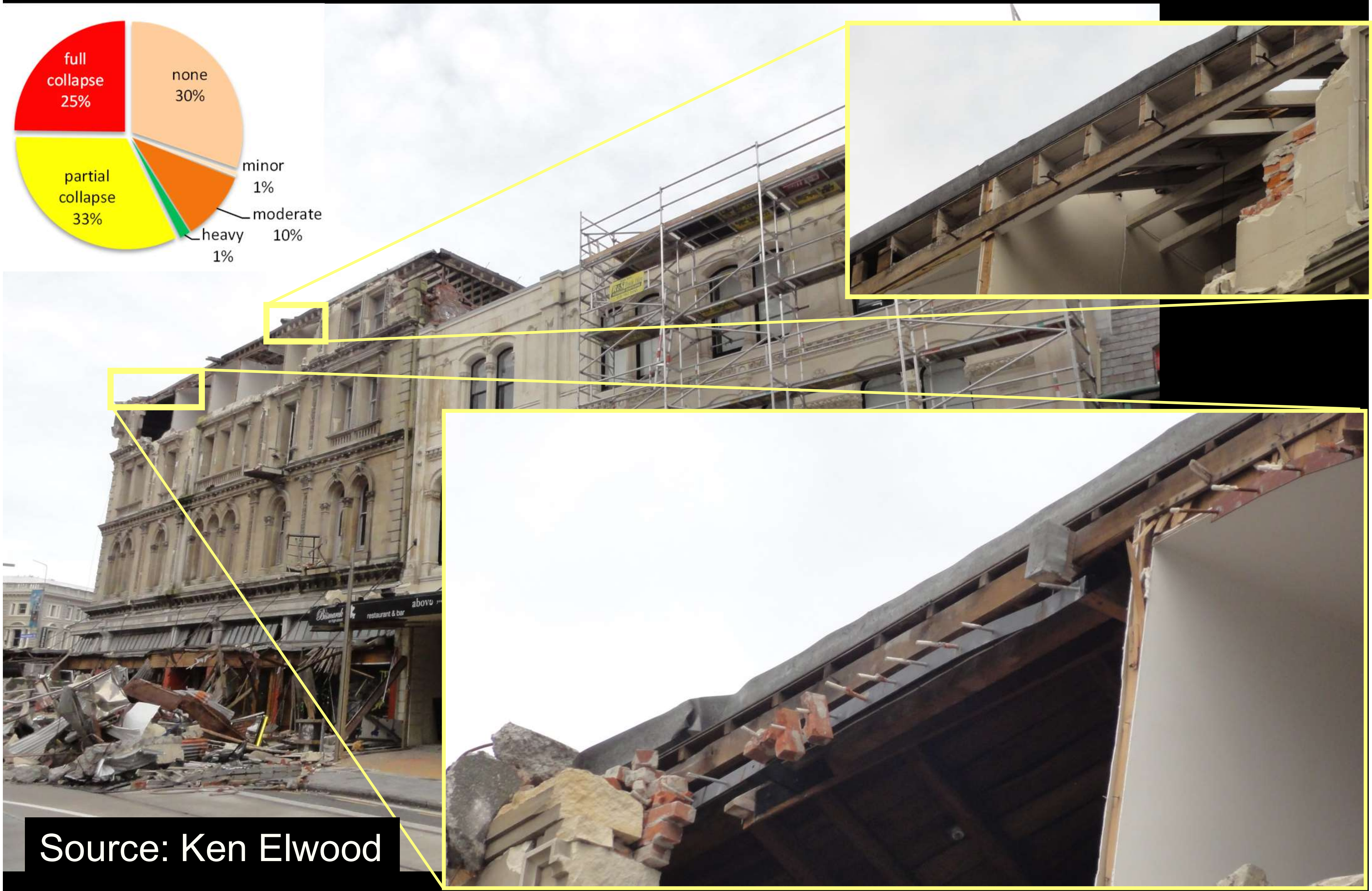


Diagram of Shear Failure

A brick building can collapse in an earthquake
if it lacks shear transfer connections

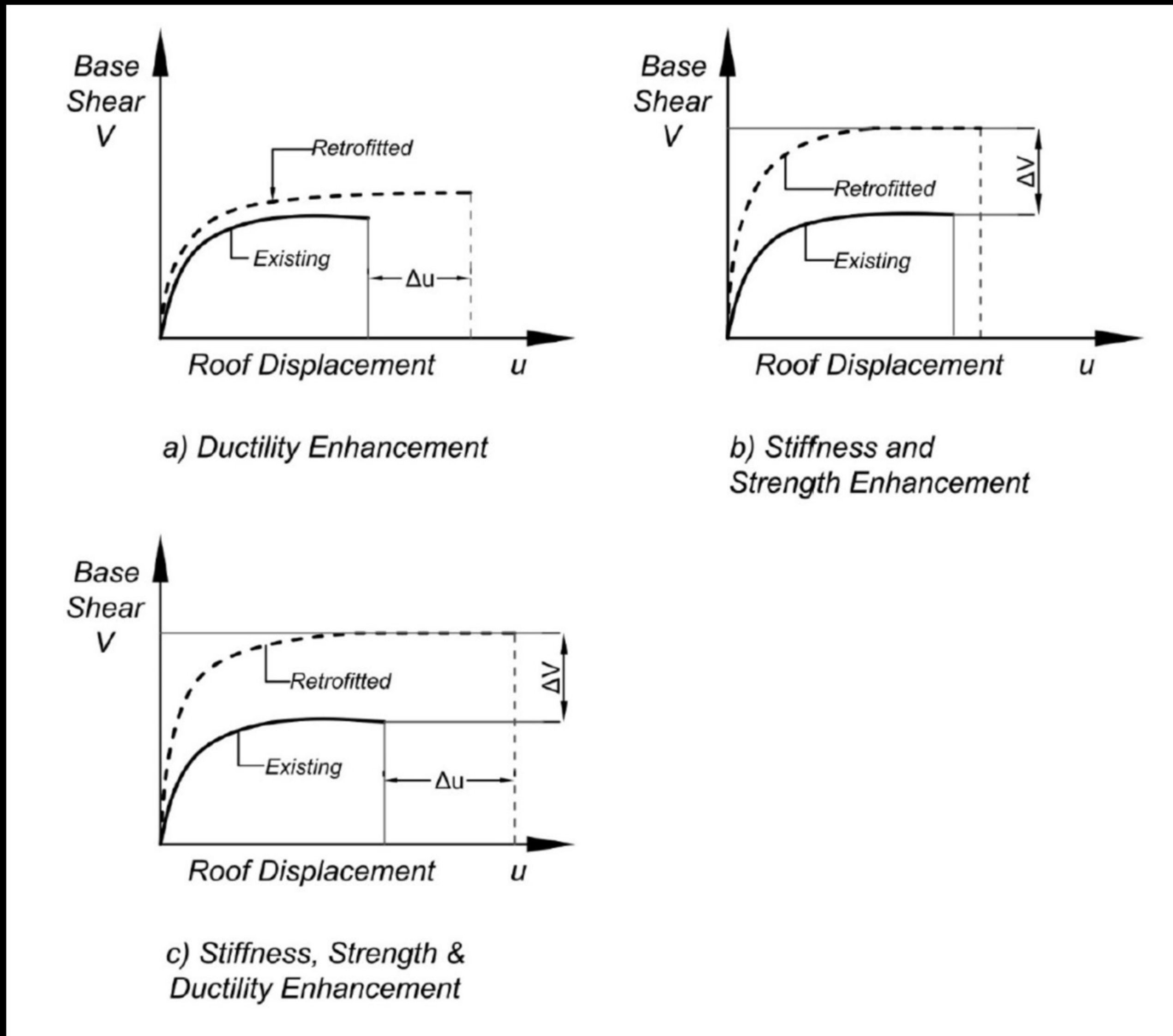
Source: FEMA 306

Wall-to-Floor Anchors (2011 Christchurch, New Zealand eq.)



Unreinforced Masonry Buildings (URM): Seismic Retrofitting Strategies and Techniques

Seismic Retrofitting: Why?



Source: Brzev and Begaliev (2018), based on Thermou, Pantazopoulou, and Elnashai (2004)

Seismic Retrofitting of Unreinforced Masonry Buildings: Objectives

I. Enhance the overall building *integrity* (box action)

C. Secure wall-to-floor/roof *connections*

W. Increase the in-plane and out-of-plane *wall* resistance (lateral load-resisting capacity)

Seismic retrofitting provisions included in HRN EN 1998-3: 2011 Section C.5 Structural Interventions

Integrity of URM Buildings: Box Action

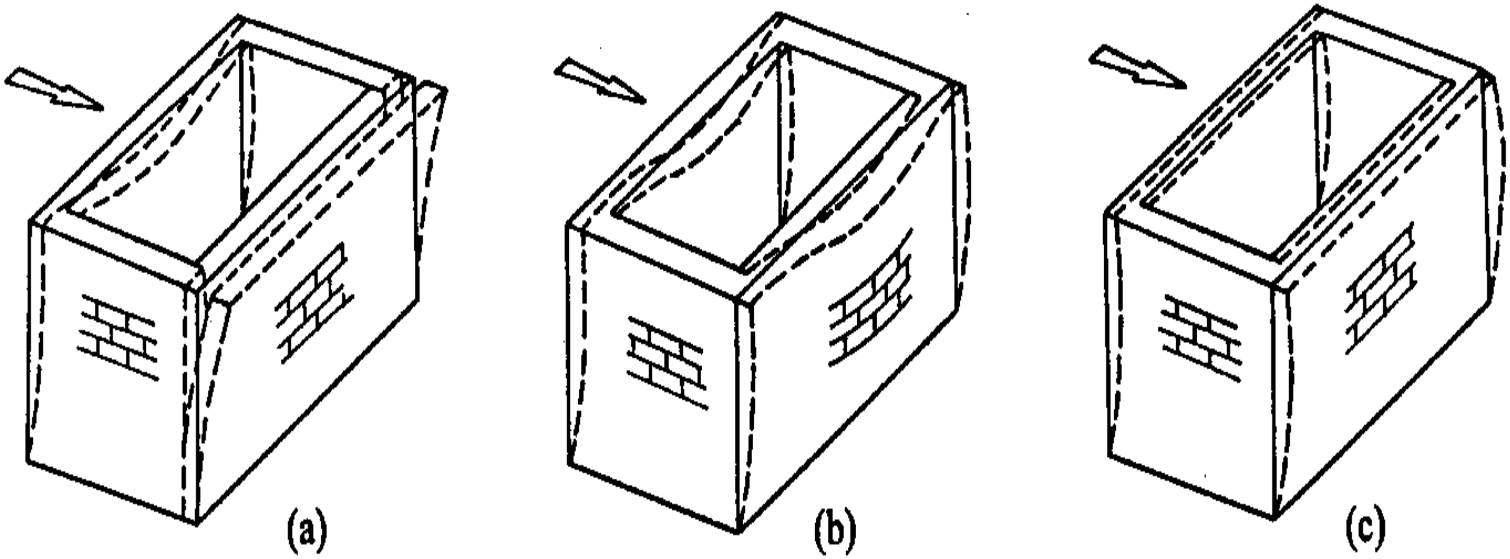


Figure 10.19. Vibration of masonry buildings during earthquake. (a) Building with wooden floors without ties, (b) building with wooden floors and tied walls, and (c) building with rigid floors and tie-beams

Source: Tomaževič (1999)

I. Improving Overall Building Integrity

I1. Use ties to improve building integrity

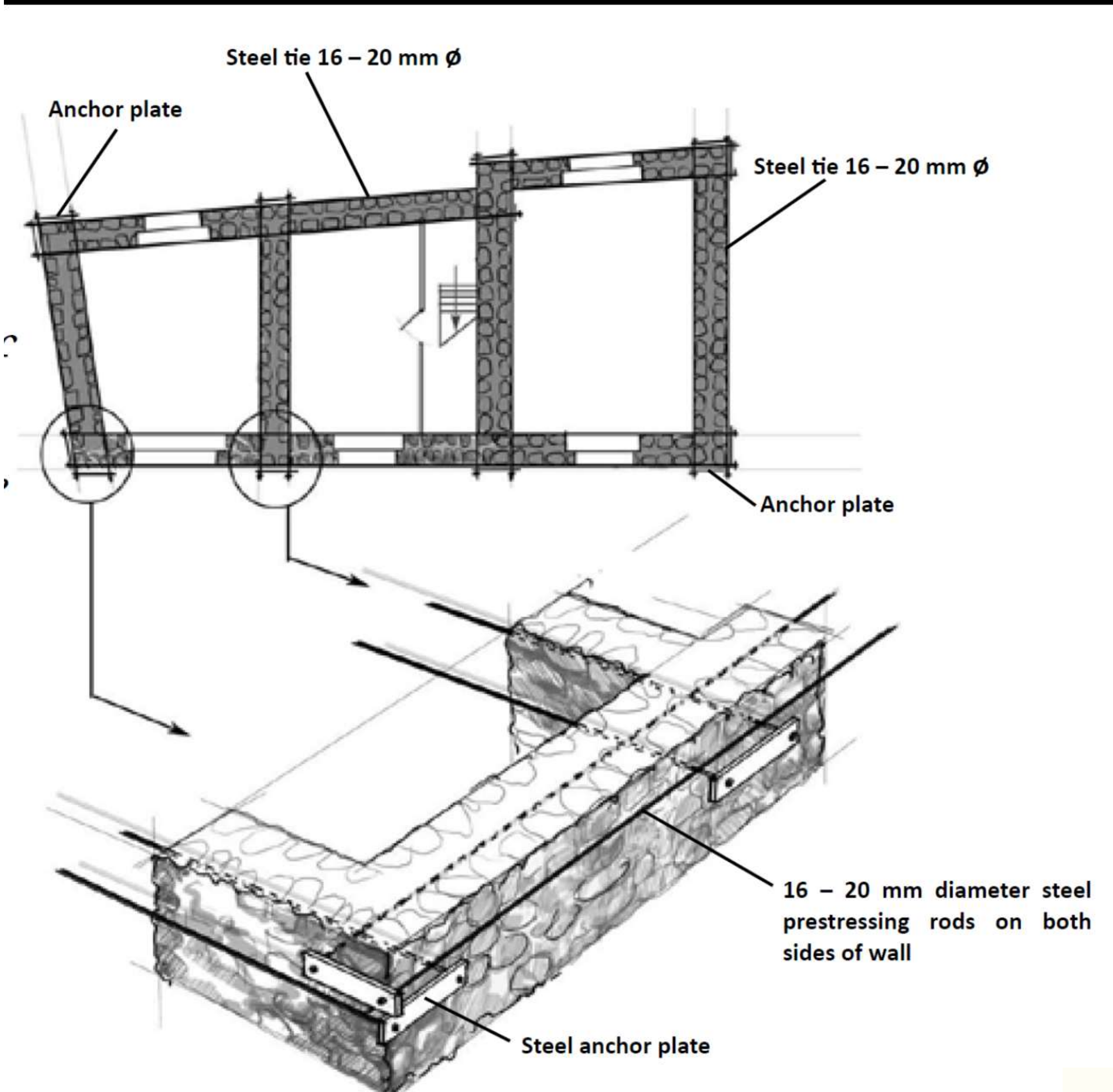
I2. Construct RC ring beams (tie beams)

I3. Strengthen existing (timber) floors

I1: Application of Ties

- Traditional technique used since the medieval age (e.g. Italy, Croatia)
- Iron ties found in historic buildings
- Modern applications: use of steel rods or composite materials, such as Fibre Reinforced Polymers (FRPs)

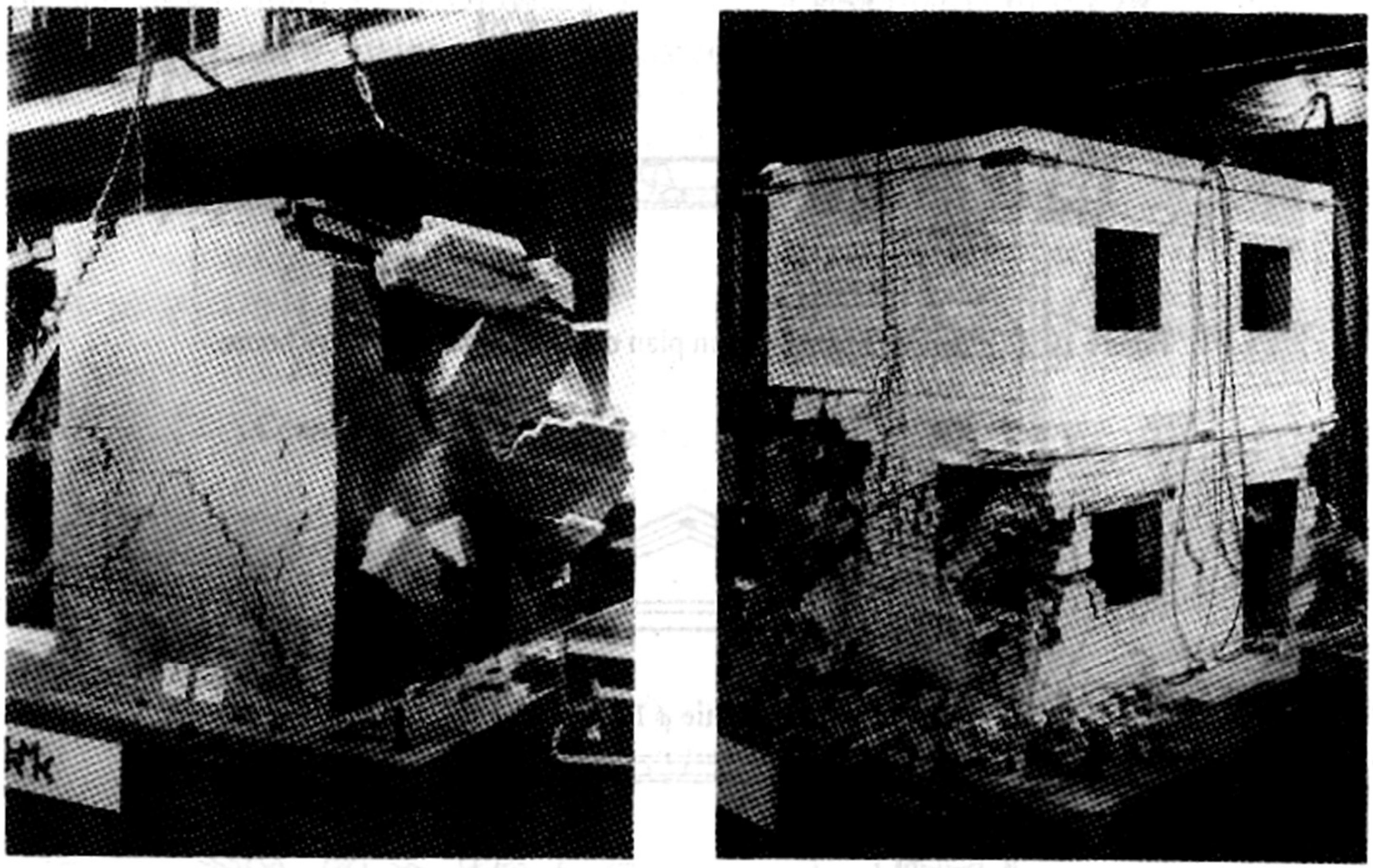
Tie Application: Stone Masonry Buildings



- Steel ties (16 - 20 mm diameter) are threaded at the ends so that they can be prestressed and secured by nuts.
- Longer anchorage plates are recommended.

Source: Tomaževič (1999)

Brick masonry buildings with steel ties: traditional solution

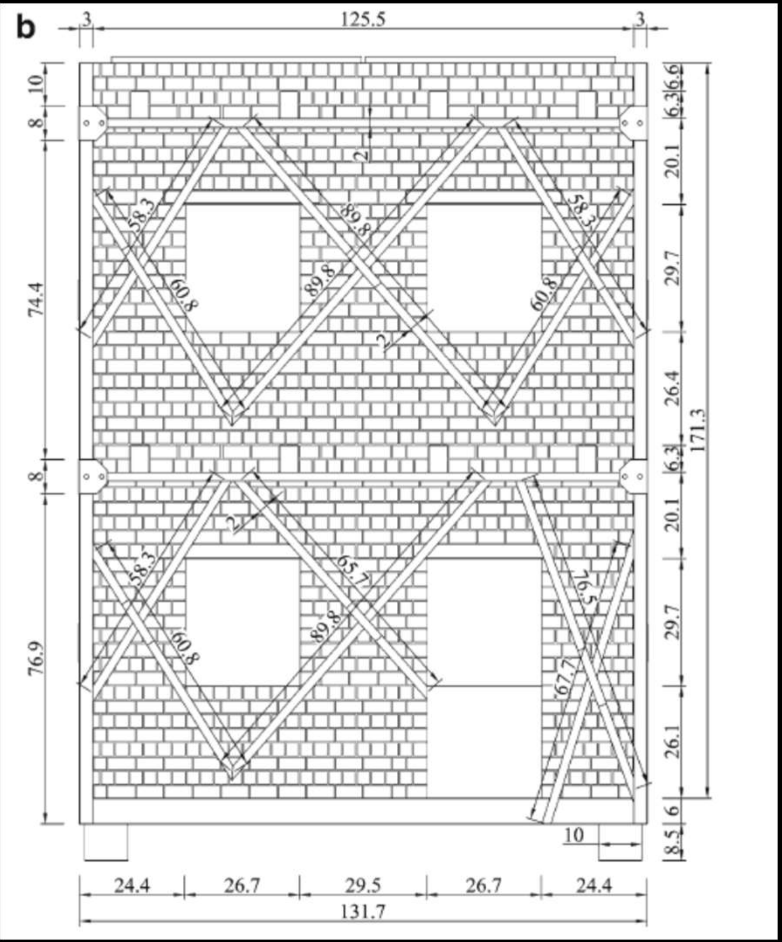


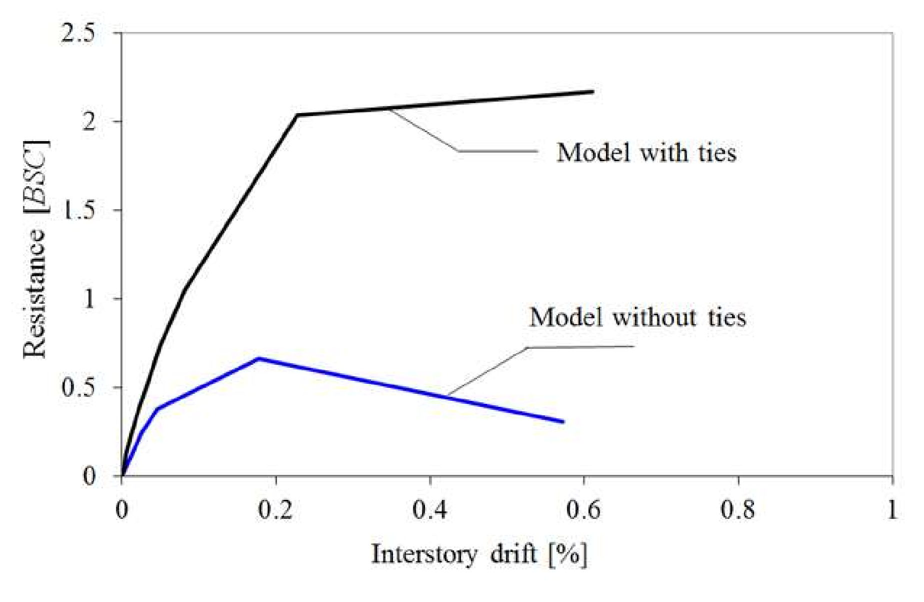
Source: Tomaževič, Lutman and Weiss (1996)

Alternative tie solution: composite (CFRP) ties

Source: Tomaževič, Klemenc and Weiss (2009)

Effectiveness of CFRP ties

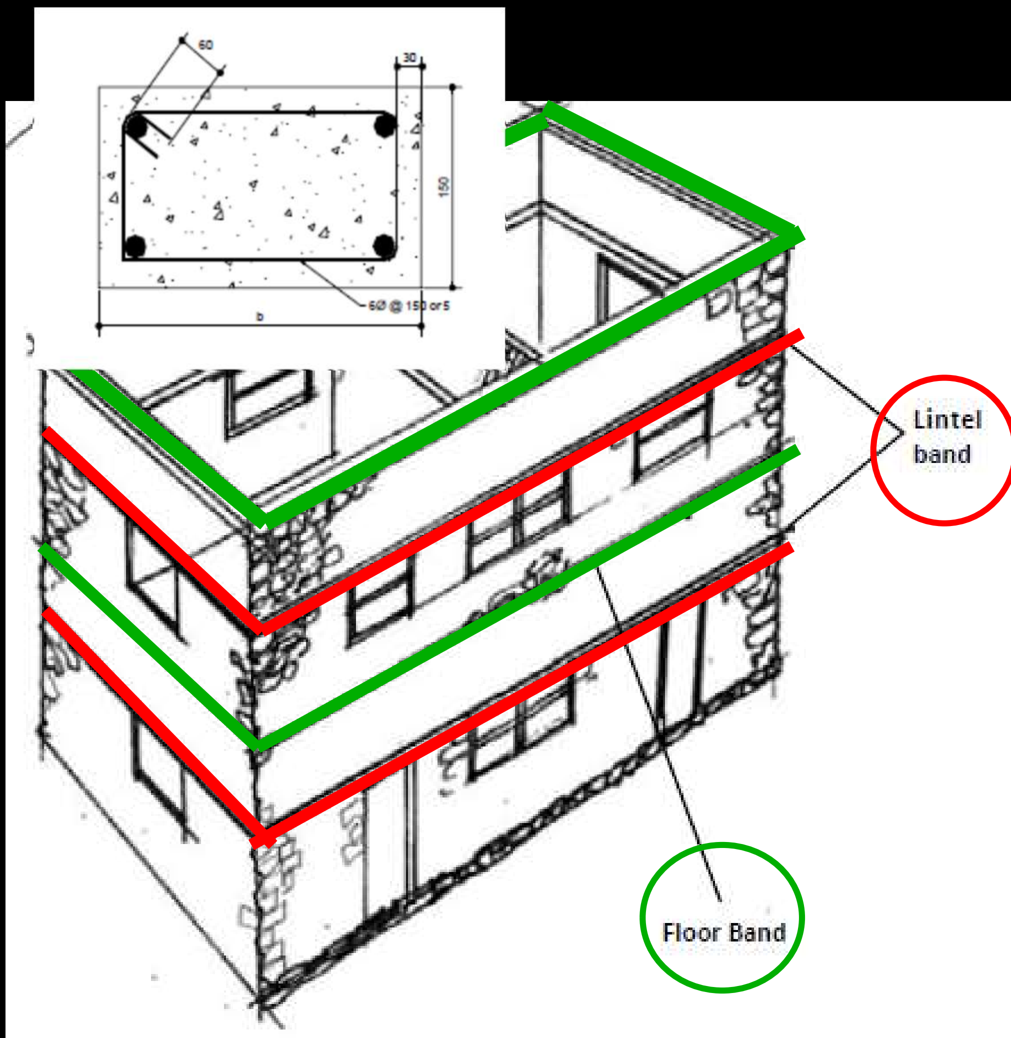




Base shear resistance versus storey drift measured during the shaking table tests of brick masonry building models with and without ties

Source: Tomaževič, Klemenc and Weiss (2009)

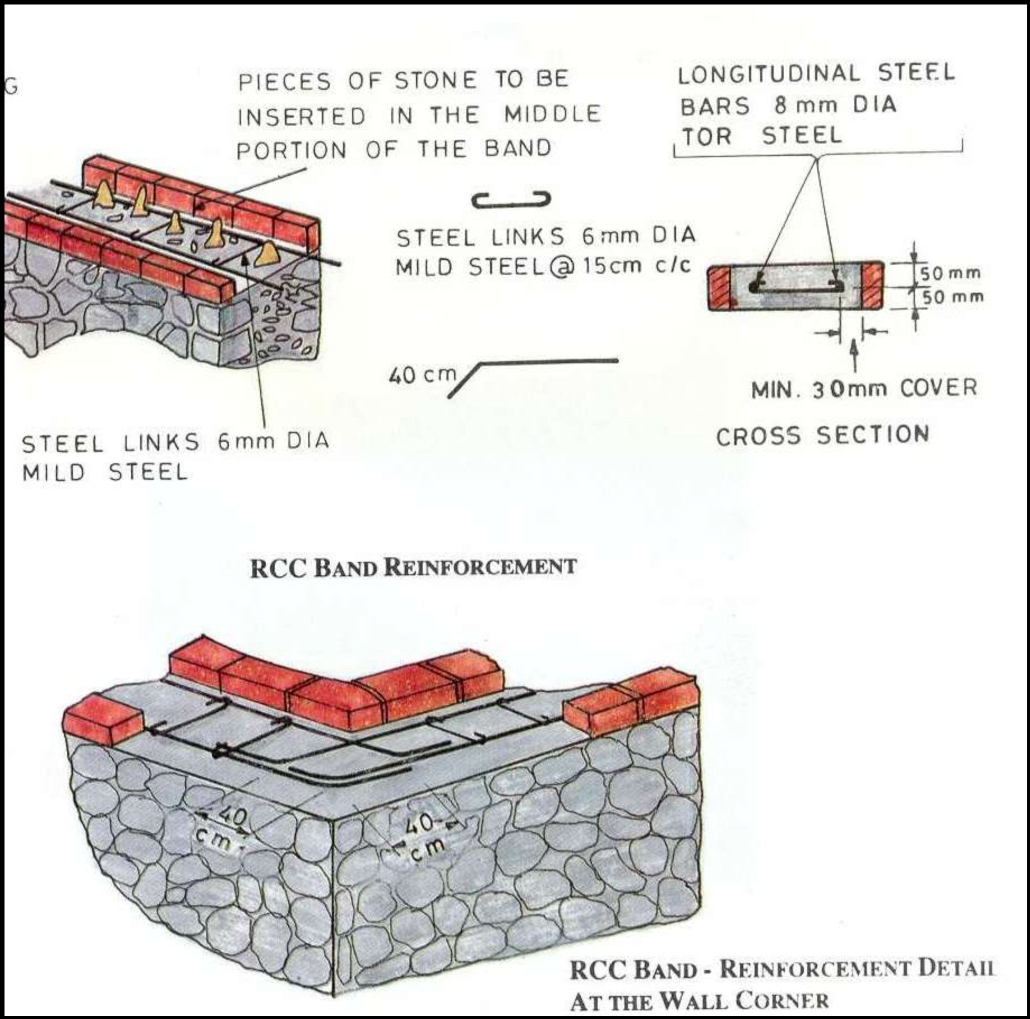
I2: Reinforced Concrete (RC) Tie Beams (Ring Beams)



Source: Bothara and Brzev (2011)

- Common provision for improving seismic safety of new URM buildings in India, Nepal, Pakistan (known as RC bands)...
- It is possible to construct new RC bands in existing URM buildings at roof level

RC Tie Beams for Seismic Retrofitting of URM Buildings



RCC BAND REINFORCEMENT

RCC BAND - REINFORCEMENT DETAIL AT THE WALL CORNER

Example: installation of RC bands at roof level of stone masonry houses damaged by the 1993 India earthquake

(bricks used as formwork)

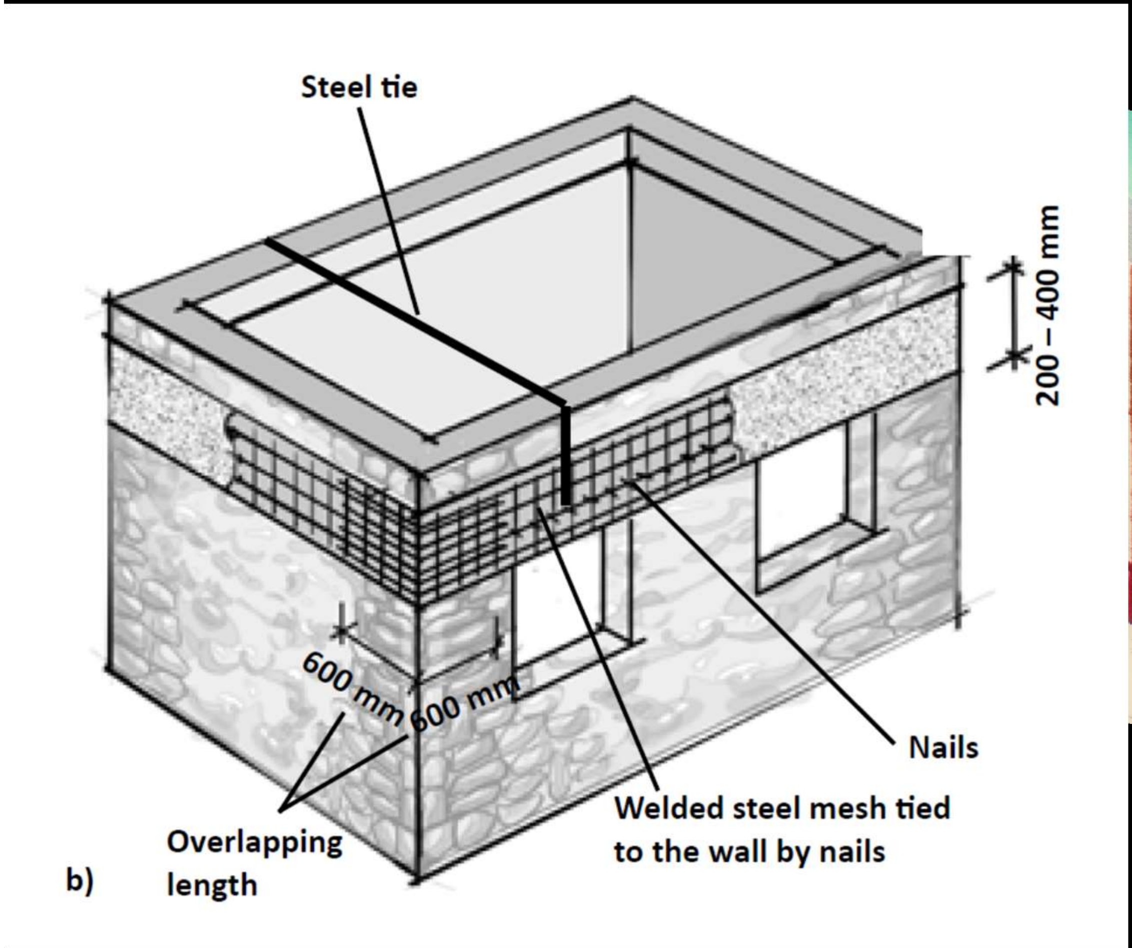
Source: GOM, India (1998)

Seismic Performance of Retrofitted URM Buildings with RC Ring Beams

- Evidence of failure of RC ring beams installed to retrofit heritage stone buildings in Italy
- Example: church of Santa Giusta in L'Aquila

(D'Ayala, 2014)

Alternative Solution: Bandage (Reinforced Plaster)

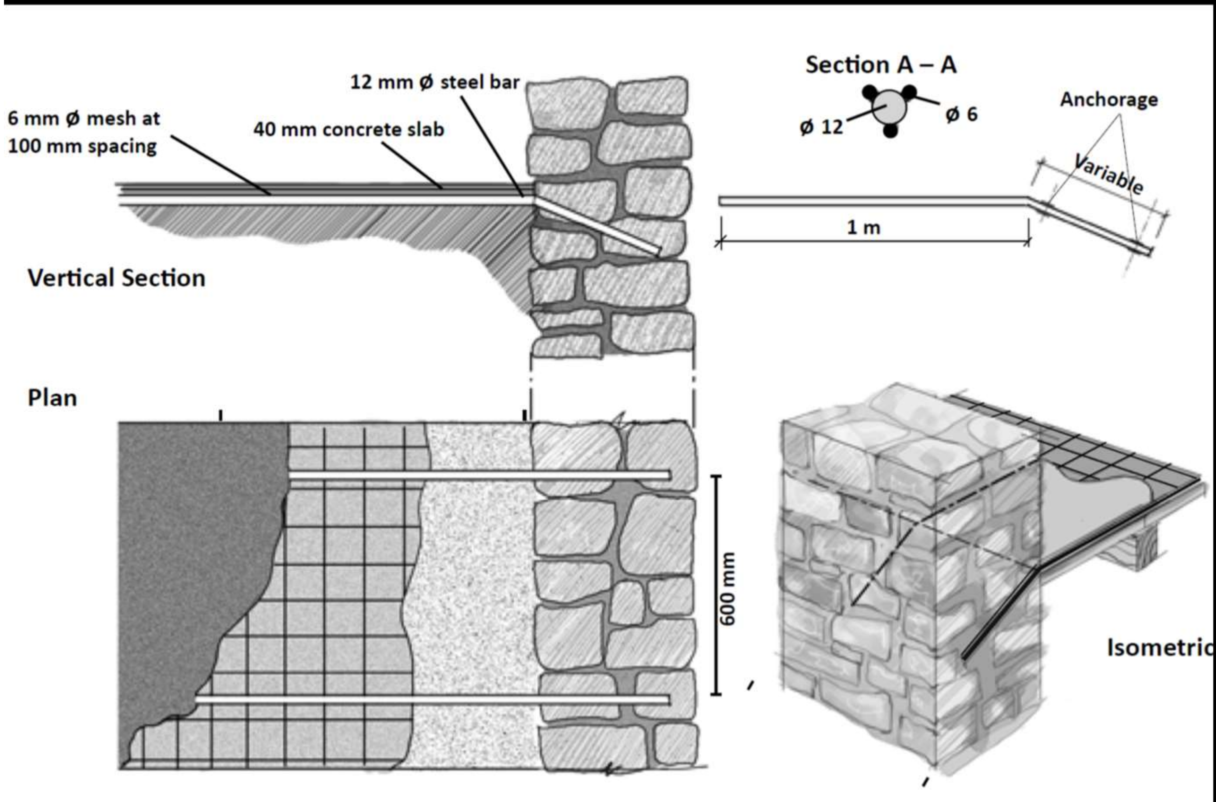


Source: Bothara and Brzev (2011)

I3: Strengthening of Existing Timber Floors

- The main purpose of strengthening is to increase the stiffness of floor system - particularly in case of flexible timber diaphragms
- Can be achieved by adding RC concrete overlay, constructing diagonal braces underneath the floor, etc.

Strengthening of Existing Timber Floors



Thin RC slab (40 mm thick) on top of the existing timber floor

Reinforced with welded wire mesh, plus steel bars anchored into the existing walls

Alternative solutions outlined by

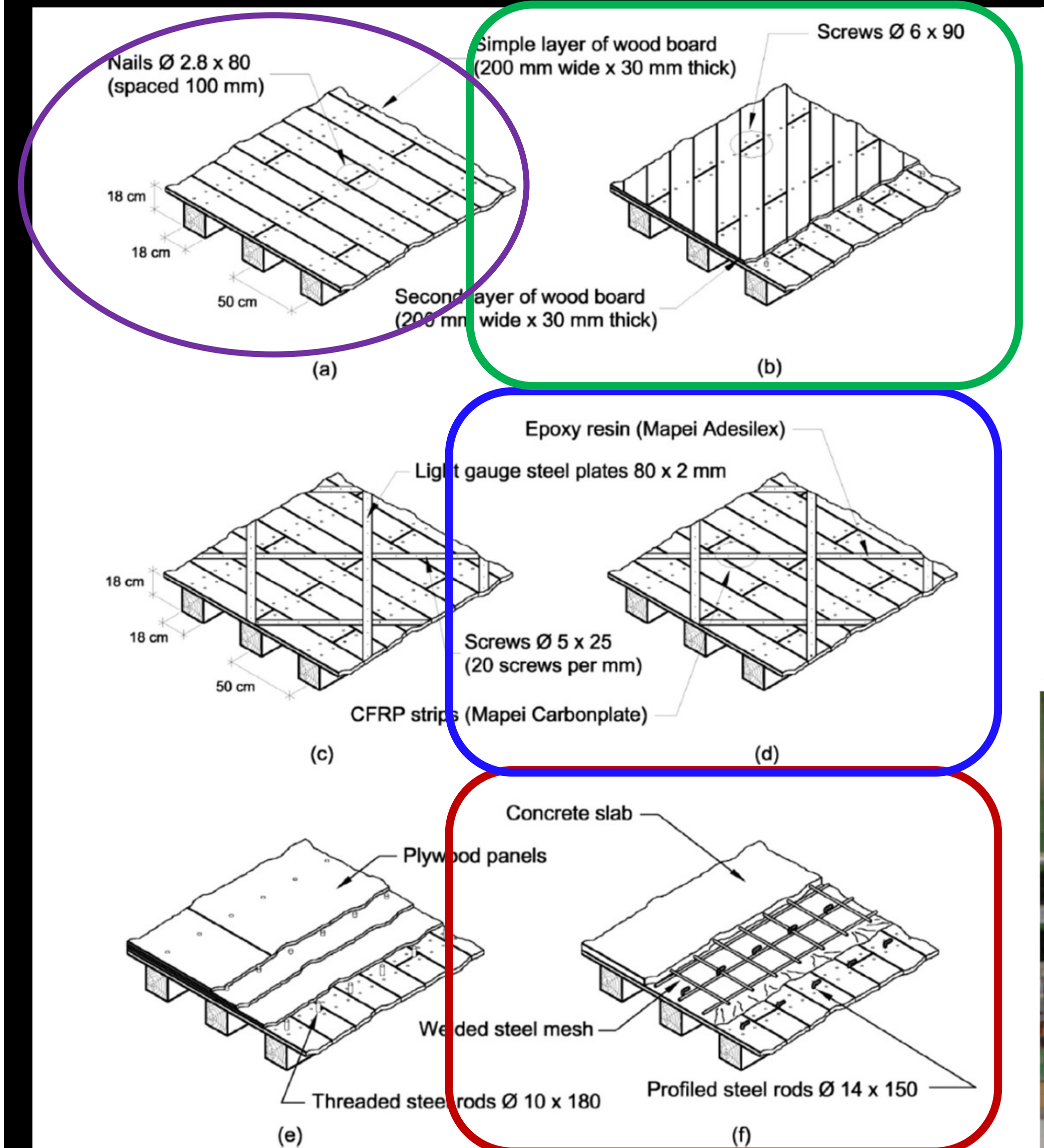
Bothara and Brzev (2011)

Source: Bothara and Brzev (2011), based on Maffei et al. (2006)

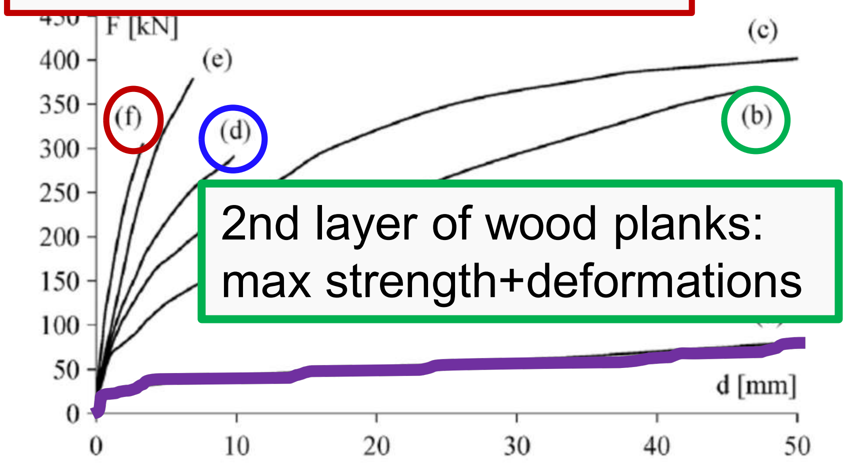
Strengthening of the Existing Timber Floors: Retrofitting example after the 2002 Molise, Italy eq.

Source: Maffei et al. (2006)

Strengthening of Existing Timber Floors: Alternative Solutions



RC slab: max stiffness



2nd layer of wood planks: max strength+deformations

Fig. 9. Results from experimentation of in-plane floor behaviour: resultant force versus mid-span displacement. (a) Existing simple layer of wood planks, (b) second layer of wood planks, (c) diagonal bracing with light gauge steel plates, (d) diagonal bracing with FRP laminae, (e) three layers of plywood, (f) reinforced concrete slab [26].

Source: Parisi and Piazza (2015)

I. Improving Overall Building Integrity: Challenges

- Effectiveness of new RC ring beams may be a challenge in heritage buildings with multi-leaf stone masonry walls, and is not permitted in Italy due to poor performance in past earthquakes.
- Strengthening of existing timber floors needs to be carefully designed. A thick layer of concrete atop an existing timber floor (or replacement of timber floor with new RC floor slab) should be avoided because such intervention may be detrimental for seismic performance
- Interventions characterized by a balanced increase of strength and stiffness are recommended (e.g. steel ties or alternative solutions for strengthening of timber floors)

C: Secure Wall-to-Floor (Roof) Connections

Most important, and in many cases the most vulnerable, feature related to seismic performance.

⇒Wall Anchors

Relatively expensive and disruptive to building occupants,

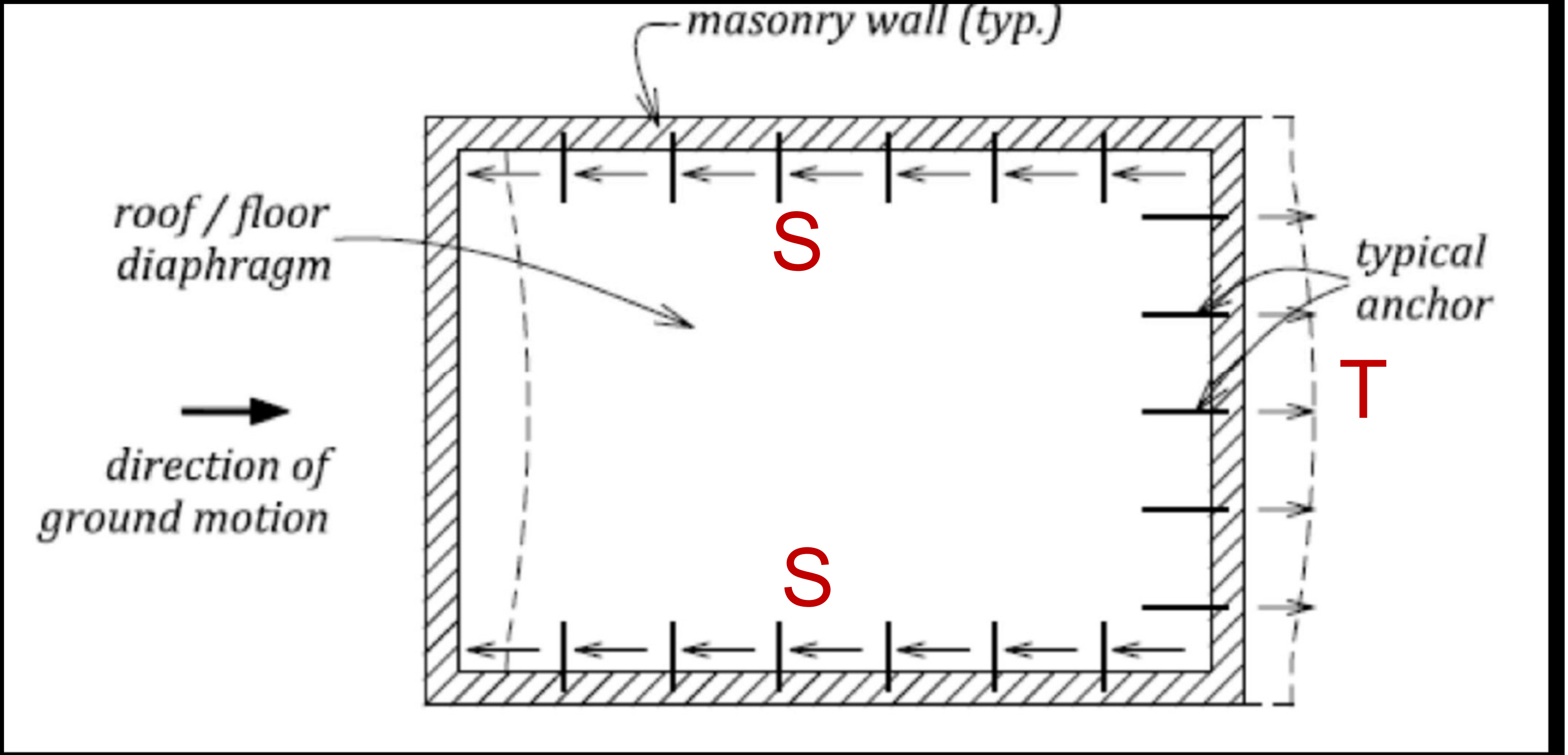
BUT

considered as the most cost-effective URM retrofit technique

Types of Wall Anchors

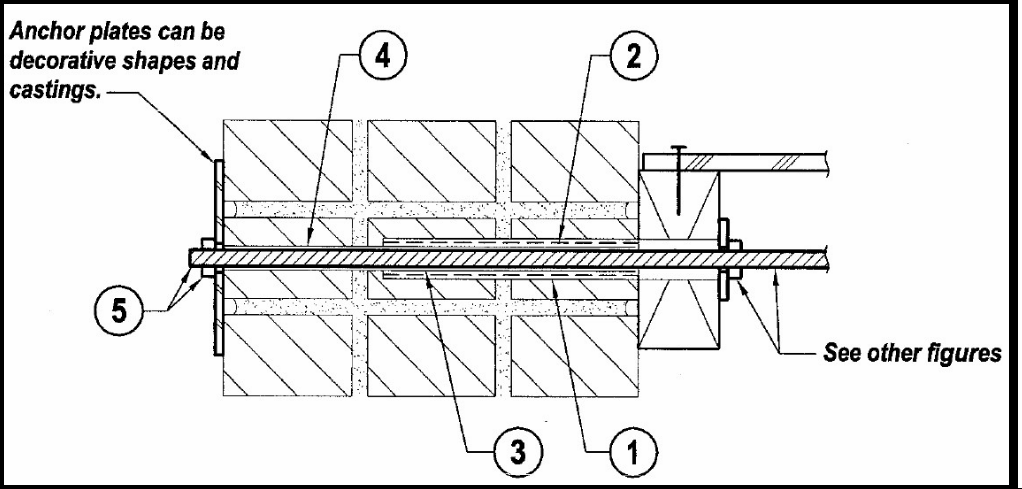
T Tension Anchors	Resist the out-of-plane forces induced by the diaphragm motion. Design based on the out-of-plane wall demand
S Shear Anchors	Resist the in-plane slippage of roof and floor systems along the face of the masonry walls. Shear anchor capacity need to be equal to diaphragm capacity

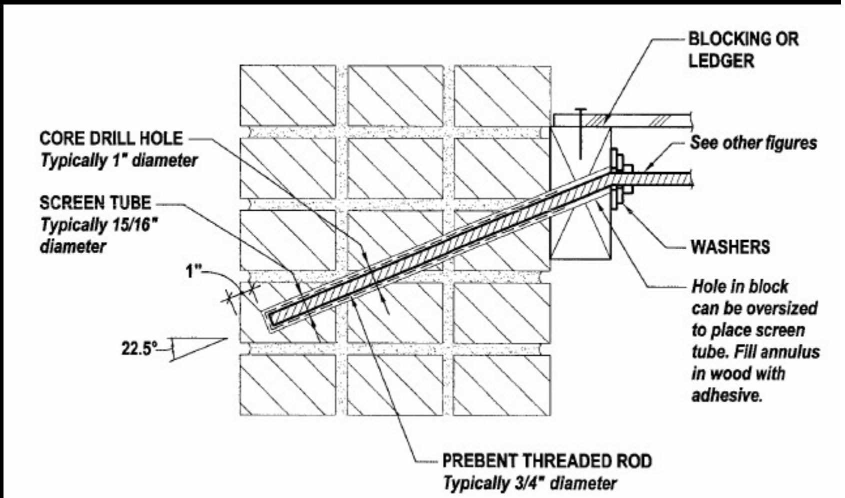
Tension and Shear Wall Anchors



Source: Brzev and Anderson (2018)

Anchor Solutions: New Zealand Experience





Source: Ingham and Griffith (2011)

C. Secure Wall-to-Floor (Roof) Connections: Challenges

- Anchors pulling through the wall due to poor quality masonry.
- Anchor pulling through the wall due to insufficient edge distance.
- Anchors pulling away from the floor/roof due to flexible ties.

=> Anchor design and construction need to be carefully executed

W: Wall Enhancement Methods

W1: Reinforced Concrete (Shotcrete) overlays

W2: Surface coatings

W3: Adhered fabrics using Fibre Reinforced Polymers (FRPs)

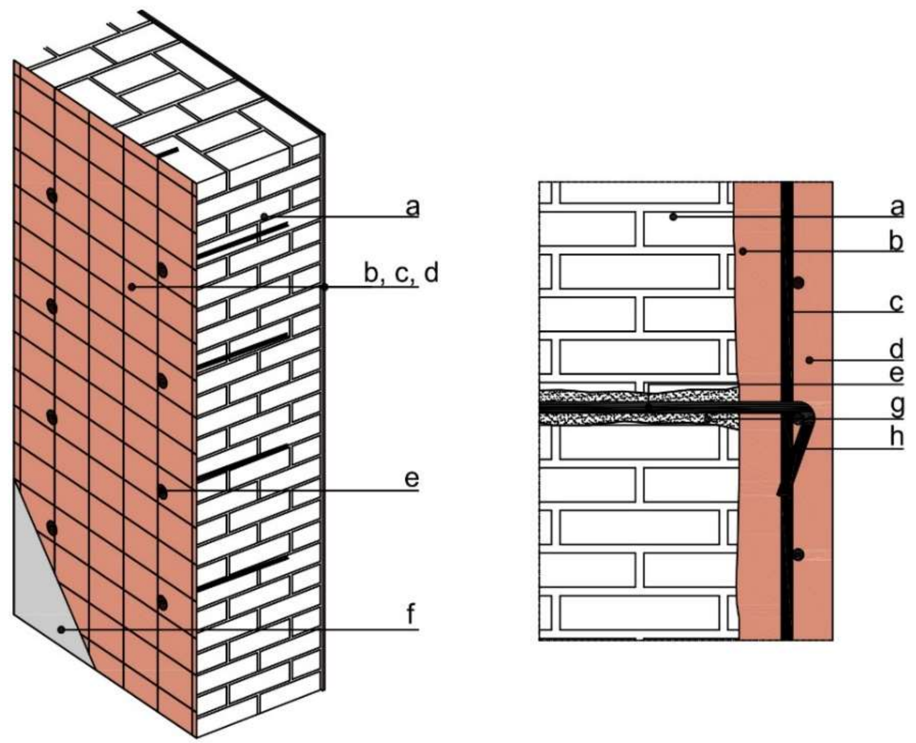
Wall Enhancement Methods: Strategies

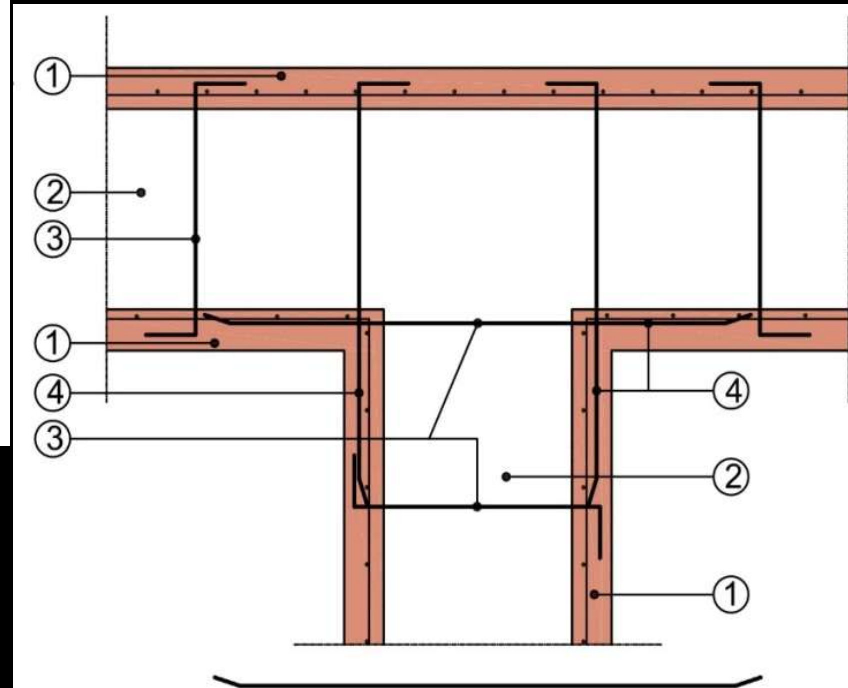
- Majority of the wall enhancement methods are aimed at increasing the lateral in-plane strength of a component.
- When lateral capacity of an existing wall or pier component is governed by a deformation-controlled action (e.g. sliding), a retrofit scheme will be most effective when it preserves or enhances the same type of action.

W1: Reinforced Concrete (Shotcrete) Overlays

- Shotcrete is sprayed onto the surface of an URM wall over a layer of reinforcement.
- Reinforcement typically consists of conventional reinforcing bars placed in the horizontal and vertical directions.
- Steel anchors are needed to ensure effective force transfer between the original wall and RC overlay

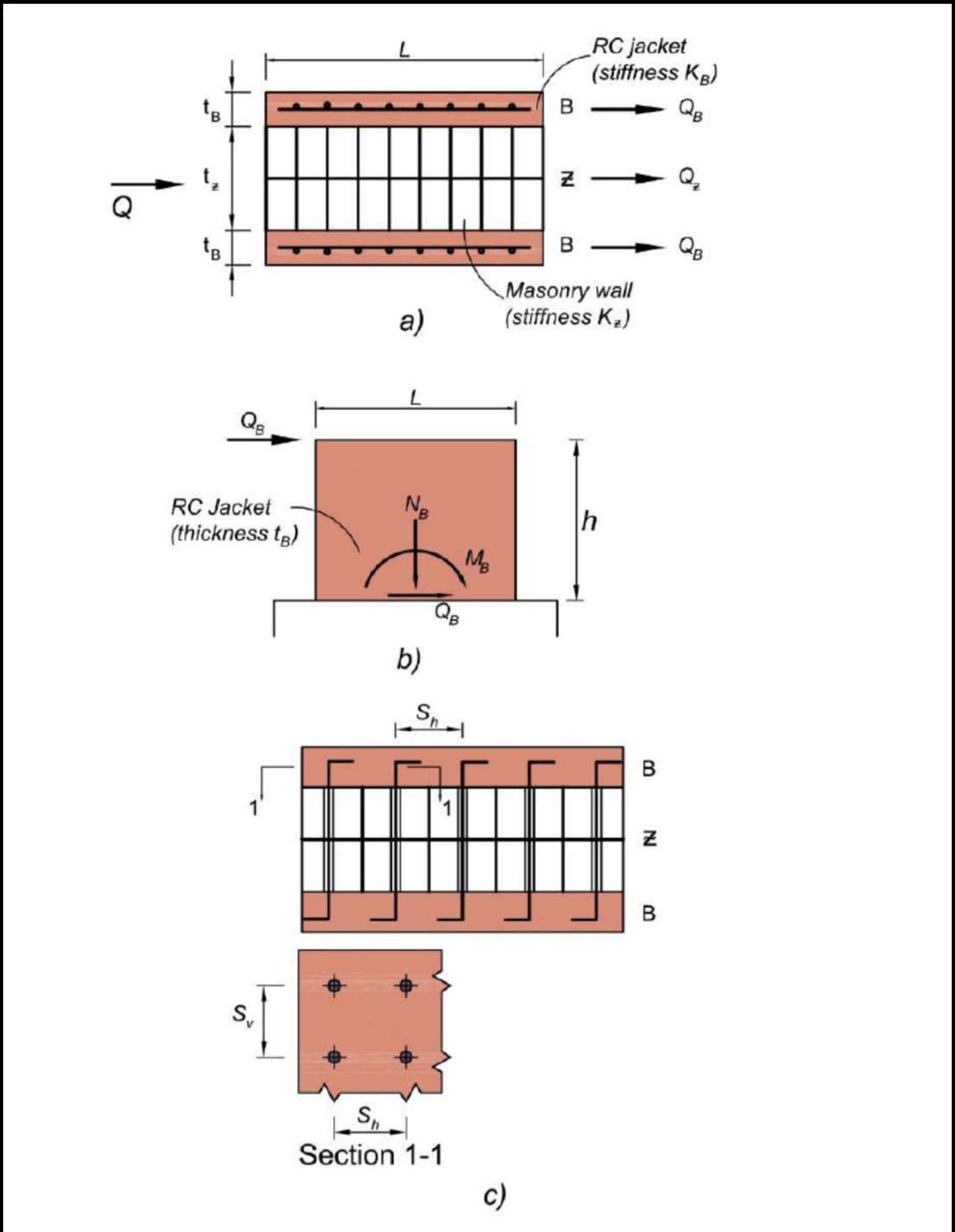
Reinforced Shotcrete Overlay: Details





Source: Brzev&Begaliev(2018)

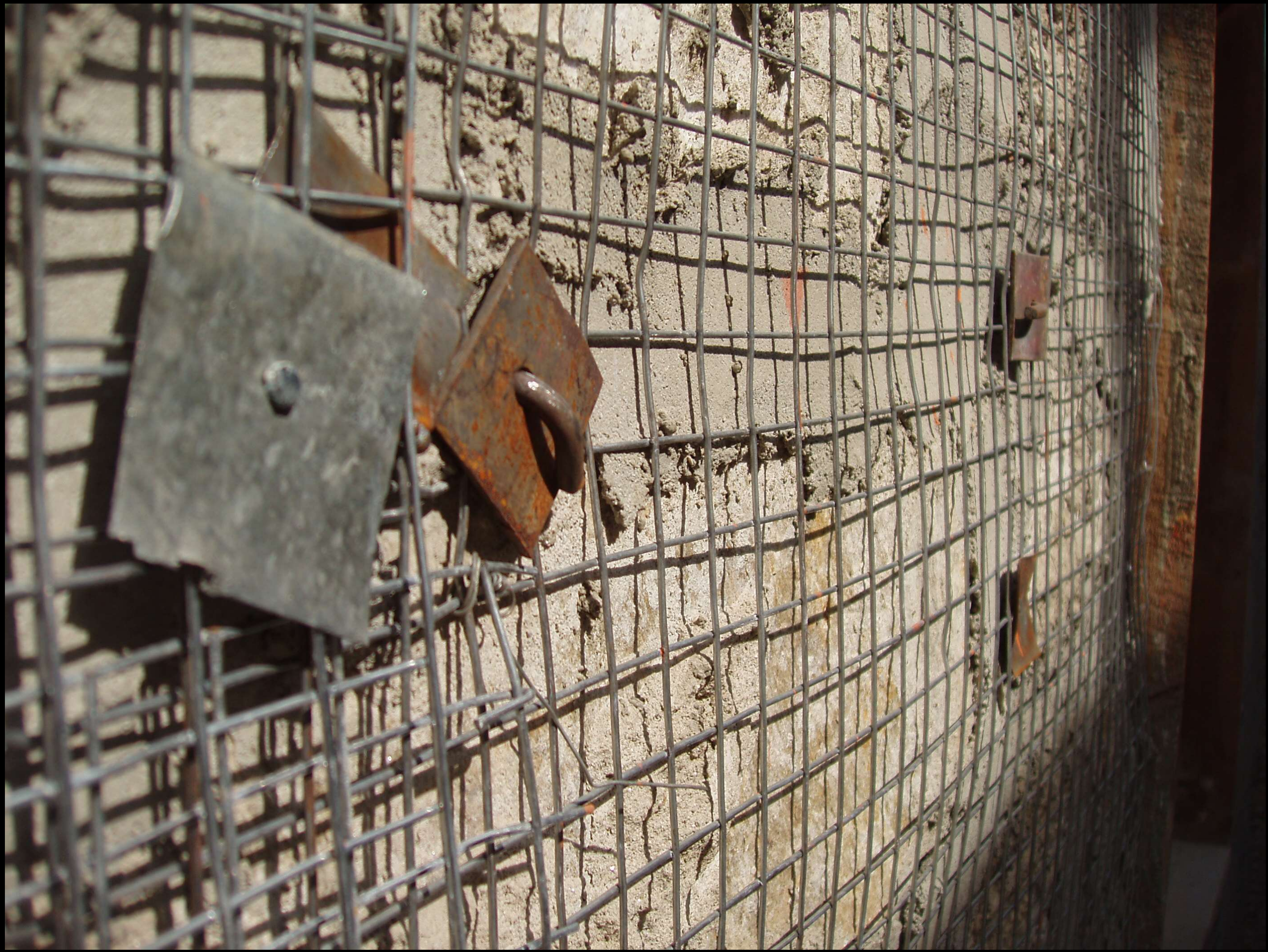
Reinforced Concrete Overlay: Design Concept



- Force redistribution between the original wall and the jacket - based on the stiffness
- It can be assumed that the jacket resists the entire shear force

Source: Brzev&Begaliev(2018)

Intallation of Wall Anchors: A Potential Challenge



Shotcrete – good performance in the 2011 Christchurch Eq. (New Zealand)

Source: Ingham and Griffith (2011)

W2: Surface Coating

- A thin cementitious coating applied on one or both sides of an URM wall. A layer of steel hardware or metal strips embedded into the coating.
- The coating is adhered to the wall with or without connectors.
- Solutions without connectors are simpler to implement!

Different Surface Coating Technologies are Available

Engineered Cementitious Composite (ECC) shotcrete (Lin et al., 2014)

University of Auckland, New Zealand

(a) Adding prebagged ECC into mixer

(b) Spraying of ECC shotcrete onto wallette

(c) Trowelling sprayed ECC flat prior to the spraying of successive layers

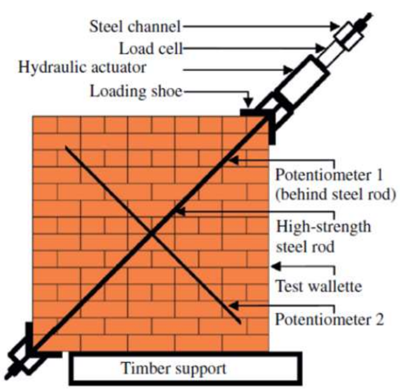
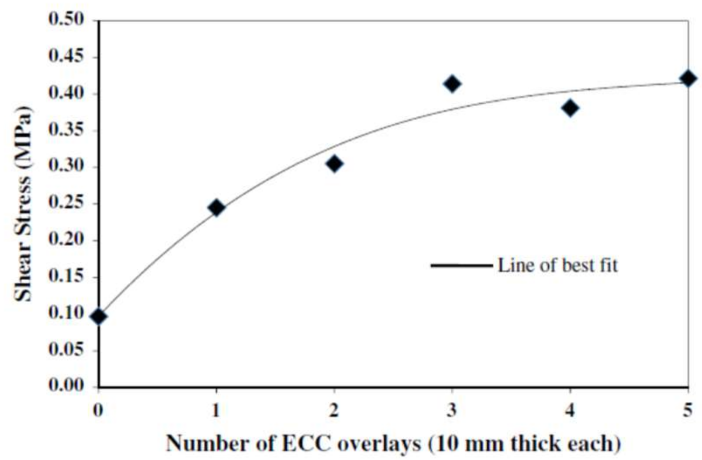


Fig. 6. Modified wallette test setup.



Eco-Friendly Ductile Cementitious Concrete (EDCC)

EDCC technology was developed and tested at the University of British Columbia, Canada (Salman Soleimani-Dashtaki and Nemy Banthia)

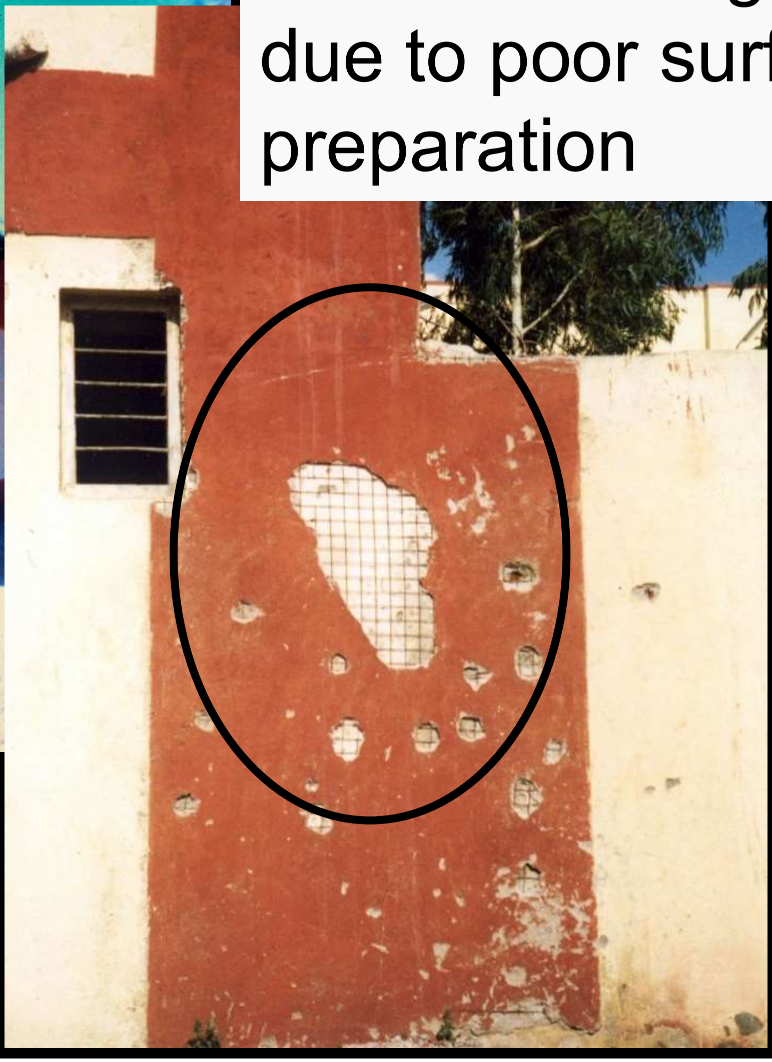
Thin overlay of sprayed fiber-reinforced concrete

EDCC combines cement with polymer-based fibres, flyash and other industrial additives

Shaking Table Testing of Masonry Walls Retrofitted with EDCC Technology (UBC, Vancouver, Canada)

Surface Coating: Application Challenges

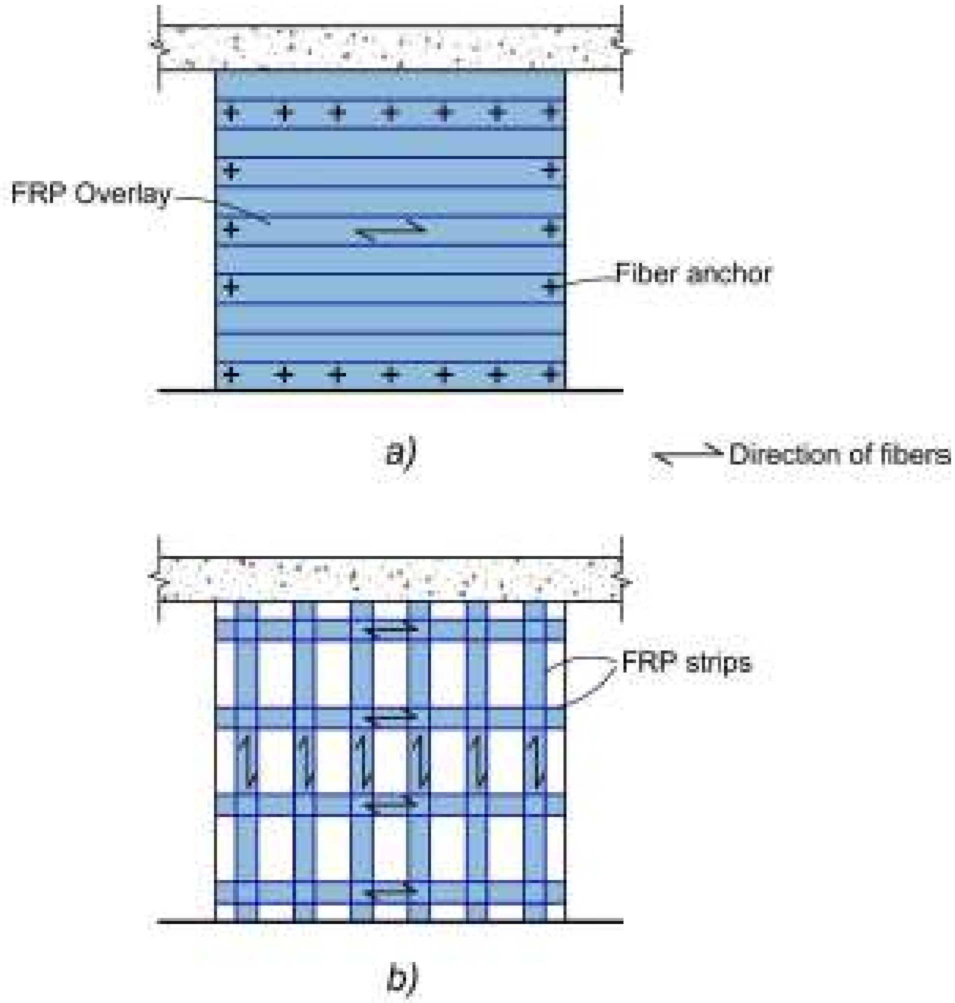
Peeling of the surface coating due to poor surface preparation



W3: Adhered FRP Fabrics

- Use of overlapping strips of high-strength fabric made out of Fibre Reinforced Polymers (FRPs) bonded to the wall surface using resin.
- Different types of fibres: glass, carbon, etc.
- Fabric can be applied to one or both sides of a wall.

FRP Overlays: Different Schemes



- Vertical strips:

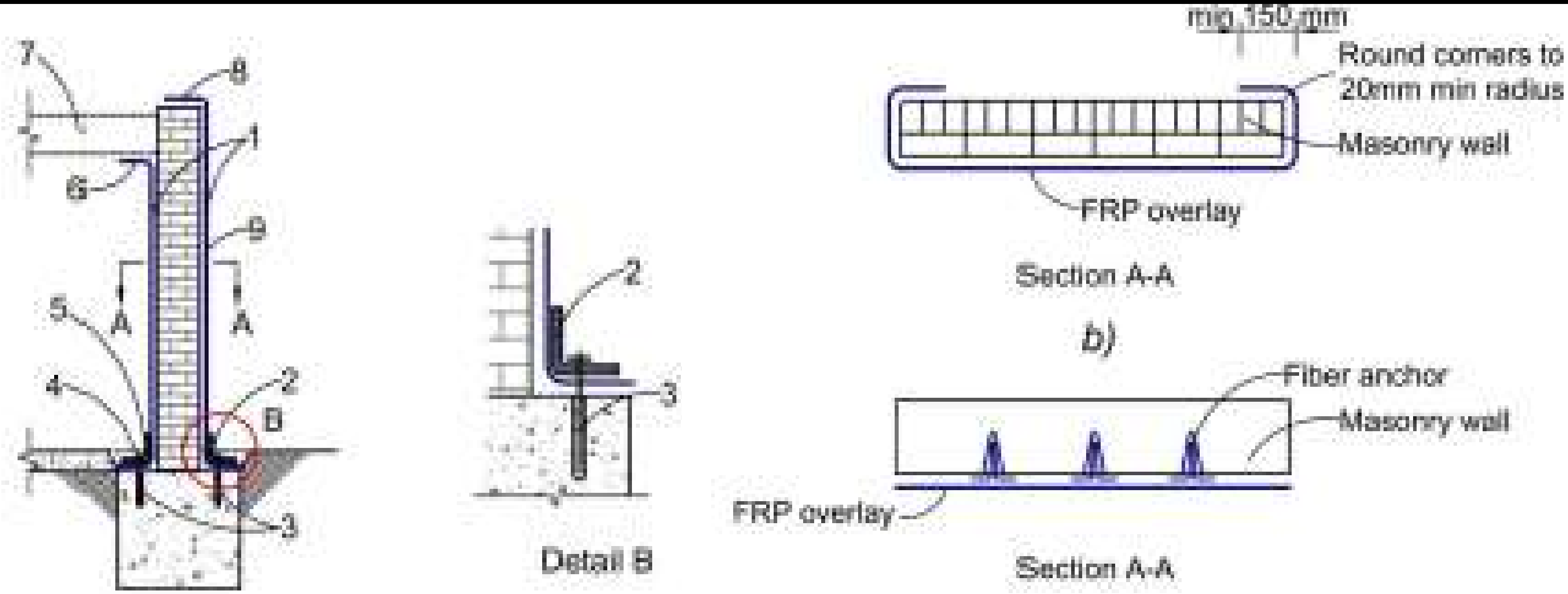
bottom edge of a fabric should be anchored into the existing footing or floor slab.

- Horizontal strips:

side edges should be anchored to the wall edges.

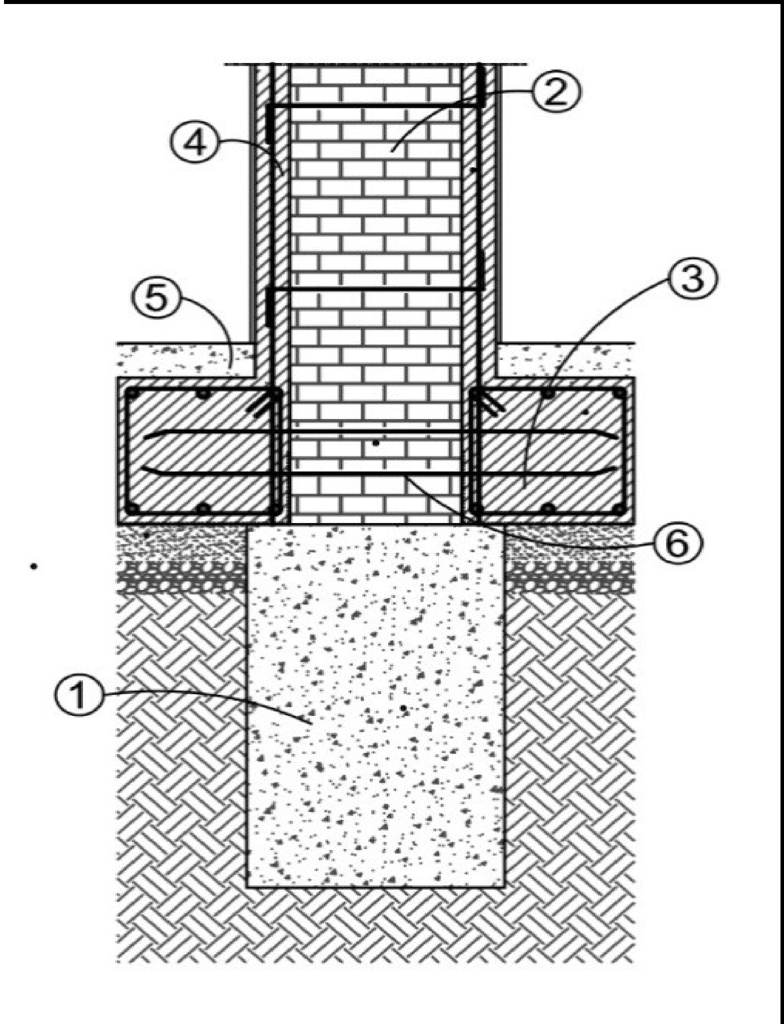
Source: Brzev&Begaliev(2018)

FRP Overlays: Application Details



Source: Brzev&Begaliev(2018)

Foundation Retrofit



Foundation retrofit is often required in conjunction with the wall retrofit, due to increased seismic demand at the base of the retrofitted wall (bending moments, shear forces).

Source: Brzev&Begaliev(2018)

W. Wall Enhancement Methods: Challenges

- Challenges are mostly related to construction.
- Design approaches are well established, however design of structures with externally applied FRP may require additional training for design engineers.
- Trained construction personnel is critical for successful implementation - for example any solution involving use of FRP technology.
- Reinforced shotcrete solution requires the use of wall anchors and is less favourable compared to alternative solutions (surface coating or FRP overlays).
- It is critical to extend the wall ehnacement solution into the foundation, and also retrofit the foundation (if needed).

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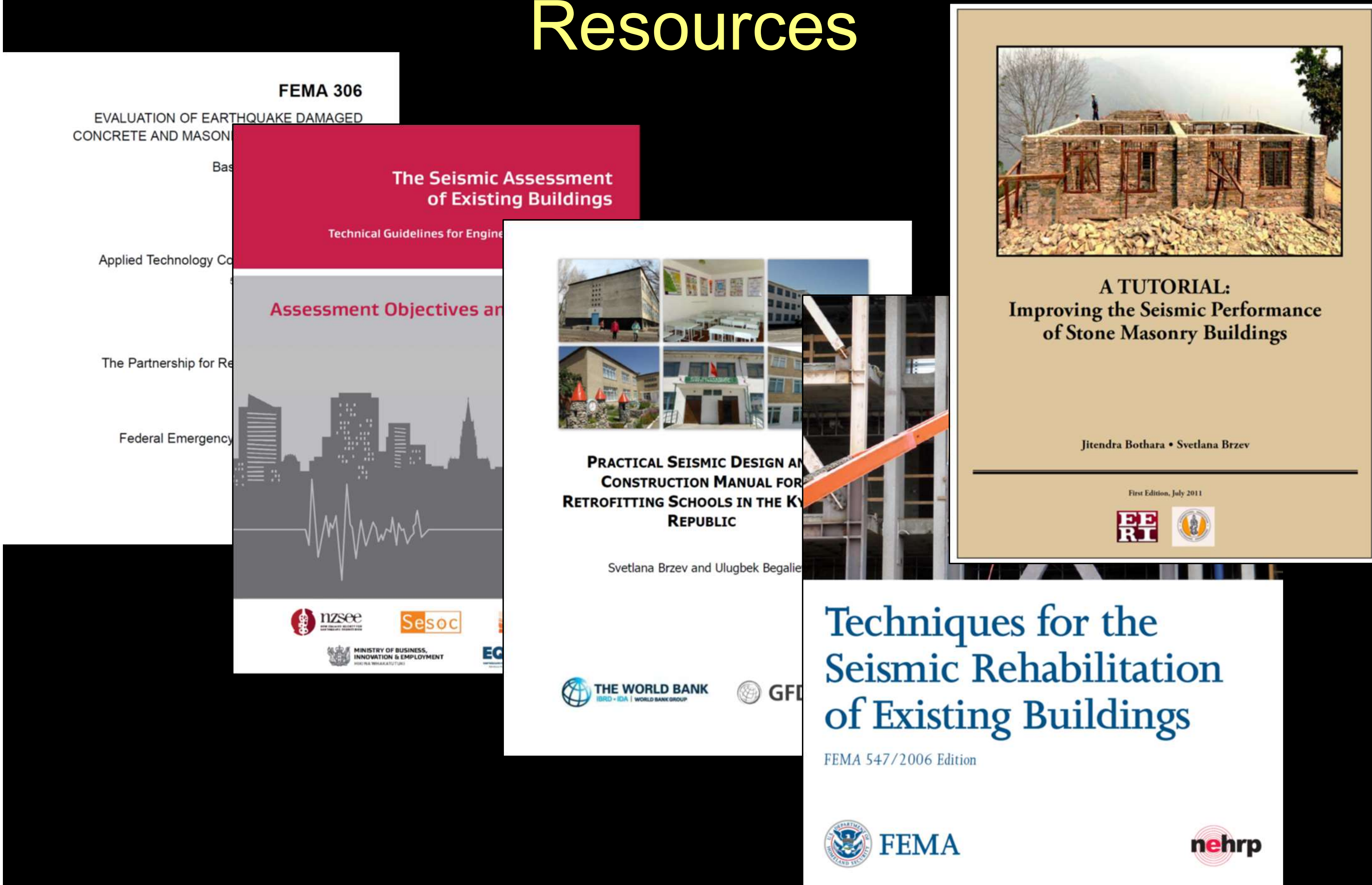
Manuals and Guidelines - Free Online Resources



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Thank you!

Hvala!