HOW CONFINED MASONRY BUILDINGS FAIL IN EARTHQUAKES

Build Earthquake Resistant Houses
Change Construction Practice Permanently

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DIGRESSION: How Confined Masonry Buildings Fail in Earthquakes

- Overturning (collapse) of masonry gable wall
- Out-of-plane failure of masonry wall
- In plane shear failure (diagonal cracking) of masonry wall (sliding shear and bending)
- Instability of interior walls and failure of unconfined walls and frames
- Shear failure of confining elements
- Bond failure between masonry and concrete elements
- Buckling of tie columns

List Courtesy Prof. Ken Elwood, UBC

Elevation Rule # 2
Allowable Slenderness

Slenderness is the height of wall divided by thickness of wall (h/t)

If the wall is tall and slender, it will be able to resist lower earthquake forces before failing

Most building codes allow a maximum h/t = 15

Architectural preference in Aceh is for a 3m tall wall. For wall thickness with plaster of 0.13m, h/t = 23

BUT, if wall has a longer continuous shear walls (not interrupted by openings) and structural cross-walls it will perform better in earthquakes

Failure Mode #1: Overturning (Collapse) of Masonry Gable

→ In an earthquake, the most vulnerable part of the single story confined masonry buildings being built in Aceh is the masonry in the gable (above the ring beam)

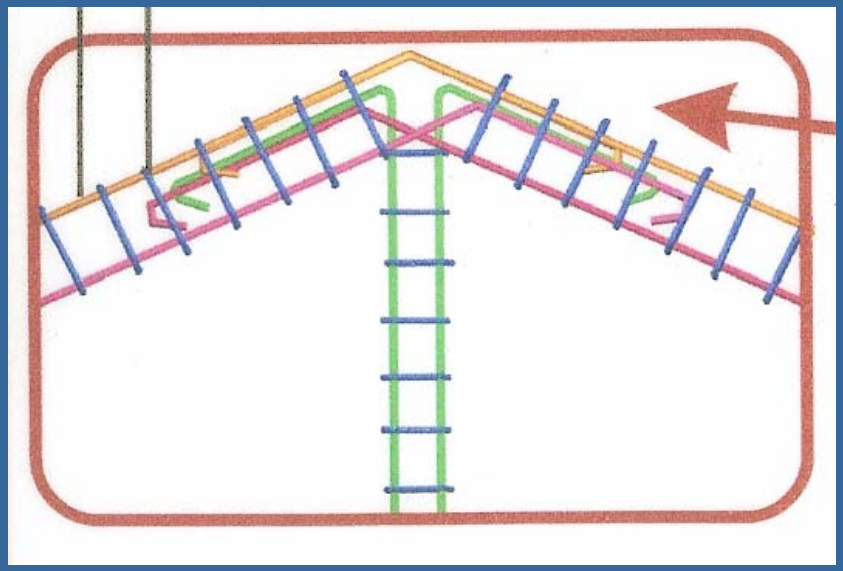
WHY

- Very high slenderness ratio
- High center of gravity (tendency to overturn)
- Very difficult to confine properly (poor connections between RC elements)
- Poor masonry and RC workmanship

Damage to gable walls in 27 May 2006 Central Java earthquake

To Prevent Collapse of Masonry in Gable: Don't Use Masonry Above Ring Beam

→ Steel detailing and connections is inadequate



Teddy Boen and YIPD

Bad Practice (Buruk)

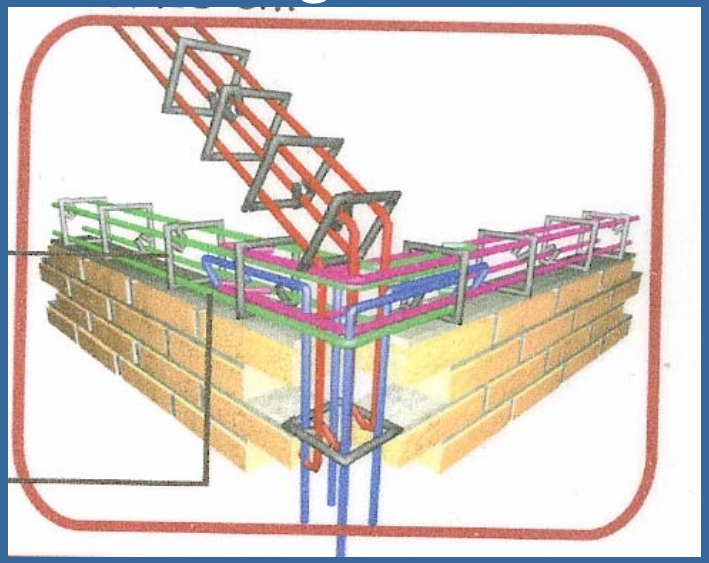
→ *Steel bars in center column not long enough to tie into diagonal beam, diagonal not connected at top or at column*

Good Practice (Baik)

→ *Steel bars in center column developed in gable beam*

To Prevent Collapse of Masonry in Gable: Don't Use Masonry Above Ring Beam

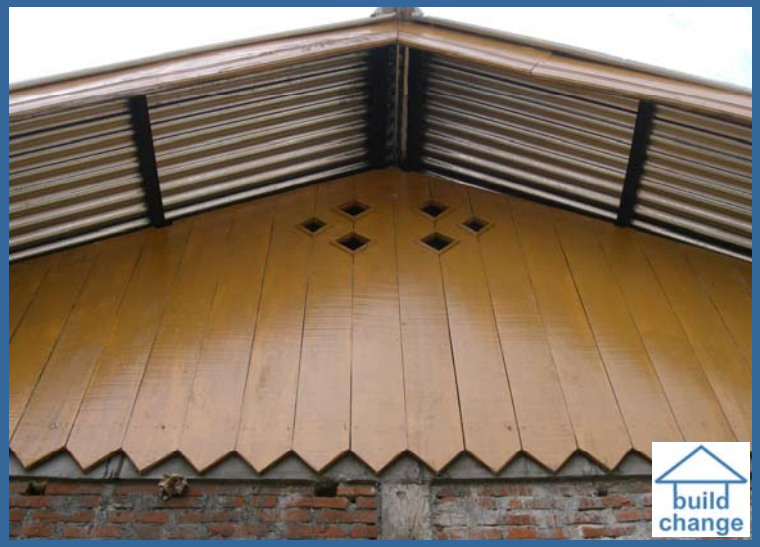
→ Very difficult to get an adequate connection between the gable beam and ring beam



Teddy Boen and YIPD

Alternatives To Masonry Above Ring Beam

(1) Use Timber or other lightweight material



(2) Use Rabung Empat or Rabung Lima (Hipped Roof)

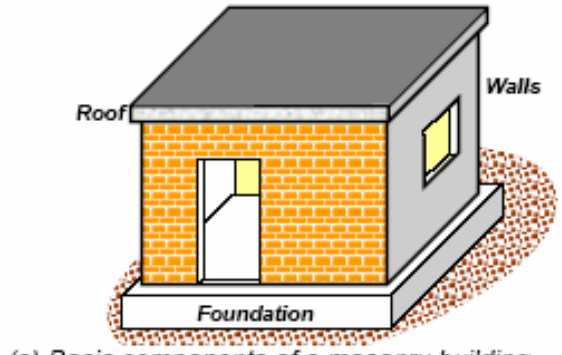
Build Change houses in Lampisang and Keunue ue, Peukan Bada Subdistrict of Aceh Besar

Alternatives To Masonry Above Ring Beam

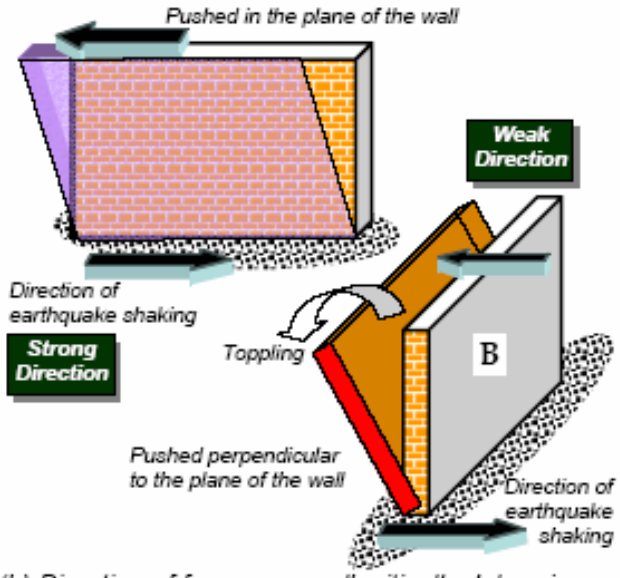
Roof Type	Materials Cost (circa April 2006)
Masonry in Gable, Full Timber Truss	Rp. 11.6 million
Papan Gable ← (Pitched)	Rp. 10.6 million
Masonry in Gable, Partial Truss	Rp. 10.2 million
Rabung Empat ← (Hipped)	Rp. 8.8 million

Failure Mode #2: Out-of-Plane Failure of Masonry Wall

→ *Houses built for municipal employees in Banda Aceh, cracking caused by 26 December 2004 earthquake*

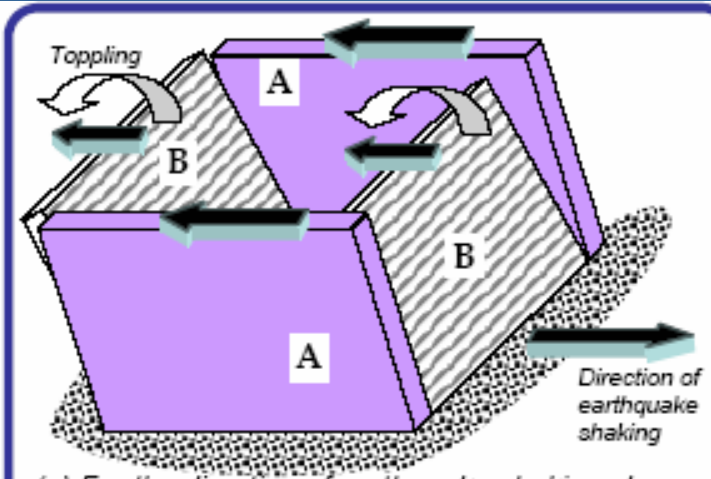


(a) Basic components of a masonry building

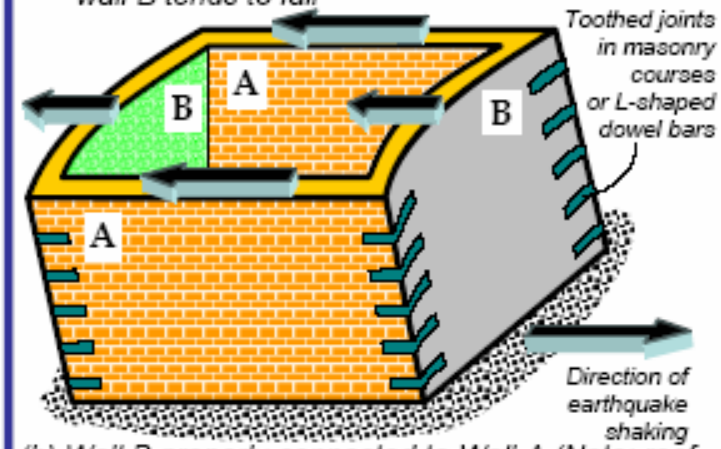


(b) Direction of force on a wall critically determines its earthquake performance

Figure 1: Basic components of a masonry building – *walls are sensitive to direction of earthquake forces.*



(a) For the direction of earthquake shaking shown, wall B tends to fail



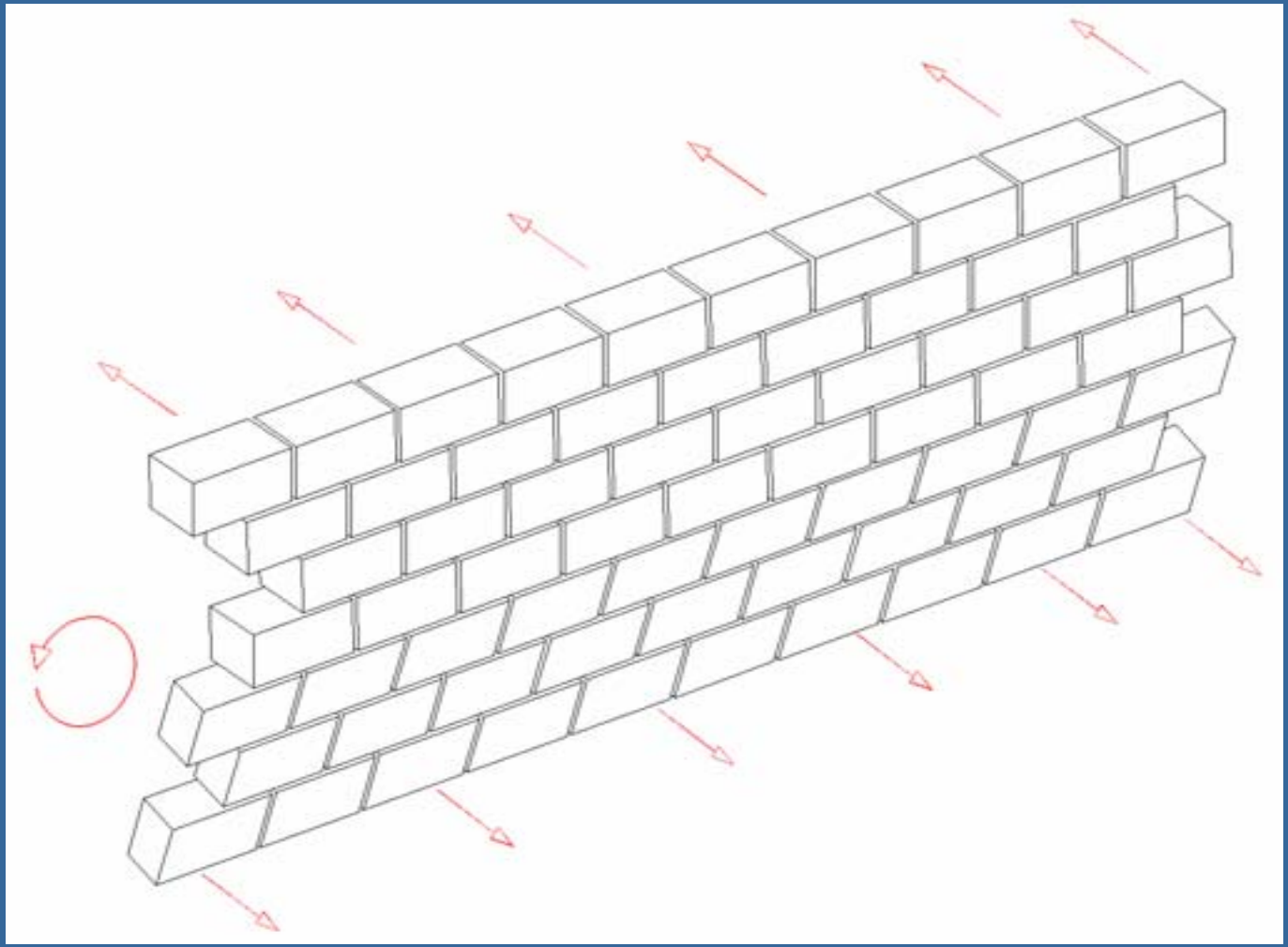
(b) Wall B properly connected to Wall A (Note: roof is not shown): Walls A (loaded in strong direction) support Walls B (loaded in weak direction)

Figure 2: Advantage sharing between walls – *only possible if walls are well connected.*

from IITK-bmtpc Earthquake Tip #12

Out-of-Plane Failure Mechanism #1
Overturning as Rigid Body

Out-of-Plane Failure Mechanism #2



Horizontal cracking along masonry bed joint

Schematic from City University of London Guideline on Confined Masonry and Interpretation of Eurocode 8

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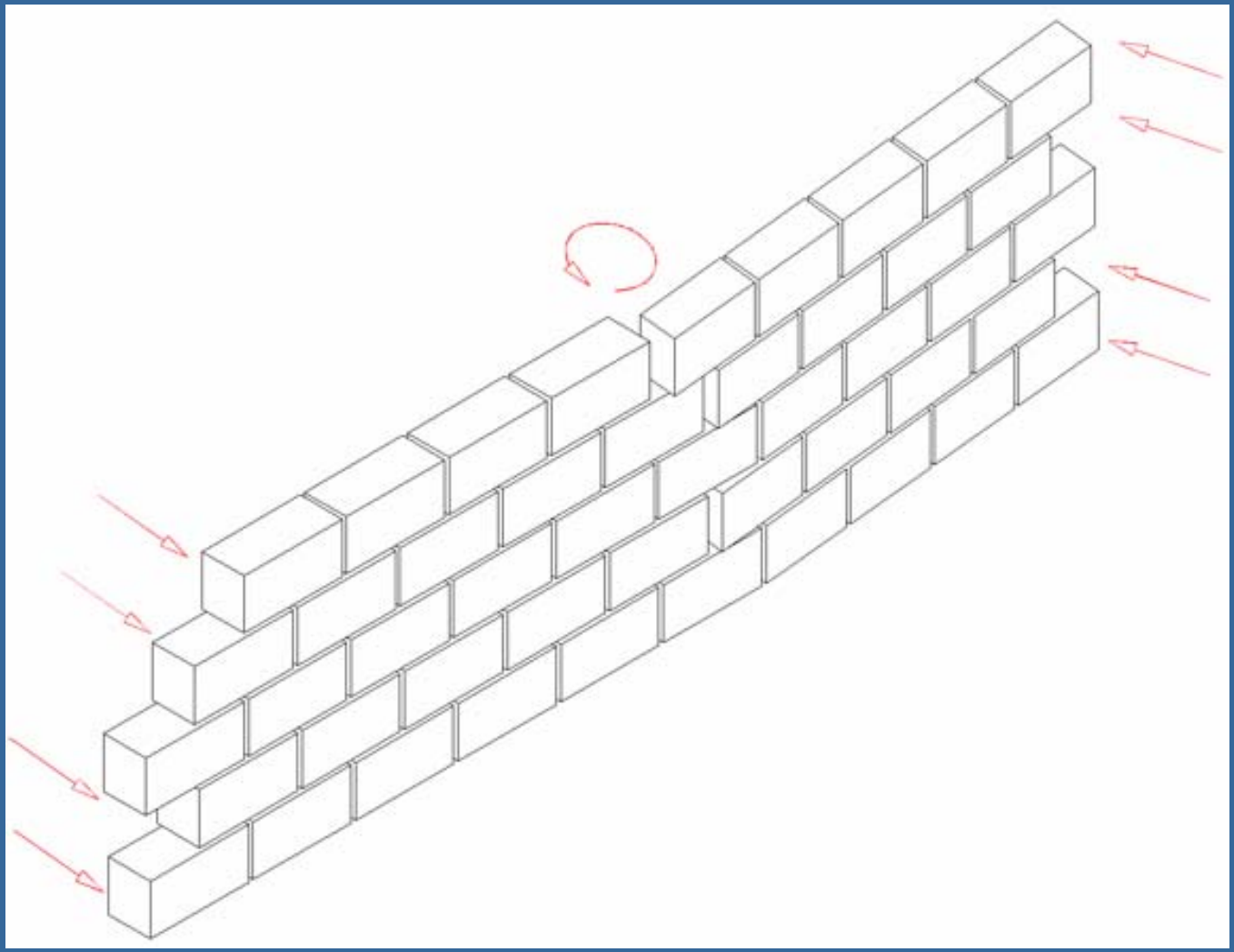
Out-of-Plane Failure Mechanism #3



Vertical cracking at center or edge of masonry

Schematic from City University of London Guideline on Confined Masonry and Interpretation of Eurocode 8

How To Limit Out-of-Plane Failure

1. Follow configuration rules and add bracing at the ring beam level and/or add cross walls
2. Restrain the masonry by tying it to the tie columns and bond beams or covering it with mesh
   a. Add horizontal reinforcement in the masonry wall, tied into tie columns, or
   b. Lay wire mesh across wall when plastered
      → Must be on both sides, tied into foundation beam and ring beam, and have loops or ties through the brick wall. NOTE: we haven't tried this yet and have concerns about durability!
3. Reduce slenderness ratio, h/t
   a. Use a different masonry bond to make a wider wall
      → But heavier wall will be more likely to crack in shear, and more deadly if it collapses; bricks in Aceh are the wrong shape, people don't want
   b. Or add a second horizontal bond beam (lintel level)
      → But top of opening is already within 0.5m of the ring beam, so very little to gain

How To Limit Out-of-Plane Failure

1. Follow configuration rules and add bracing at the ring beam level and/or add cross walls
   - Follow the configuration rules
   - Add cross walls every at minimum spacing of 4m
   - Add bracing at the ring beam level for wall spans 4m long or greater

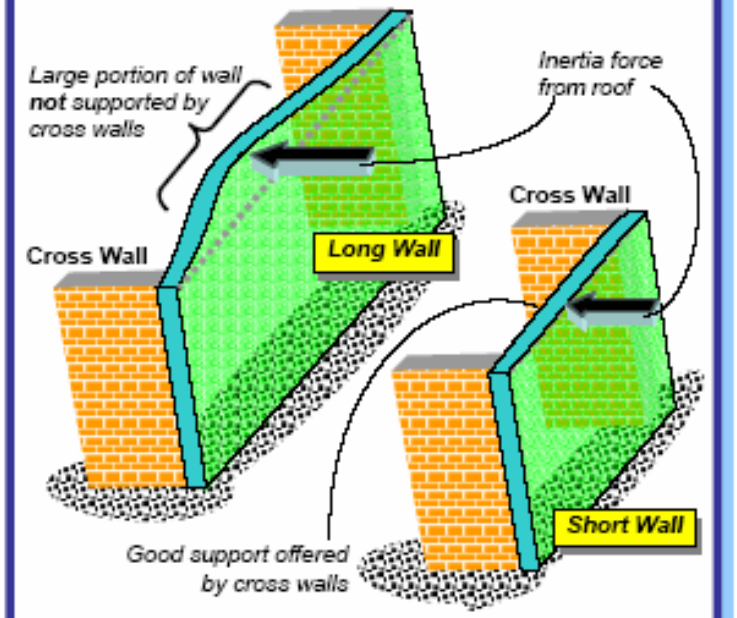


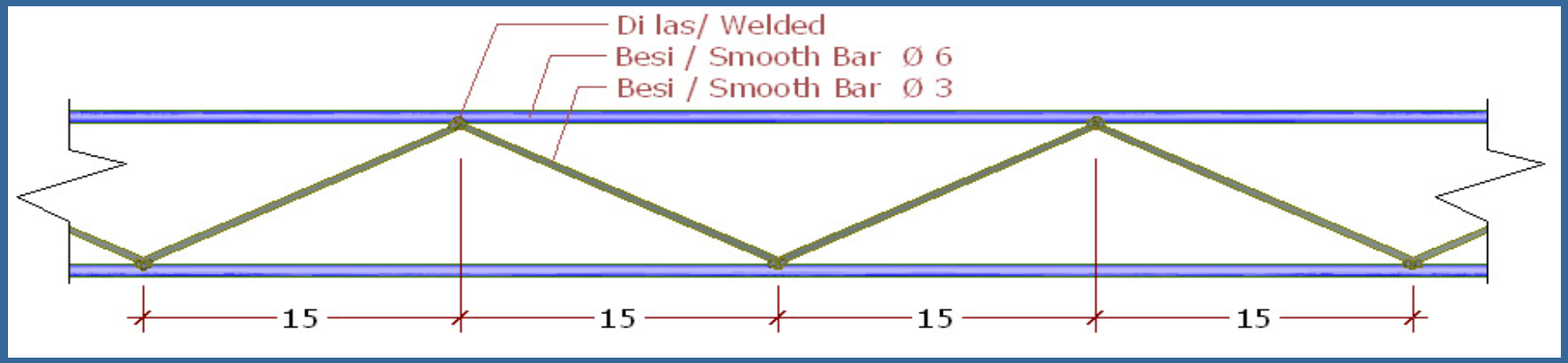
Figure 3: Slender walls are vulnerable – *height and length to be kept within limits. Note: In this figure, the effect of roof on walls is not shown.*

from IITK-bmtpc Earthquake Tip #12

How To Limit Out-of-Plane Failure

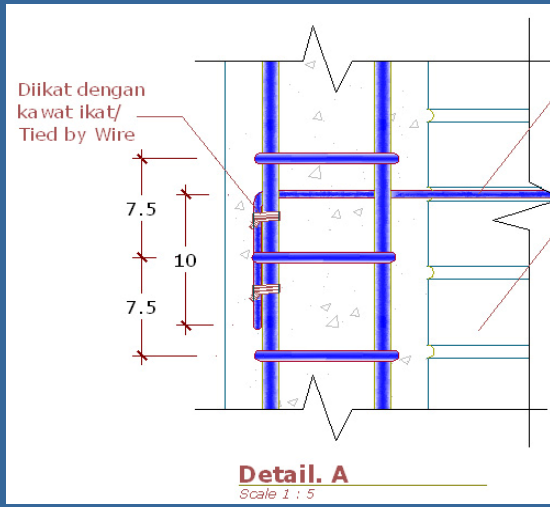
2. Restrain the masonry by tying it to the tie columns and bond beams or covering it with mesh
   a. Add horizontal reinforcement in the masonry wall, tied into tie columns, or
   b. Lay wire mesh across wall when plastered
      → Must be on both sides, tied into foundation beam and ring beam, and have loops or ties through the brick wall. NOTE: we haven't tried this yet and have concerns about durability and ease of construction!

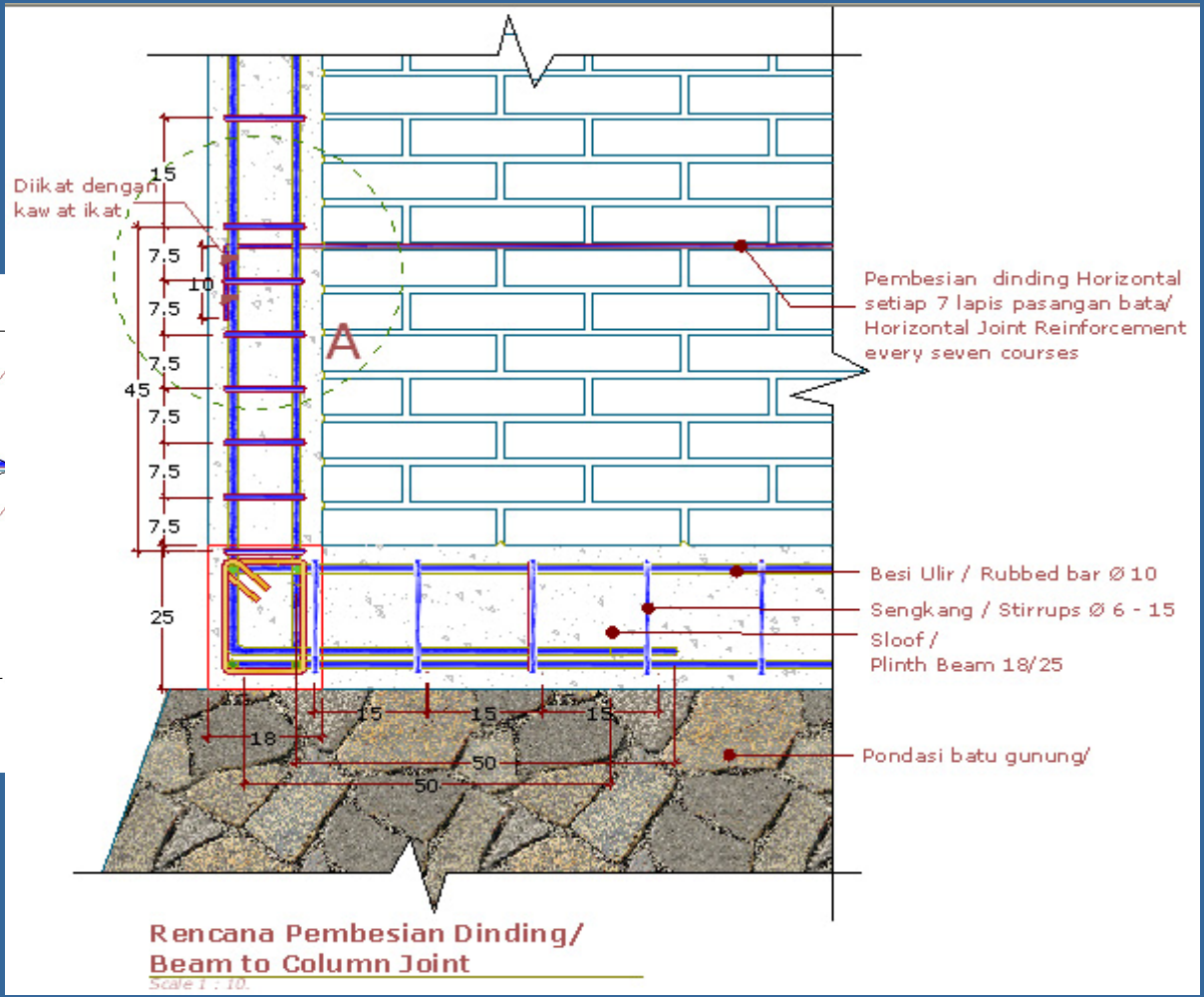
2a. Horizontal Reinforcement in Masonry, Tied into Columns



- → Frequency depends on spacing between columns
- → Use above door and window frames
- → 2 cm mortar below
- → 2 cm mortar below
- → Adds ~Rp. 2.2 million to cost of 36m^2 house

2a. Horizontal Reinforcement in Masonry, Tied into Columns





2a. Horizontal Reinforcement in Masonry, Tied into Columns

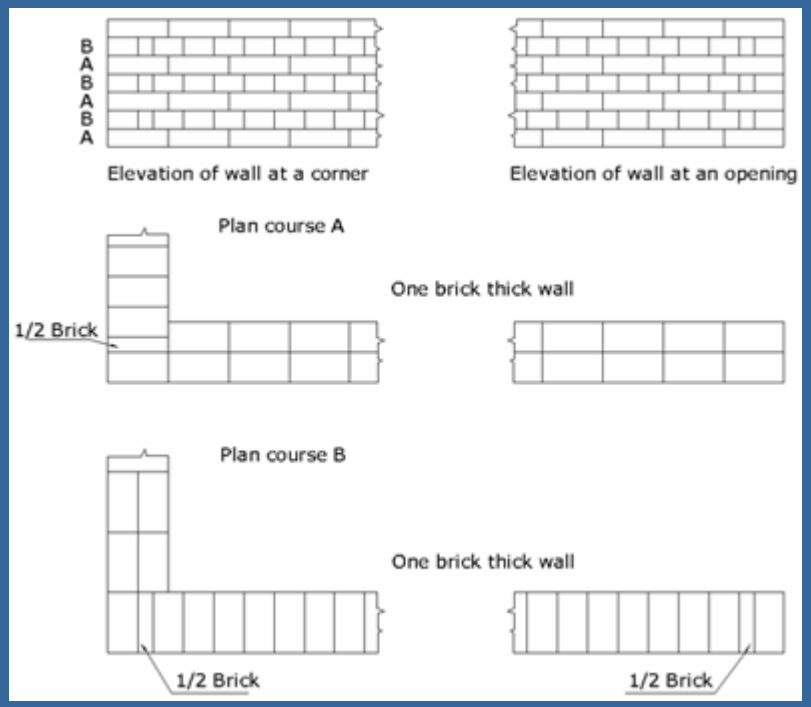
3a. Reduce h/t by Using Different Masonry Bond (Full Brick Thick)

But,

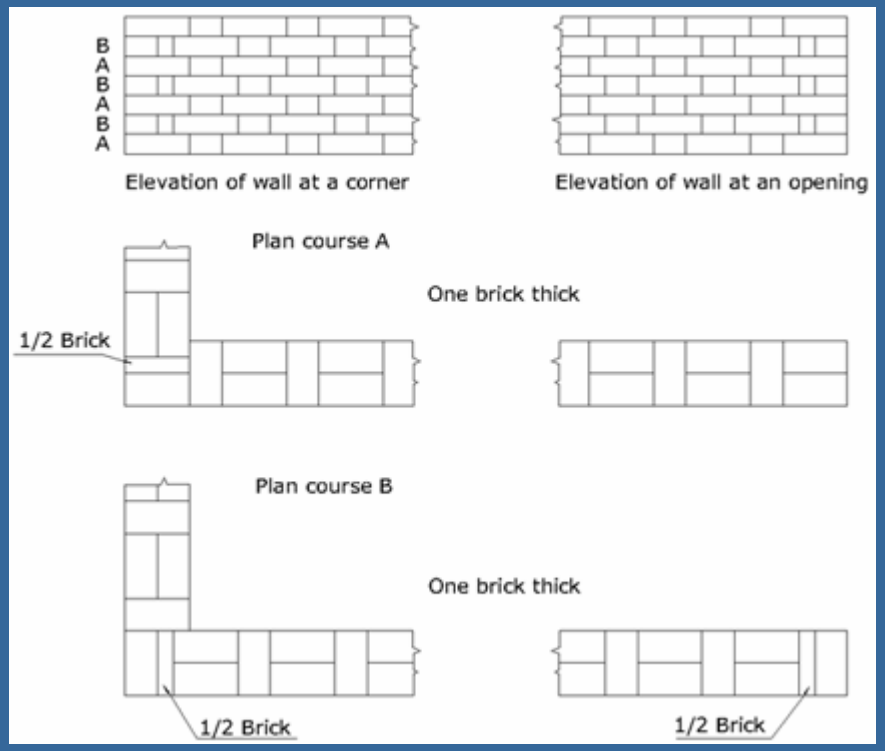
- Creates heavier wall more prone to shear failure
- Common window and door frames in Aceh are too narrow
- Bricks in Aceh are wrong proportion to use a proper masonry bond
- Aceh homeowners prefer tall, slender wall (based on limited sampling)

Acceptable Bonds for Full Brick Wide Wall

English Bond



Flemish Bond



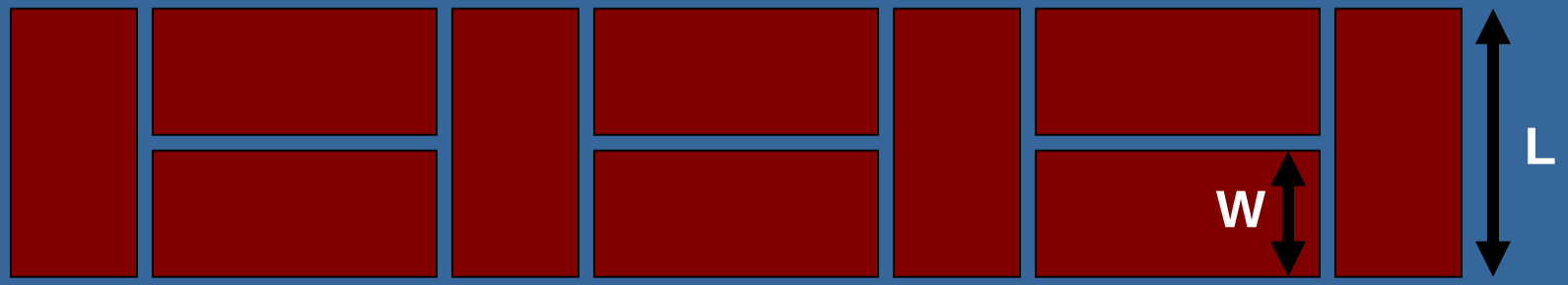
Schematics from City University of London Guideline on Confined Masonry and Interpretation of Eurocode 8

Bricks Common in Aceh are the Wrong Proportion for Full Brick Bonding

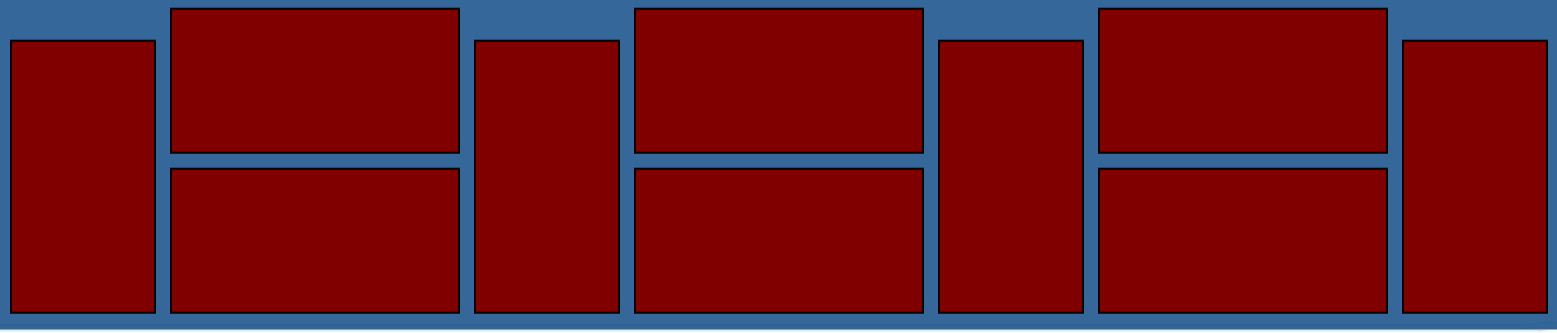
Length of brick must be at least twice the width plus width of joint

L > 2W + 1.5 cm

Flemish Bond using bricks with correct proportion (top view)



Flemish Bond using Aceh bricks with wrong proportion (top view)



This Bond is Not Recognized/Acceptable

3b. Add a Second Horizontal Beam at Lintel Level

- Must be at least 0.5m between top of lintel tie beam and bottom of ring beam for any gain, cultural preference for a tall opening with vent on top doesn't accommodate this

How To Limit Out-of-Plane Failure

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2. Restrain the masonry by tying it to the tie columns and bond beams or covering it with mesh
   a. Add horizontal reinforcement in the masonry wall, tied into tie columns
   b. Lay wire mesh across wall when plastered
      → Must be on both sides, tied into foundation beam and ring beam, and have loops or ties through the brick wall. NOTE: we haven't tried this yet!

Best solution is combination of 1 and 2a

3. Reduce slenderness ratio, h/t
   a. Use a different masonry bond to make a wider wall
      → But heavier wall will be more likely to crack, and more deadly if it collapses; bricks in Aceh are the wrong shape, people don't want
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