Seismic Design and Behaviour of Confined Masonry Buildings

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Why Confined Masonry?

- Unreinforced masonry (URM) and non-ductile reinforced concrete frame constructions exhibited poor seismic performance during the past earthquakes
  - Resulted in unacceptably huge loss of lives and properties

Collapse of unreinforced masonry building, California 1933
(Historical Society of Long Beach)
Why Confined Masonry?

- Unreinforced masonry (URM) and non-ductile reinforced concrete frame constructions exhibited poor seismic performance during the past earthquakes.

A warning placard at an URM’s entrance in California.

Such placards are now required statewide, enforceable with penalties upon building owners and local government.
Why Confined Masonry?

- Unreinforced masonry (URM) and non-ductile reinforced concrete frame constructions exhibited poor seismic performance during the past earthquakes
  - Resulted in unacceptably huge loss of lives and properties

Collapse of non-ductile RC frame buildings

Bhuj, India (2001)  
Turkey (1999)
To overcome the deficiencies of URM and non-ductile reinforced concrete (RC) frame system, different methods of reinforcing masonry panels have been developed over the years.

- Urgent need for developing and promoting alternative building technologies for low and medium-rise buildings.

Confined masonry (CM) construction has evolved based on the satisfactory performance in past earthquakes.

- First introduced in Italy as an alternative to URM buildings which were almost completely destroyed in the 1908 Messina earthquake.
- Practiced in Chile since 1930’s and in Mexico since 1940’s.
- Popular for low-rise residential buildings in many countries, of South and Central America, Asia and Eastern Europe.
Why Confined Masonry ?...

- During one of the Chilean Earthquakes only **16% of confined masonry houses** were partially collapsed as compared to collapse percentage of **57% for unreinforced brick masonry buildings**
- Provide fair amount of in-plane shear capacity, out-of-plane stability and ductility - **preferred especially in higher seismic zones**

Confined masonry building in M8.0 2007 Pisco, Peru Eqk (collapse of nearby adobe house)
What is Confined Masonry?

- Confined Masonry is a construction system where the walls are built first, and the columns and beams are poured in afterwards to enclose (confine) the wall.

- **Concept**

  The walls are tied down to the foundation.

  The **ties** work like a string around a parcel.

*Source: Swiss Agency for Development*
Most appropriate alternative to URM

- Confined masonry **construction is similar** to unreinforced masonry except for the inclusion of RC confining elements
  - Local masons can be quickly trained and become accustomed to it.
- Marginal increase in construction costs and, thereby, keeping it **economically feasible**

Source: Blondet (2005)

Courtesy - Quinn, D
Key Components: Confined Masonry Building
Confined Masonry vs Infilled RC Frames

- Different from regular infilled RC frames:
  - construction methodology, and
  - load transfer mechanism under gravity and lateral load
Confined Masonry vs Infilled RC Frames

- Different from regular infilled RC frames:
  - *construction methodology*, and
  - *load transfer mechanism* under gravity and lateral load

**Regular infilled RC frame**
- Concrete first
- Walls later

**Confined masonry wall**
- Walls first
- Concrete later

Source: Tom Schacher
Confined Masonry vs Infilled RC Frames...

- **load transfer mechanism** under gravity and lateral load

**Confined masonry wall**
- Masonry walls mostly resist the gravity loads
- Under lateral seismic loads, walls behave similar to RC shear walls
- Straightforward transmission of forces

**Regular infilled RC frame**
- Small fraction of gravity loads are transferred to walls
- Infill wall panels act as compressive diagonal struts due to lack of good bonding
- Complicated transmission of forces
Advantages of confining walls with tie-beams and tie-columns

- Improved wall-to-wall and floor/roof-to-wall connection which guarantees better transfer of forces analogous to closed box-type action during a seismic event.

- Greater in-plane and out-of-plane stability of slender structural walls, and

- Enhanced strength, ductility, and energy dissipation capacity when compared to the unreinforced load bearing masonry walls.
Confined Masonry vs Infilled RC Frames…

- Regular infilled RC frame

- Confined masonry wall with tooothing at wall-to-tie-column interface
Confined Masonry Walls Under Lateral Loads

Three stages:

A – Onset of cracking

B – Cracking propagates through RC tie-columns

C - Failure
Confined Masonry Walls Under Lateral Loads…

- Lateral load carrying capacity of Confined Masonry walls will depend on:
  - Strength of the masonry used (brick, adobe, concrete masonry, etc.)
  - Location of RC tie-columns and tie-beams
  - Cross-sectional details of RC tie-columns
    - Geometric details, and
    - Reinforcement details (longitudinal and transverse reinforcement)
  - Type of interface between wall edge and tie-column
  - Presence of openings
Good bonding between a masonry wall and adjacent RC tie-columns can be achieved by

- **‘toothing’** at the wall-to-tie-column interface
- providing dowels anchored into RC tie-columns.

‘Toothing’ is also referred as ‘shear-key’ and ‘toothed shear-key’.

![Diagram showing the role of wall-to-tie-column interface with toothed edges and shear connectors](image-url)
Experimental Study: Role of Tooothing

- **Specimen details** - RC members designed as per Mexican code

![Regular infill frame](image1)

![Confined masonry with coarse toothing](image2)

![Confined masonry with fine toothing](image3)

![Confined masonry with no toothing](image4)
Loading history

- **Out-of-plane loading**
  - Real ground motion (e.g. 1952 Taft N21E component)
  - Scaled to match the given hazard level (e.g., Taft 0.40g compared with DBE in Zone V)

### IS 1893-2002 & Equivalent Taft ground motion

<table>
<thead>
<tr>
<th>Seismic Zone</th>
<th>PGA (g)</th>
<th>Designation during the test</th>
<th>Peak acceleration (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-</td>
<td>-</td>
<td>Level I</td>
<td>0.055</td>
</tr>
<tr>
<td>Zone II</td>
<td>0.10</td>
<td>Level II</td>
<td>0.111</td>
</tr>
<tr>
<td>Zone III</td>
<td>0.16</td>
<td>Level III</td>
<td>0.177</td>
</tr>
<tr>
<td>Zone IV</td>
<td>0.24</td>
<td>Level IV</td>
<td>0.266</td>
</tr>
<tr>
<td>Zone V</td>
<td>0.36</td>
<td>Level V</td>
<td>0.400</td>
</tr>
</tbody>
</table>
In-plane loading

- Slow cyclic in-plane drifts (ACI 374.1-05) using displacement-controlled actuator
- Three cycles at each drift level

Loading history…

- In-plane loading
- Slow cyclic in-plane drifts (ACI 374.1-05) using displacement-controlled actuator
- Three cycles at each drift level
Cracking Patterns

Separation of masonry panel with RC element at drift level of 0.2%. Significant OOP deflection and on the verge of possible collapse.

Perform similar to wall $S_{CT}$ under in-plane and OOP loads. However, the damage is more uniformly distributed.

Rocking of panels due to severe damage at toe of tie-column. Acted like a shear wall and moves almost rigidly with the base under OOP loads.

Acted like a shear wall under combined loading. Severe crushing of bricks led to greater strength degradation.
Out-of-plane Behaviour

- **Out-of-plane (OOP) displacement**
  - Infill wall showed continuous increase in OOP deflection and likely to collapse after 1.75% drift
  - OOP displacement in confined walls remains fairly constant
**In-plane Behaviour**

- **Idealized tri-linear plots**
  - Confined masonry wall SC\textsubscript{FT} with *fine tootthing performed* better than other schemes due to its higher ductility and reduced rate of strength and stiffness degradation.
Material Quality... Masonry Units

- **Seismic resistance** of confined masonry house designs depends upon **strength and quality of masonry units** used.

- **Acceptable masonry units** for confined masonry construction:
  
<table>
<thead>
<tr>
<th>Masonry Units</th>
<th>Standards</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete Blocks (Solid and Hollow)</td>
<td>IS: 2185 (Part 1)-2005</td>
</tr>
<tr>
<td>Burnt Clay Hollow Bricks</td>
<td>IS: 3952-1988</td>
</tr>
<tr>
<td>Autoclaved Cellular (Aerated) Concrete Blocks</td>
<td>IS: 2185 (Part 3)-1984</td>
</tr>
</tbody>
</table>

- Units not permitted for confined masonry construction: **masonry units with horizontal perforations, and natural stone masonry and adobe (sun-dried earthen units)**
Material Quality... Masonry Units

- **Minimum Compressive Strength of masonry units (determined based on the net area)**
  - Clay brick units
    - Upto 2-storey building - 3.5 MPa
    - More than 2-storey building - 7.0 MPa
  - Concrete blocks - 7.0 MPa
Material Quality... Mortar

- Type M1, M2, H1 and H2 mortars per IS 1905 shall be used

<table>
<thead>
<tr>
<th>Mortar mix (cement: lime: sand)</th>
<th>Min strength (28 days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type H1 – 1 : 1/4 : 3</td>
<td>10.0</td>
</tr>
<tr>
<td>Type H2 – 1 : 1/2 : 4 1/2</td>
<td>6.0</td>
</tr>
<tr>
<td>Type M1 – 1 : 1 : 6</td>
<td>3.0</td>
</tr>
<tr>
<td>Type M2 – 1 : 2 : 9</td>
<td>2.0</td>
</tr>
</tbody>
</table>

- Requirements of a good mortar are workability, flow, water retentivity in the plastic state and bond, extensibility, compressive strength, and durability in the hardened state.
- Compressive strength of mortar, in general, should not be greater than masonry unit.
- Bond strength, in general, is more important (Lime-based mortars should be preferred)
Concrete and Reinforcement

- **Concrete**
  - Minimum grade of concrete shall be M15 as per IS 456
  - Concrete mix should provide adequate workability (slump = 75-100 mm)
  - Size of the coarse aggregate should be less than 12.5 mm

- **Reinforcement**
  - Fe 415 grade steel (see IS: 1786-2008) shall be used for reinforced concrete tie-columns and tie-beams.
  - Mild steel bars may be used for the stirrups in tie-columns and tie-beams.
Design Considerations

- Building Configuration

- A regular building configuration is one of the key requirements for satisfactory earthquake performance
  - The building plan should be of a regular shape
  - The building’s length-to-width ratio in plan shall not exceed 4
  - The walls should be built in a symmetrical manner
  - The walls should be placed as far apart as possible, preferably at the façade, to avoid twisting (torsion) of the building in an earthquake
Building Configuration

- There are at least two lines of walls in each orthogonal direction of the building plan, and the walls along each line extend over at least 50% of the building dimension.

\[ L_1 + L_2 \geq 0.5L \]
\[ L_3 \geq 0.5L \]

- The walls should always be continuous up the building height – vertical offsets are not permitted.
- Openings (doors and windows) should be placed in the same position on each floor.
Building Configuration…

Irregular

No

Regular

Yes

No

More than 4 times the width

Yes

Less than 4 times the width
Building Configuration…

a) No

b) Yes

c) No

d) Yes
Building Configuration...

Discontinuous walls

No

Continuous walls

Yes

Inadequate location openings
Minimum Design Dimensions Requirements

- Tie-beam in parapets $\geq 500$ mm
- Tie-column spacing $\leq 2.5$ m
- $H/t \leq 25$
- $t \geq 110$ mm
- Confining elements around openings
- Tie-columns at wall intersections
Minimum Design Dimensions Requirements...

- Minimum tie-column and tie-beam dimensions (*depth × width*) shall be **150 mm × t** (where *t* is wall thickness)
Minimum Design Dimensions Requirements…

- **Minimum Dimension of Masonry Walls**
  - Wall thickness \((t)\) should not be less than 110 mm.
  - Maximum wall height/thickness \((H/t)\) ratio shall not exceed 25
  - Unsupported wall height \((H)\) shall not exceed 2.5 m
  - Height-to-width ratio of wall should be kept less than 2 for the better lateral load transfer

- **Parapets**
  - When a parapet is not confined by tie-beams, height should not exceed 500 mm,
  - Otherwise the height limit is 1.2 m.
Wall with Openings

- Presence of large openings have a negative effect on seismic performance buildings, especially if openings are not confined.

- Size of Opening
  - **Large opening** - total area > 10% of wall panel area, and
  - **Small opening** - total area ≤ 10% of wall panel area.
Large Openings

- When reinforced concrete tie-columns are not provided at the ends of an opening
  - Contribution of wall to seismic resistance of the building should be disregarded but should be strengthened per IS 4326
Wall with Openings

- Regular infilled frame with window opening and lintel beam only

- Confined masonry wall with continuous horizontal bands
Large Openings

\[ A_{op} > 0.1 \, L \times h \]
Not considered in calculations, \( A_T = 0 \)

\[ A_{op} > 0.1 \, L \times h \]
\[ A_{T,1} = L_1 \times t, \]
\[ A_{T,2} = L_2 \times t \]

\[ A_{op} > 0.25 \, L \times h \]
**Small Openings**

- \( A_{op} < 0.1 \, L \times h \)
- \( A_T = L \times t \)
- \( A_{op} < 0.1 \, L \times h \)
- \( A_T = (L_1 + L_2) \times t \)
- \( A_{op} < 0.1 \, L \times h \)
- \( A_T = L_1 \times t \)

- Small opening can be ignored when it is located outside the diagonals.
Design of Confined Masonry Building

- **Wall Density Requirements**
  
  - **Wall density** $w_d$ is a key indicator of safety for low-rise confined masonry buildings subjected to seismic and gravity loads.
  
  - Provide an initial assessment on required wall area.
  
  - Confined masonry buildings with adequate wall density resist the effects of major earthquakes without collapse.

$$W_d = \frac{A_w}{A_p}$$

- $A_P = $ area of the building floor plan
- $A_W = $ cross-sectional area of all walls in one direction
Wall Density

- Wall density value should be determined for both directions of the building plan

\[ A_p = \text{product of the wall length and thickness} \]

Source: Meli et al. (2011)
Wall Density…

- **Minimum Wall Density for Zone V**

<table>
<thead>
<tr>
<th>Number of Stories</th>
<th>Rock or Firm Soil</th>
<th>Medium and Soft Soil</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Solid Clay Bricks</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1.5</td>
<td>2.5</td>
</tr>
<tr>
<td>2</td>
<td>3.0</td>
<td>4.5</td>
</tr>
<tr>
<td></td>
<td>Solid concrete blocks</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>2.0</td>
<td>3.5</td>
</tr>
<tr>
<td>2</td>
<td>4.0</td>
<td>6.5</td>
</tr>
</tbody>
</table>

- These Wall Density values should be used for **Simple Buildings**

*Source: Meli et al. (2011)*
Wall Density…

- Requirements of **Simple Building**
  - exterior walls extend over at least 50% of the length of each end of the building plan at each story

\[ l_1 + l_2 + l_3 + l_4 \geq 0.5L \]
\[ w_1 + w_2 \geq 0.5W \]

*Source: Meli et al. (2011)*
Wall Density…

- Requirements of *Simple Building*…
  - exterior walls extend over at least 50% of the length of each end of the building plan at each story

*Source: Meli et al. (2011)*
Limit State Design of Confined Masonry Walls

- **Design loads** ($F_d$)
  
  $$F_d = \gamma_f \times \text{Characteristic loads}$$

  - $\gamma_f =$ partial safety factor
    - 1.5DL + 1.5LL
    - 1.5DL + 1.5(WL or EL)
    - 0.9 DL + 1.5(WL or EL)
    - 1.2DL+1.2LL+1.2(WL or EL)

- **Design strength of materials** ($f_d$)
  
  $$f_d = \frac{\text{Characteristic strength of material}}{\gamma_m}$$

  - partial safety factor, $\gamma_m$ should be taken as 2.0 for masonry, 1.5 for concrete and 1.15 for steel
Limit State Design of Confined Masonry Walls…

- **Axial Load Resistance** \( (P_u) \)

\[
P_u = k_s \left( 0.4 f_m A_m + 0.45 f_{ck} A_c + 0.75 f_y A_s \right)
\]

- \( A_m \) = Net area of masonry
- \( A_c \) = cross-sectional area of concrete excluding reinforcing steel
- \( A_{st} \) = Area of steel
- \( f_y \) = yield strength of the reinforcing steel
- \( k_s \) = stress reduction factor as in Table 9 of IS:1905-1987
Limit State Design of Confined Masonry Walls…

- Moment resistance due to combined axial load and in-plane bending
  
a) When $0 \leq P \leq P_u/3$

\[ M_u = 0.3Pd + M_{uf} \]

\[ M_{uf} = 0.87 f_y A_s (l_w - b) \]

b) When $P > P_u/3$

\[ M_u = \left[ 0.15Pd + 1.5M_{uf} \right] \cdot \left( 1 - \frac{P}{P_u} \right) \]
Limit State Design of Confined Masonry Walls…

- Design for Shear

Three stages:
A – Onset of cracking
B – Cracking propagates through RC tie-columns
C - Failure

- Contribution of reinforced concrete tie-columns is not considered in the design to increase a safety margin
Design for Shear

- Masonry shear resistance \((V_u)\)

\[
V_u = 0.8 \left( 0.5v_m A_T + 0.4P_d \right) f
\]

but

\[
V_u \leq 1.5v_m A_T
\]

where \(P_d\) is the design compressive axial load which shall include permanent loads only and with the partial safety factor of 1.0, and \(v_m\) is masonry shear strength

\[
v_m = 0.18\sqrt{f_m}
\]

\[
f = 1.55 \text{ if } H/L \leq 0.2
\]
\[
f = 1.7 - 0.7H/L \text{ if } 0.2 < H/L \leq 1.0
\]
\[
f = 1.0 \text{ if } H/L > 1.0
\]
Design of Tie-Columns and Tie-Beams

- **Minimum amount of longitudinal reinforcement**
  - Total area of reinforcement should be **not less than 0.8 %** of the gross cross-section area of the column

- **Minimum amount of transverse reinforcement (ties)**
  - Transverse reinforcement in the form of closed stirrups (ties) with the minimum area $A_{sc}$ equal to

$$A_{sc} = 0.002s \times h_c$$

  - where $h_c$ is the dimension of tie-column or tie-beam in the wall plane and $s$ is the tie spacing.

- Tie spacing ($s$) should not exceed the lesser of 200 mm and $1.5t$
Construction Details

- Example of Confined Masonry Construction at IITGN
  - Six G+3 (four-storey) hostel buildings with single- and double-occupancy rooms
  - Thirty G+2 (three-storey) staff and faculty quarters.
Example of Confined Masonry Construction at IITGN

- **Fly Ash Lime Gypsum (FALG) bricks** with min. compressive strength of 9.0 MPa were used for above grade construction,

- For foundations below the plinth level burnt clay bricks with a min. compressive strength of 5.0 MPa were used.

*Source: IITGN*
Construction Details...

FALG brick manufacturing plant

Brick manufacturing machine

Brick supply at the plant

FALG bricks at the construction site

Source: IITGN
Confined Masonry Construction at IITGN

- **Mortar**
  - 1:1:6 - cement: lime: sand mortar (Type M1 mortar) according to the IS:1905 standard.
  - Hydrated Lime Class ‘C’ in the form of a fine dry powder was used

- **Concrete**
  - M25 grade with a minimum 300 kg cement per m³, and water/cement ratio of 0.5 or less was used
  - The required slump was 50 to 100 mm for tie-columns and 30 to 50 mm for tie-beams
Confined Masonry Construction at IITGN…

- **Reinforcement**
  - High strength TMT bars (Fe500D grade).
  - Smaller bar sizes (8 mm) were used for ties in tie-beams and tie-columns,
  - 10, 12, and 16 mm bars were used for longitudinal reinforcement

- **Minimum Requirement**
  - *Longitudinal reinforcement* in tie-columns and tie-beams should consist of **minimum 4 reinforcing bars** with the **minimum 8 mm diameter**.
  - **Minimum 6 mm diameter** bars should be used for **ties** in tie-columns and tie-beams
Confined Masonry Construction at IITGN…

- Wall footings

Source: IITGN
**RC Plinth Band**

- RC plinth band was constructed continuously beneath the walls.
- The plinth band cross-sectional dimensions were 350 mm square.
- Reinforcement consisted of six 12 mm diameter longitudinal reinforcing bars and 8 mm closed ties at 100 mm spacing c/c with 135 degree hooks.

First, the reinforcement cages were laid in position. Next, vertical reinforcement for the RC tie-columns was erected from the plinth level and anchored into the plinth bands.

Once the reinforcement was laid, shuttering was erected on each side along the band.
Confined Masonry Construction at IITGN...

- RC Plinth Band

Source: IITGN
Confined Masonry Construction at IITGN…

- **RC Plinth Band**
  
  - Longitudinal reinforced need to be anchored properly
  
  - In this project, the longitudinal reinforcement was anchored into the plinth band using 90 degree hooks extended into the plinth band by 450 mm
  
  - Size of the RC plinth band was more robust than what it would have been otherwise.
Confined Masonry Construction at IITGN…

- **RC Plinth Band**

  - *Plinth band reinforcement cage set in place*
  - *Formwork for plinth band construction*
  - *Tie-column longitudinal reinforcement anchored into plinth band*
  - *Plinth level in a building showing tie-column reinforcement extending above the plinth band*
Construction of Confined Masonry Walls

- Masonry walls were constructed on top of the RC plinth band (at the ground floor) or the RC slabs (at upper storey levels)

Source: IITGN
Construction of Confined Masonry Walls...

- The confined masonry walls were 230 mm thick (one brick thick) and were constructed in English bond
- Horizontal mortar bed joint was about 10 to 12 mm thick

Source: IITGN
Construction of Confined Masonry Walls…

- Tothing at the wall to tie-column interface
  - Tothing is important for achieving a satisfactory bond between masonry walls and adjacent RC tie-columns

Source: EERI
Construction of Confined Masonry Walls...

- Tothing at the wall to tie-column interface...

Tothing 1/3-1/4 of a block: (max 1/2 of brick length)

GOOD!

Tothing 1/2 of a block: (> 1/2 of brick length)

TOO BIG!

Source: EERI
Construction of Confined Masonry Walls…

- Tothing at the wall to tie-column interface...

Toothed wall edges at an interior tie-column

Toothed wall edges at a corner tie-column

Source: IITGN
Tooting at the wall to tie-column interface...

Tooting at cross wall intersections

Source: IITGN
Wall construction stages

- 1.5 m of wall height (approximately one-half of the overall storey height) was to be constructed in one lift, followed by casting of RC tie-columns
- Construction suspended for 3-4 days for the wall to achieve sufficient strength so that the concrete for the tie-columns could be poured
- This procedure was repeated at each storey level
Construction of Confined Masonry Walls...

- Wall construction stages...

Wall construction completed up to 1.5 m height (one lift)

Tie-column construction completed up to 1.5 m height

Sequence of wall and tie-column construction

Source: IITGN
Reinforced concrete lintel bands

- Building RC bands is common for load-bearing masonry construction.
- RC lintel bands were constructed atop the openings (doors and windows) at each storey level.
- **First**, reinforcement cages were assembled on the ground.
- **Subsequently**, formwork was set in place and concrete was poured.
- The upper courses of the brick masonry wall beneath the band had to be wetted before the concrete was poured to prevent the bricks from absorbing water from the fresh concrete.
Construction of Confined Masonry Walls...

- Reinforced concrete lintel bands

Reinforcement cages set in place
Formwork for lintel bands

**Construction of RC lintel bands**

Source: IITGN
Construction of Confined Masonry Walls…

- Masonry and RC-tie-column construction above the lintel band level

Source: IITGN
Construction of Reinforced Concrete Tie-column

- RC tie-column act in unison with the masonry walls to ensure the seismic safety of a confined masonry building

For rebars:
- min Ø 8 mm

For stirrups:
- min Ø 6 mm

Source: EERI
Construction of Reinforced Concrete Tie-column…

Source: Meli et al. (2011)

Alternate position of stirrup hooks

Source: EERI
Spacing of transverse reinforcement (ties) in tie-columns

Length over which the reduced tie spacing - twice the column dimension (2b or 2t), or \( h_0 / 6 \)
Construction of Reinforced Concrete Tie-column...

- **IITGN project** - Longitudinal reinforcement in the tie-columns consisted of 4 high strength TMT steel bars of 12 to 16 mm diameter (depending on the location)
- For ties 8 mm diameter bars were placed at spacing of 150 mm centre to centre.

*Source: IITGN*
Construction of Reinforced Concrete Tie-column...

- **Construction sequence** - Casting the concrete in RC tie-columns at each storey level was done in two stages.
  - **First**, a masonry wall was constructed up to the specified height equal to approximately one-half of the storey height
  - **Next**, concrete was poured to the same height in adjacent tie-columns

Source: IITGN
Construction of Reinforced Concrete Tie-beam

- Anchorage of Longitudinal Bars: T-connection

Source: EERI
Construction of Reinforced Concrete Tie-beam

extend hooked bars from the inside to the outside

Connection with straight bars.

Connection around the inner corner.

Source: EERI
Construction of Reinforced Concrete Tie-beam

- Anchorage of Longitudinal Bars: L-connection

Rebars must cross like the fingers of a hand!

Source: EERI
Construction of Reinforced Concrete Elements

- **Lap Length**

  - Longitudinal reinforcing bars should be spliced within the middle third of the column height or beam span.
  - The splices should be staggered so that not more than 2 bars are spliced at any one location.

*Source: EERI*
Shuttering

Source: EERI
Shuttering

- Column shuttering was placed in position on two faces of an interior tie-column, while the masonry acted as shuttering on the remaining two faces.

- Shuttering was extended by 25 to 50 mm beyond the toothing on the wall. It had to be fixed properly in position to maintain the required shape and size of the tie-columns.

- The shuttering faces were joined together using a mix of clamps and steel wire ties. Also, nails were driven into bricks to attach formwork to the masonry walls.
Shuttering...

Formwork must be well braced!

Source: EERI
Shuttering...

Shuttering in place at an interior tie-column

Steel wire ties were used to fix shuttering in place

Masonry wall surface showing a hole in a brick created to secure the formwork in place

Source: IITGN
Shuttering...

At upper floors

Wooden scantling
Tie wire
Nails for tie wire
Shuttering

Ø 8 mm rebars built in tie-beam

Source: EERI
Shuttering...

Never add water to make the concrete more liquid and “flow down better”!

Use a stick (or rebar) and a hammer to help the concrete flow down, to compact it and avoid air pockets. **Use a mechanical vibrator if one is available!**
Shuttering…

Use wood planks to connect formwork.

Formwork must be well fastened!

Source: EERI
Shuttering...

Formwork can be nailed to the walls on both sides.

Source: EERI
Construction of Slab

Laying slab reinforcement

Concrete Pouring and Compaction

Completed floor slab construction

Source: IITGN
Construction Cost

<table>
<thead>
<tr>
<th>Building type</th>
<th>Structural System</th>
<th>Built-up Area (m²)</th>
<th>Structural Cost (Rs. Crore*)</th>
<th>Cost of Structure (Rs. per m²)</th>
<th>Total Cost (Rs. Crore*)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Faculty and Staff Housing</td>
<td>Confined Masonry</td>
<td>49,270</td>
<td>42.5</td>
<td>8,626</td>
<td>127</td>
</tr>
<tr>
<td>Hostels</td>
<td>Confined Masonry</td>
<td>35,943</td>
<td>32.0</td>
<td>8,903</td>
<td>79</td>
</tr>
<tr>
<td>Academic Buildings</td>
<td>RC Frame with Masonry Infill</td>
<td>45,200</td>
<td>71.0</td>
<td>15,708</td>
<td>192</td>
</tr>
</tbody>
</table>

- The cost savings are due to a smaller amount of concrete and steel because of smaller member sizes in confined masonry buildings compared to RC frame buildings.

Source: IITGN
Finished Buildings… Faculty and staff housing

Source: IITGN
Finished Buildings… Faculty and staff housing

Source: IITGN
Finished Buildings… Student hostels

Source: IITGN
Finished Buildings… Student hostels

Source: IITGN
Summary

- Confined masonry construction is commonly adopted in countries/regions with very high seismic risk, such as, Mexico, Chile, Peru, Indonesia, China, etc.

- If properly built, shows satisfactory seismic performance

- Confined masonry construction have been exposed to several earthquakes (Brzev 2014):
  - 1985 Mexico City (Magnitude 8.0)
  - 2001 El Salvador (Magnitude 7.7)
  - 2003 Bam, Iran (Magnitude 6.6)
  - 2007 Pisco, Peru (Magnitude 8.0)
  - 2010 Chile (Magnitude 8.8)
  - 2010 Haiti (Magnitude 7.0)

Confined masonry buildings performed very well in these major earthquakes – some buildings were damaged but no human losses
Summary

- Most suitable alternative for low- and medium rise buildings of unreinforced masonry and non-ductile RC frames
- Most suitable for India as 80-90% construction are ‘Mistry (mason) Technology’
  - Local masons can be quickly trained
  - Economically feasible

Extensive engineering input not required!
Thank You!

Questions and Suggestions…

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