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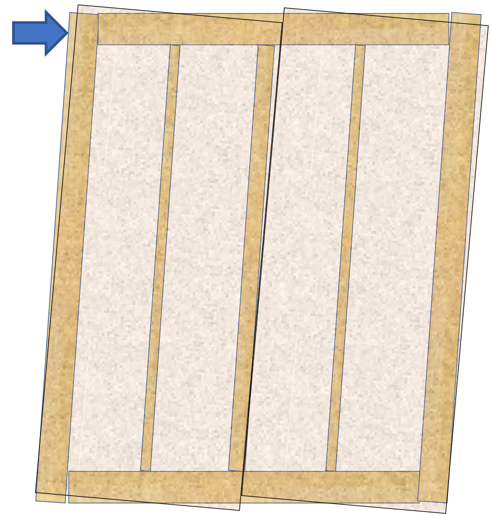
TIMBER ENGINEERING - VSM196

LECTURE 13 –

STABILIZING TIMBER STRUCTURES,
DESIGN OF SHEAR WALLS

SPRING 2020



Graphic: R. Steiger, Empa

Topic

- Stabilizing timber structures
- Design of shear walls

- [DoTS: Chapter 6 & 8]

Content

- Stabilizing of multi-storey building
- Horizontal load transfer in buildings
- Design of shear walls
- Design of floor diaphragms

- Design examples A1, A2, A5

Intended Learning Outcomes of this lecture

- You understand the transfer of horizontal forces in buildings
- You can distinguish different bracing for multi-storey timber buildings
- You can determine the resistance of shear walls under horizontal loads
- You will be able to model and design floor diaphragms and shear walls

Review on Stability and Bracing

- Stability or lateral bracing must be provided to a structure, for example:
  - Provision of lateral bracing members
  - The use of roof and/or floor diaphragms
  - The use of shear walls as diaphragms

- Main design requirements relates to ULS
  - There is no displacement criterion (SLS) for diaphragm structures! See also lecture from Structural system – SS- Force path 08 by Björn Engström and STDtoEC5, Ch (9.2. – 9.4)

Main design requirements

Table 9.1 Main design requirements for bracing and diaphragm structures and the associated EC5 limit states

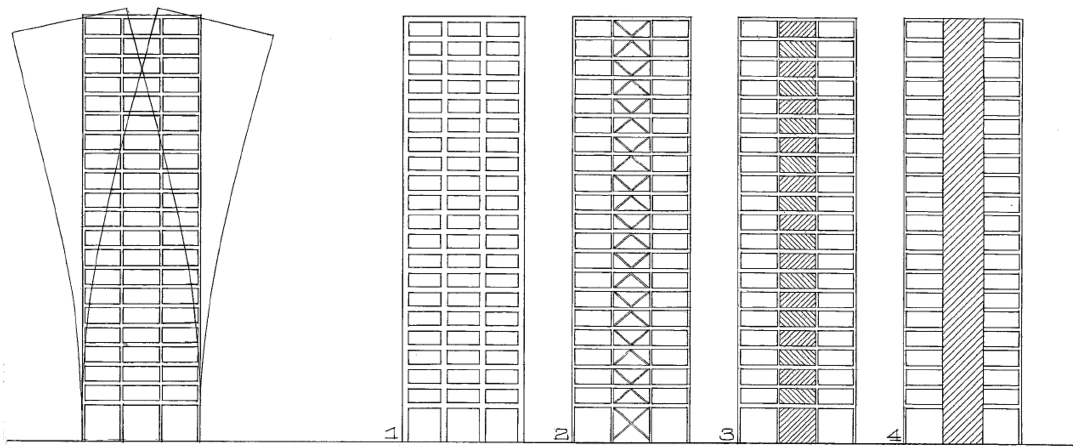
Element	Design or displacement effect	EC5 limit states
Bracing members	Axial stress, including the effect of lateral instability	ULS
	Deflection	ULS
Diaphragm floors and roofs	Retention of static equilibrium (sliding, uplift (for roofs))	ULS
	Bending stress	ULS
	Shear stress	ULS
Diaphragm walls	Retention of static equilibrium (sliding, uplift)	ULS
	Racking resistance	ULS

Examples in STDtoEC5, Chapter 9

Bracing systems for multi-storey buildings

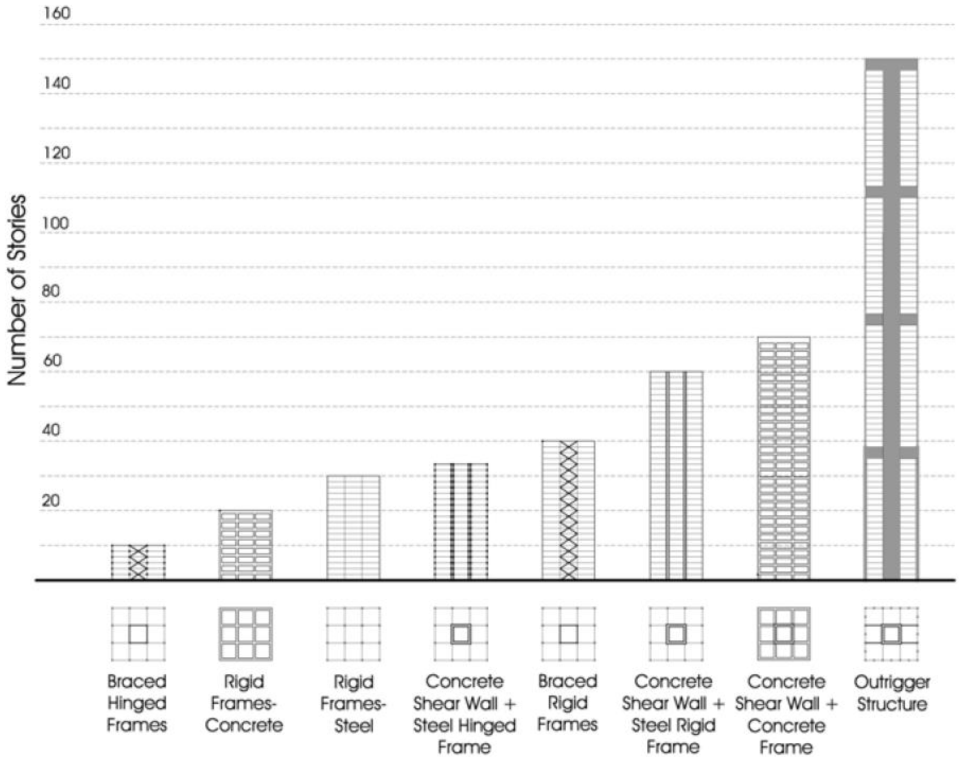
Examples

- Post and beam systems

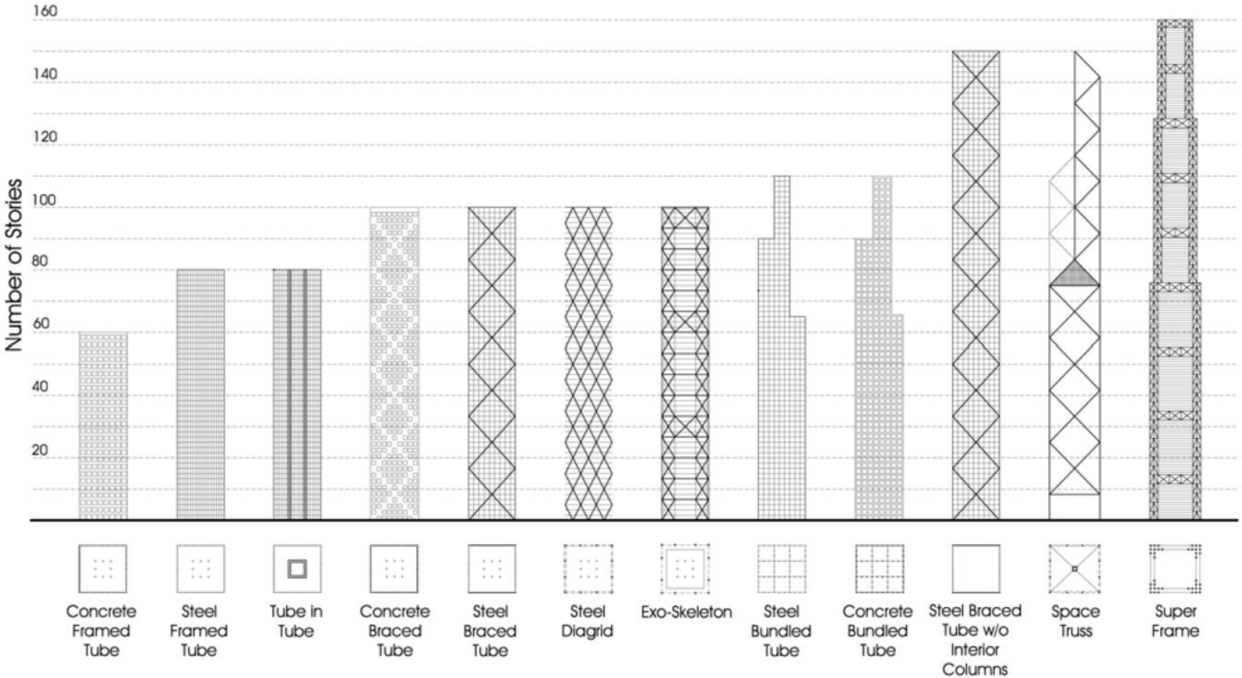


Deflection due to horizontal load | Frame | Bracing | Shear walls | Core

Examples

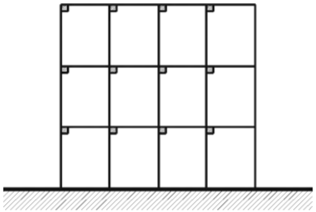

Number of Stories
160
140
120
100
80
60
40
20
Braced Hinged Frames
Rigid Frames-Concrete
Rigid Frames-Steel
Concrete Shear Wall + Steel Hinged Frame
Braced Rigid Frames
Concrete Shear Wall + Steel Rigid Frame
Concrete Shear Wall + Concrete Frame
Outrigger Structure

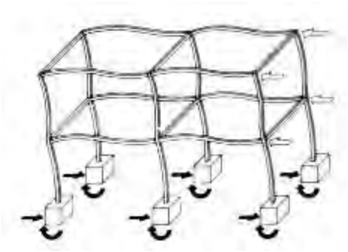
Examples


160
140
120
100
80
60
40
20
Number of Stories
Concrete Framed Tube
Steel Framed Tube
Tube in Tube
Concrete Braced Tube
Steel Braced Tube
Steel Diagrid
Exo-Skeleton
Steel Bundled Tube
Concrete Bundled Tube
Steel Braced Tube w/o Interior Columns
Space Truss
Super Frame

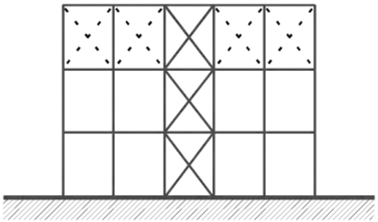
Concepts

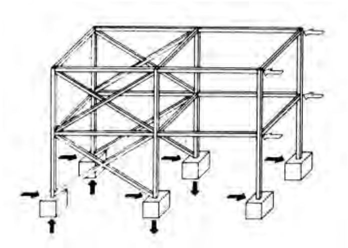
- Frame



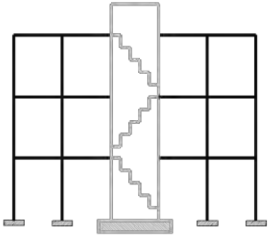


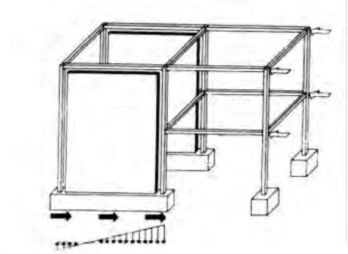
- Bracing





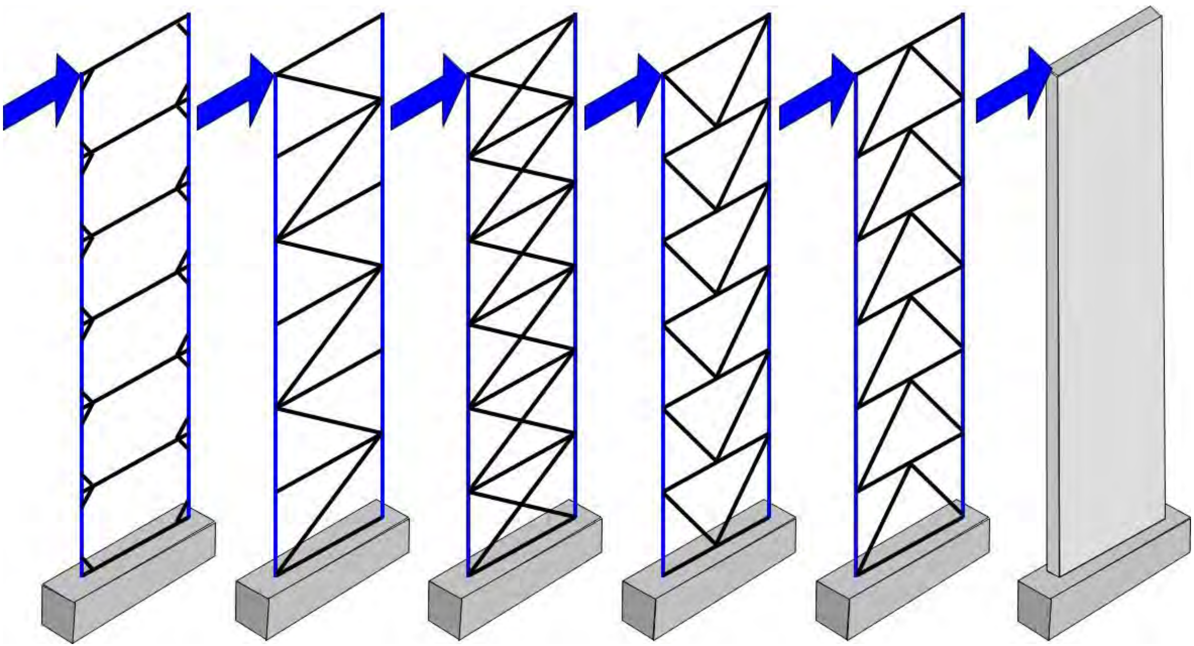
- Core





Examples

- Frames, Bracing and Walls



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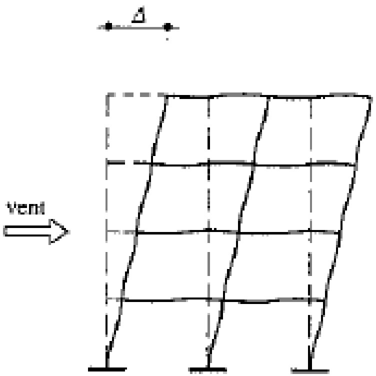
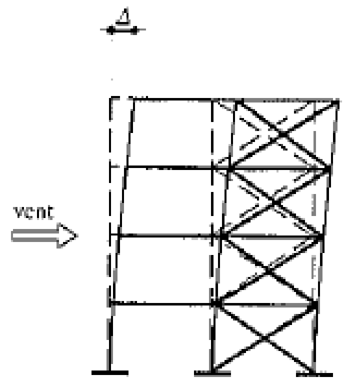
Comparison

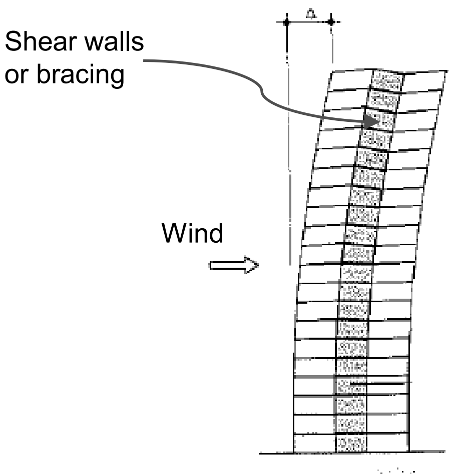


a) Large deflections:
frames effect are rather unusual in timber structures → difficult to create moment-rigid connections

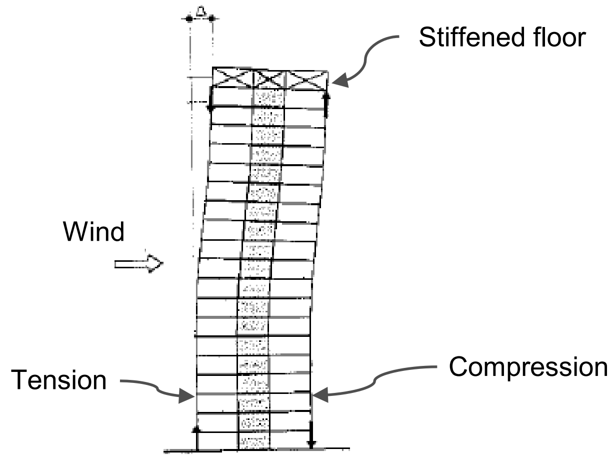


b) Small deflection:
Wind truss is a very effective method to reduce deflection

Optimization



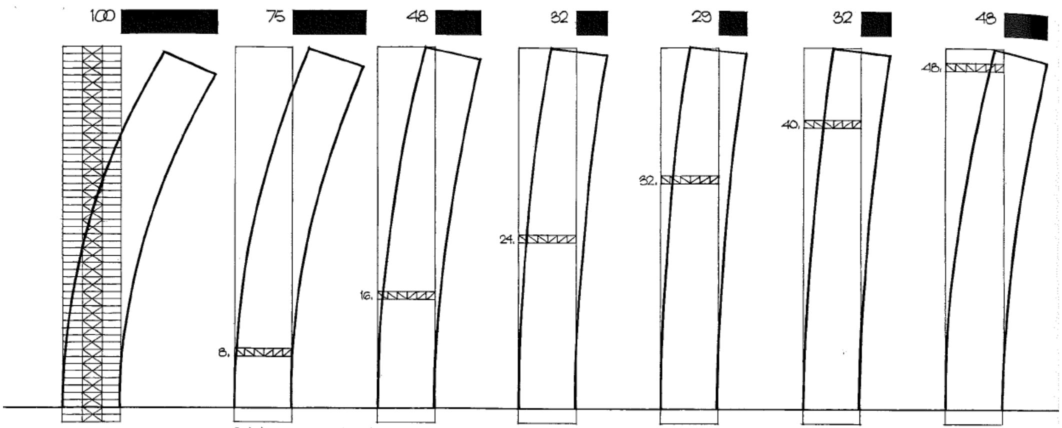
Large deflections



The presence of a rigid floor rigidly connected to shear walls/ bracing and external element (outriggers) can help reduce deflection

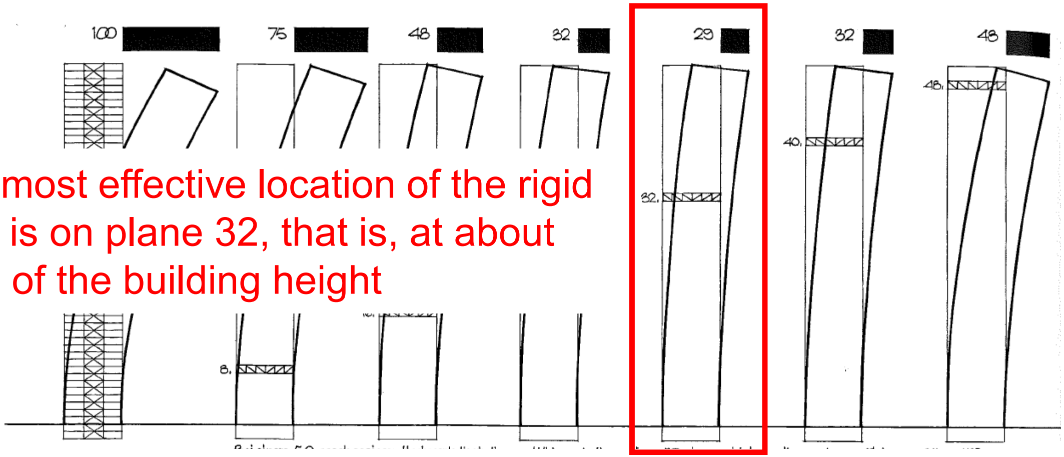
Optimization

- Example:
  - 50-storey building
  - horizontal stabilization by mean of bracing, shear walls or core + rigid floor + outriggers



Optimization

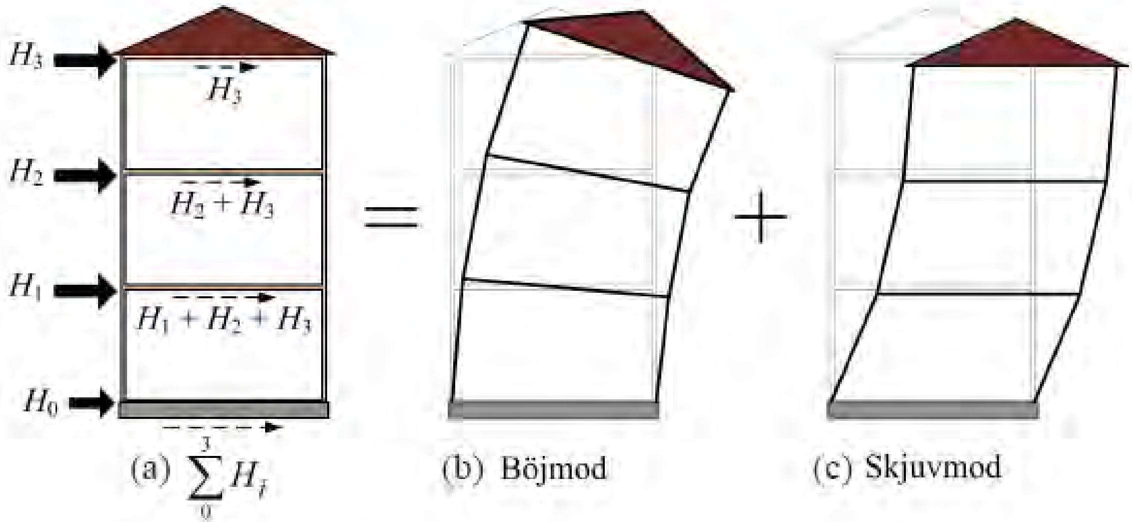
- Example:
  - 50-storey building
  - horizontal stabilization by mean of bracing, shear walls or core + rigid floor + outriggers



The most effective location of the rigid floor is on plane 32, that is, at about 65% of the building height

Bracing of Timber Buildings

Bending and shear deformations

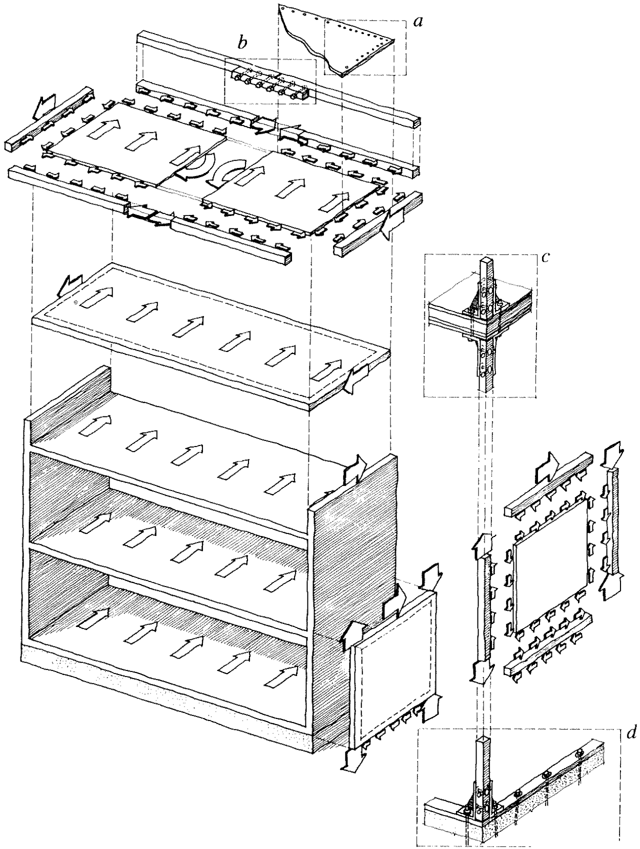


b) Typical for very stiff system such as concrete

c) Typical for weaker system such as wood-based shear walls

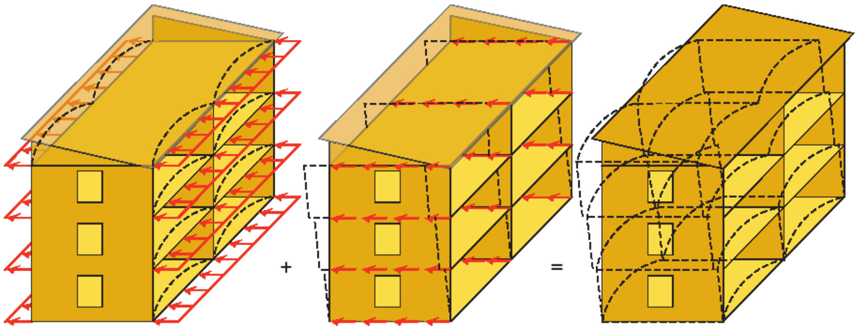
Källsner & Girhammar 2008

Elements of multi-storey timber buildings



Bracing multi-storey timber buildings

- Bracing of multi-storey timber buildings with load bearing walls and floors



- Floor diaphragms transfer horizontal loads to the wall diaphragm
- Very important to properly connect walls and floor in order to allow for the transmission of shear forces between members and between walls and concrete foundation

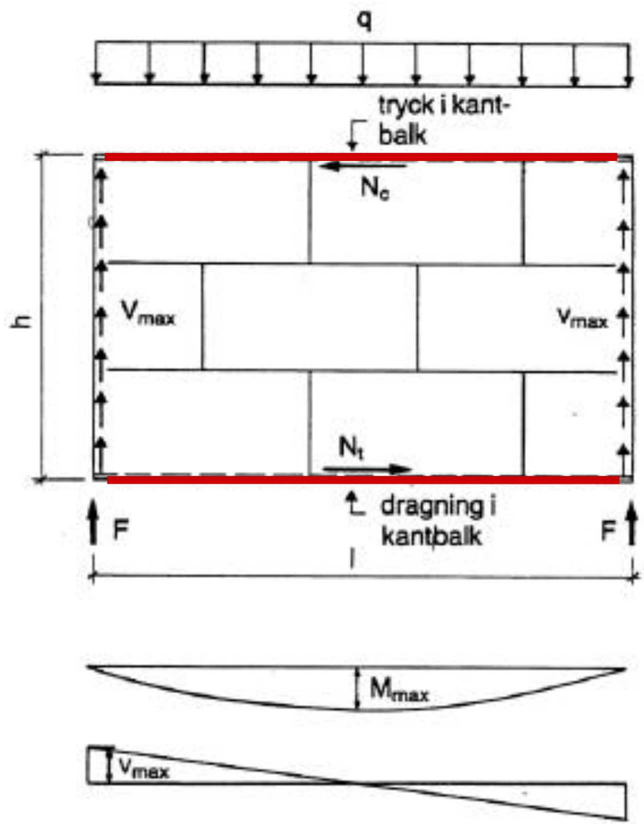
Shear wall *and/or* diaphragm

- An in-plane or plate-type structural element
- Designed to transmit forces in its own plane as diaphragm action
- Term diaphragm structure is applied to horizontal elements such as floor or roof
- Term shearwall is applied to vertical elements such as walls or partitions
- horizontal roof or floor diaphragm are designed to distribute lateral loads to the shearwall elements, which carry them further to the foundation

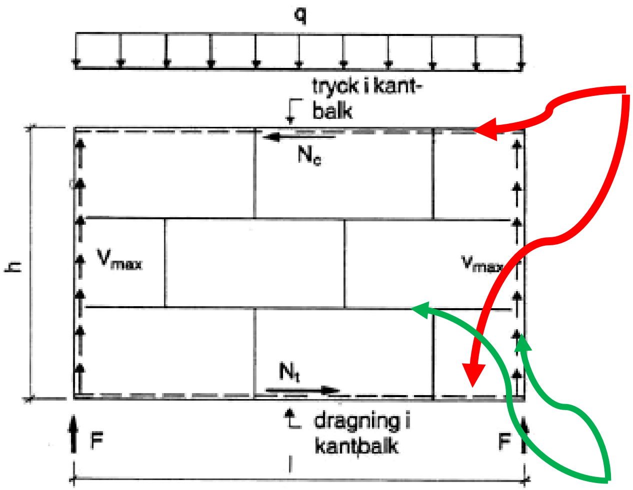
Diaphragms

Structural model for diaphragms

- Load
- Compression in header joist
- Shear flow v_{max} at the edges of the plates
- Tension in header joist
- Reaction force
- Bending moment
- Shear distribution



Structural model for diaphragms



All of the bending is assumed to be taken by the edge beams and consequently they must be continuous or detailed to be able to transfer the tensile or compression loading to adjacent sections.

The floor skin transfers the shear to the vertical braced frames. All of the shear must be taken by the panel material. The shear stress is higher closer to the edges of the diaphragm

Design procedure EC5

- Roof and floor diaphragms EC5:9.2.3
  - Simplified analysis: ultimate design is failure in the fasteners (not in the panels)
  - Condition - the span $2b \le l \le 6b$

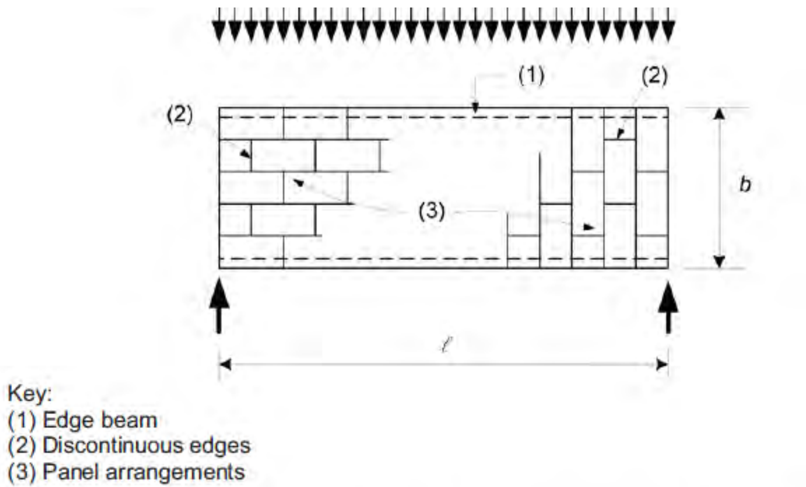


Figure 9.4 – Diaphragm loading and staggered panel arrangements

$M = ql^2/8$

$T = C = M/b = ql^2/8b$

$V_{max} = ql/2$

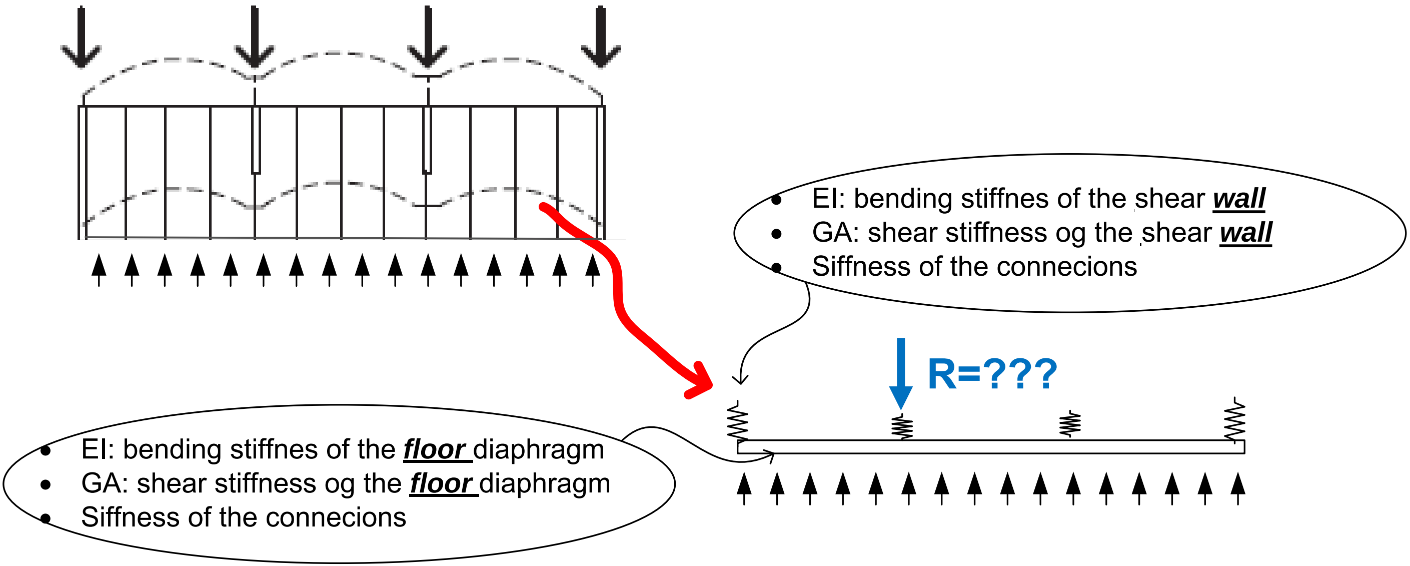
Shear flow $v = V/b$

Fundamental statics

- The system floor diaphragm - shear wall is highly statically indeterminate, thus…

- …lateral load distribution depends on the ratio between the rigidity of the roof (or floor) diaphragm and the rigidity of the supporting structure.

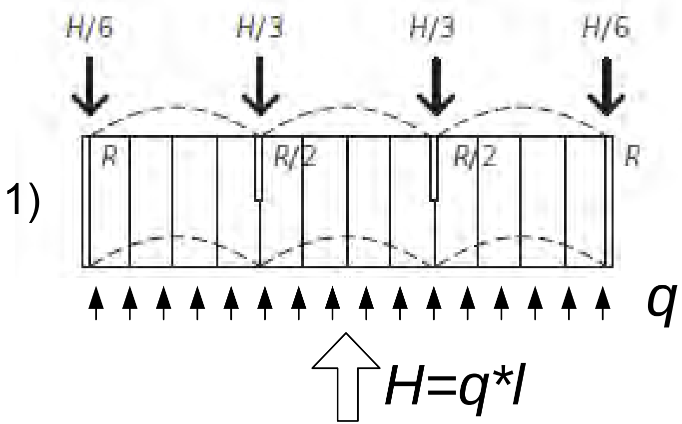
Fundamental statics

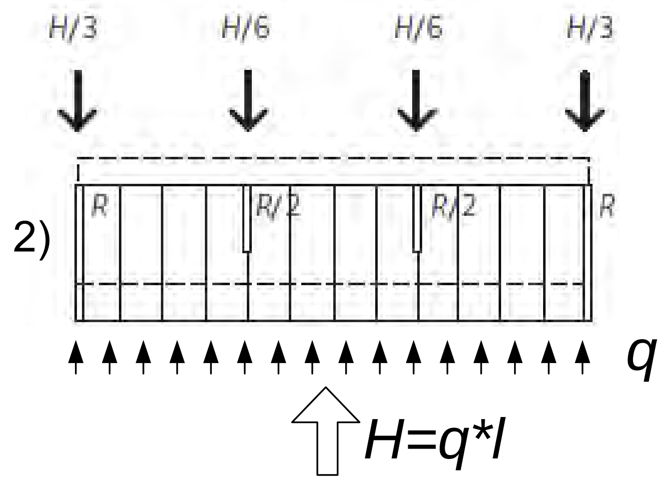


Fundamental statics

- The engineering approach is to consider to extreme cases, namely:
    1. Shear walls much more rigid than floor diaphragms
    2. The opposite, i.e. floor diaphragms much more rigid than shear walls

Fundamental statics



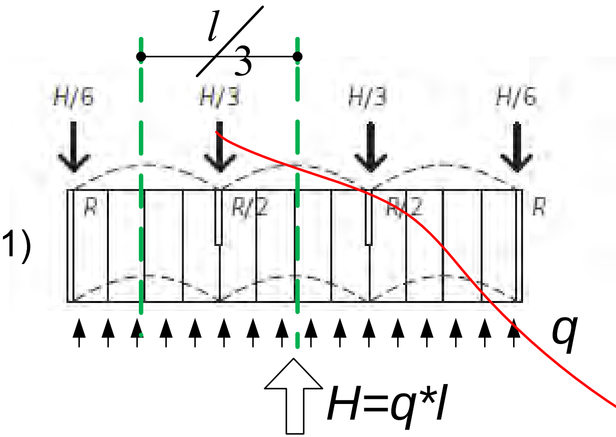


1. Shear walls much more rigid than floor diaphragms
2. Floor diaphragms much more rigid than shear walls

Fundamental statics

- forces in the shear walls in case
  1. Shear walls much more rigid than floor diaphragms

1)



Reaction force in the wall diaphragm =

$$q \cdot \frac{l}{3} = \frac{H}{3}$$

load distribution is a function of the tributary façade area

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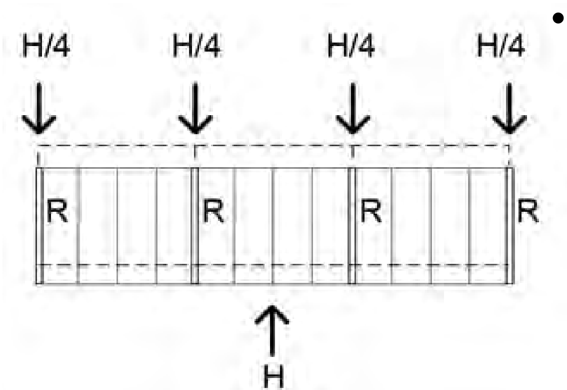
Fundamental statics

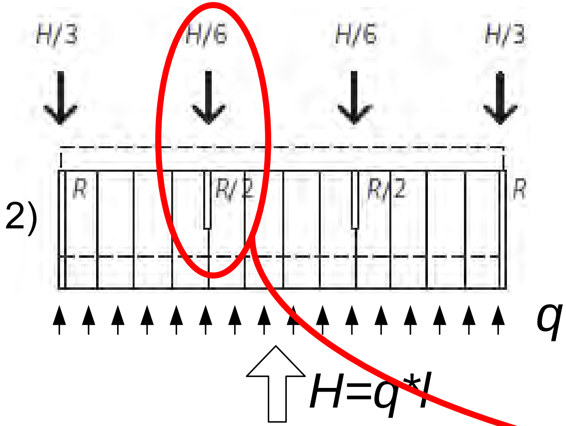
- forces in the shear walls in case
  2. Floor diaphragms much more rigid than shear walls



- Rigid body
  - Four walls with equal rigidity (R)
  - Each wall carries the same force H/4

Fundamental statics

- forces in the shear walls in case
  2. Floor diaphragms much more rigid than shear walls



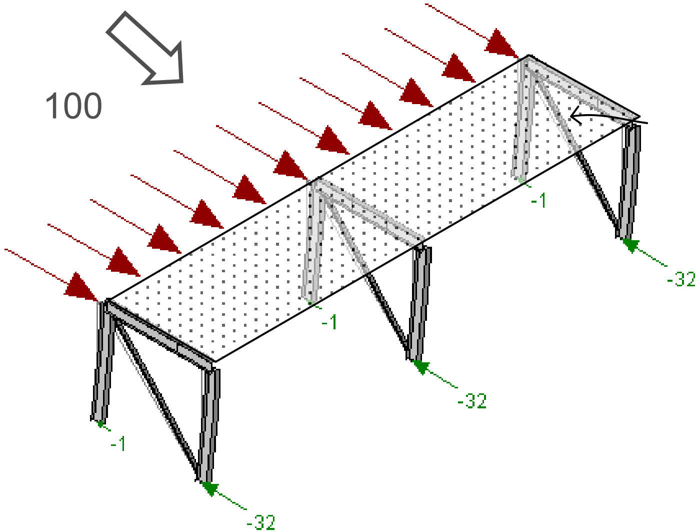
- The total horizontal action H is redistributed in proportion to the wall rigidities.
- The total rigidity is: $\sum R = 2 \cdot (R + \frac{R}{2}) = 3 \cdot R$
- Hence, the interior walls resists:

$$V_i = H \cdot \frac{0,5 \cdot R}{3 \cdot R} = \frac{H}{6}$$

Benchmarking

Fundamental statics: test of model

- Infinitely rigid floor diaphragm

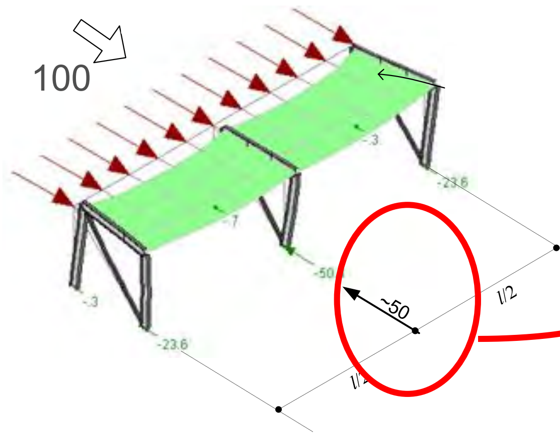


As expected, reaction forces in the walls are the same (load repartition according to the stiffness of the walls)

Fundamental statics: test of model

- floor is more flexible than the walls

100



$$V_i = q \cdot \frac{l}{2} = \frac{H}{l} \cdot \frac{l}{2} = \frac{H}{2} = 50$$

As expected, reaction forces in the walls are functions of the tributary façade area

Rule of thumb

- In most of typical timber structures, where the spacing of shear walls is relatively small, e.g.:
    - CLT-buildings
    - Timber frame buildings with both floors and walls equipped with sheathing material (e.g. plywood or OSB)

⇩

- The assumption of infinitely rigid floor diaphragm is considered realistic

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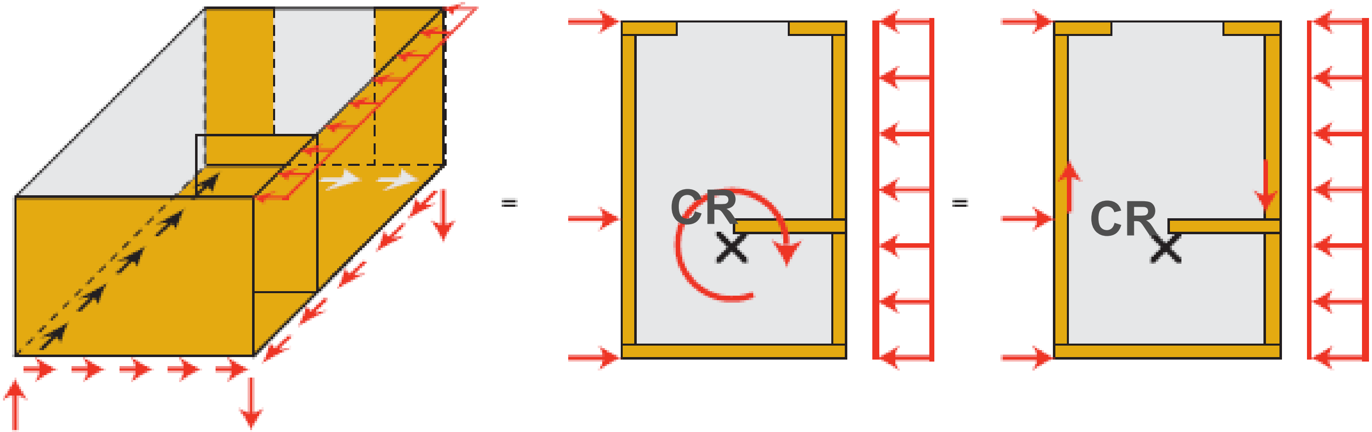
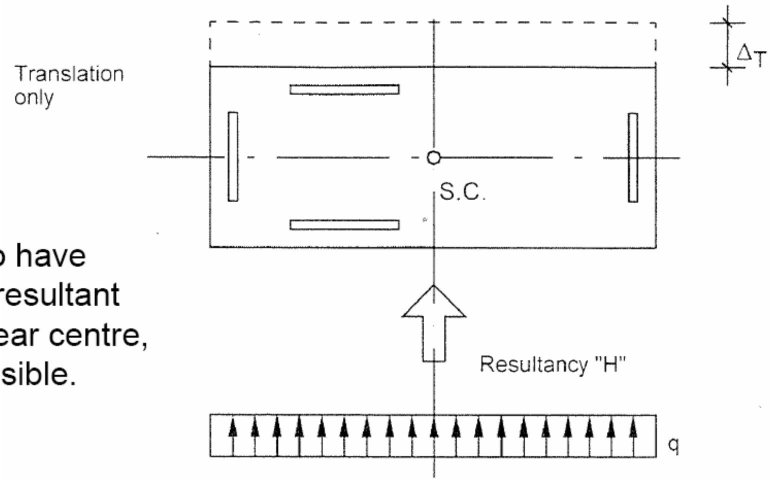
Rigid diaphragm – non-symetrical building

- The centre of rigidity (CR) has to be calculated



Rigid diaphragm

Resultant in shear centre

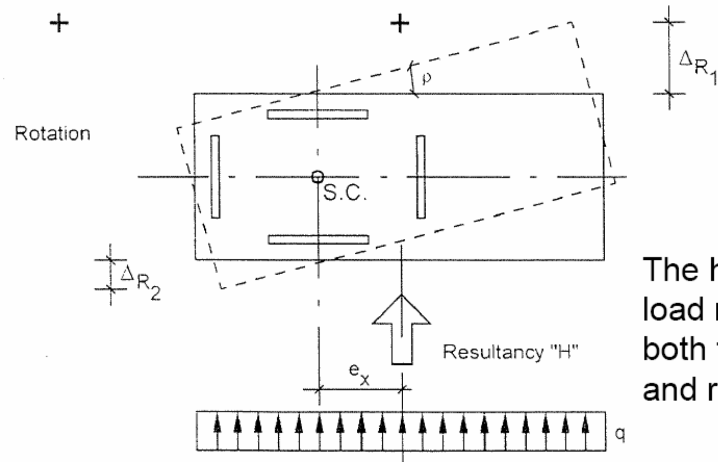


Try to have load resultant in shear centre, if possible.

- cf. DoTS, Ch. 3 & Figs. 6.12 and 6.13.
- See also lectures in Structural Systems

Rigid diaphragm

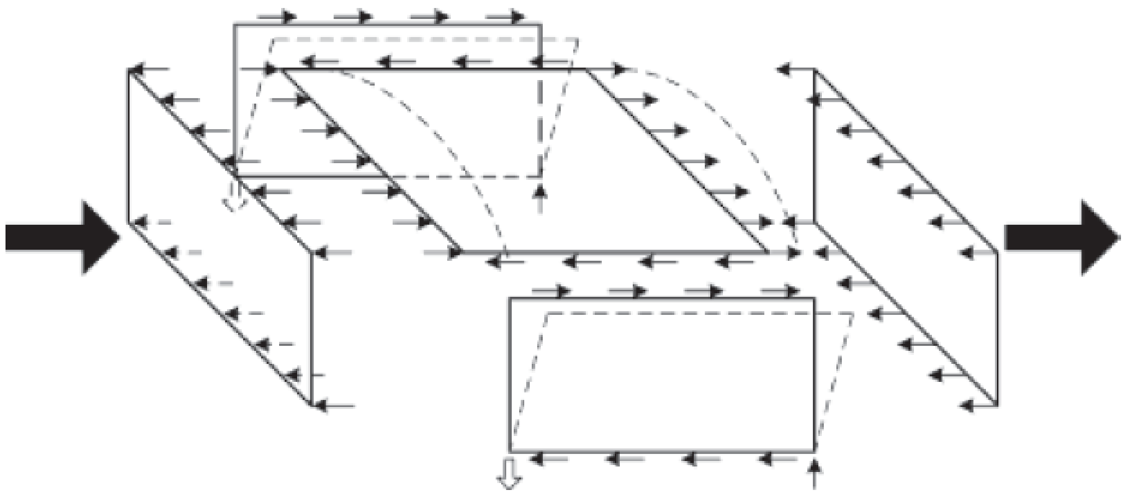
Resultant outside shear centre



The horizontal load results in both translation and rotation.

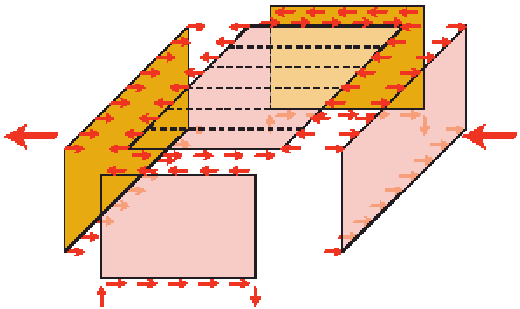
Shear Walls

Transver of the horizontal loads through floor elements to the shear walls

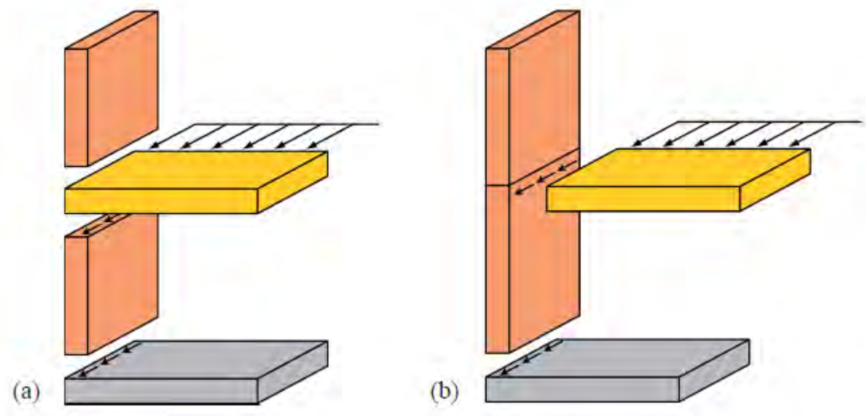


- Broken lines represent element deformations
- Condition: windward stud in the shear walls must be completely anchored

Diaphragm action - transfer of wind loads



Principle sketch



Transfer loads from floor to walls

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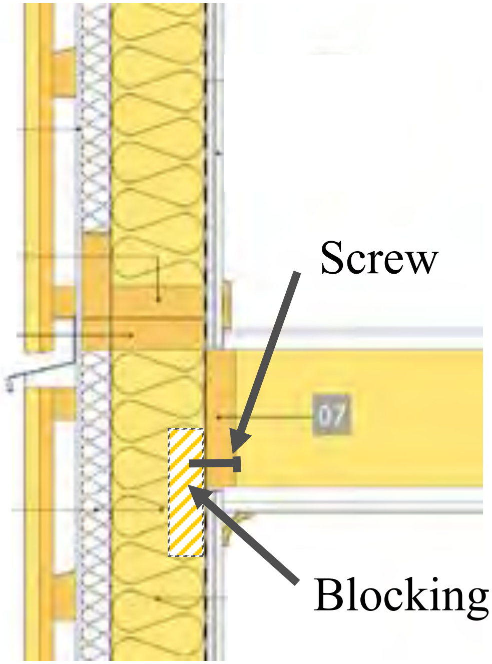
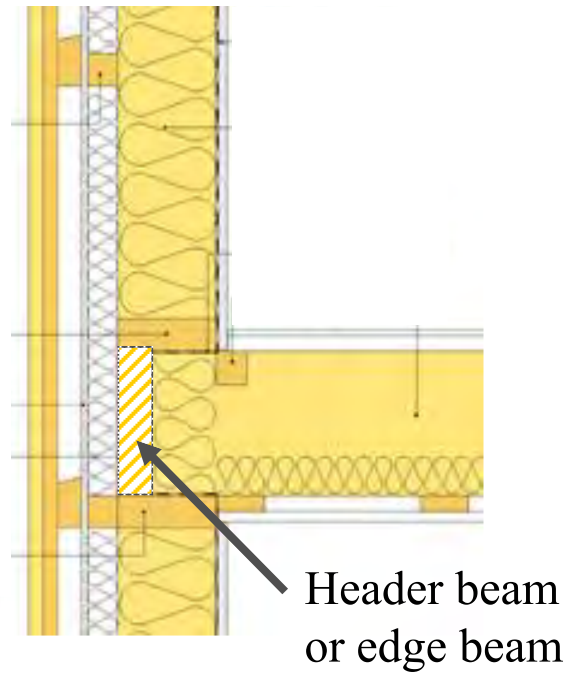
Connections and detailing - examples



Wall-floor: gable side



Wall-floor: long side

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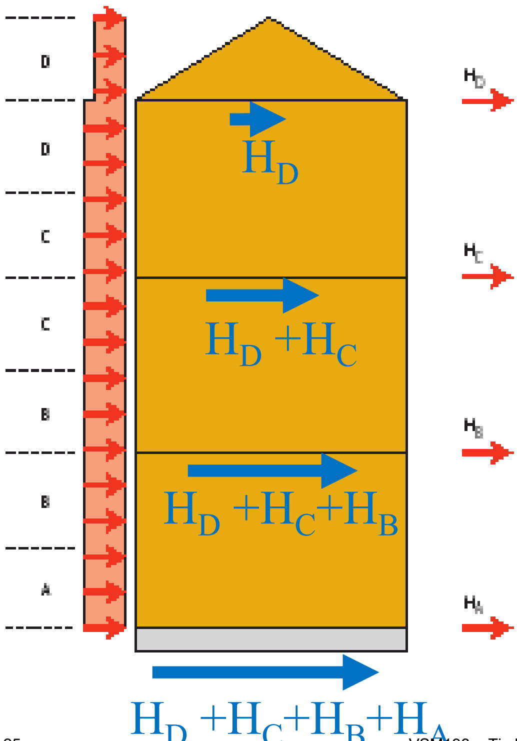
Equivalent loads on floors, walls and foundation

Load distribution

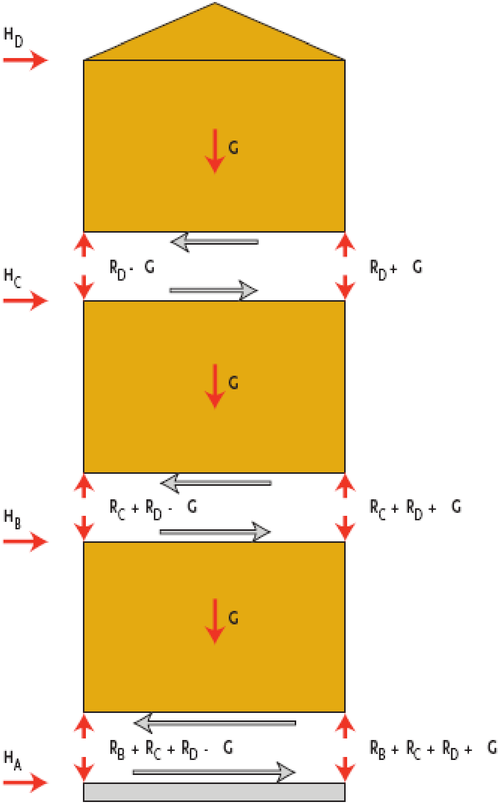
Loads on : floor



Forces acting on shear walls

Reaction forces – need for anchorage?

- Equilibrium with regards to reaction forces



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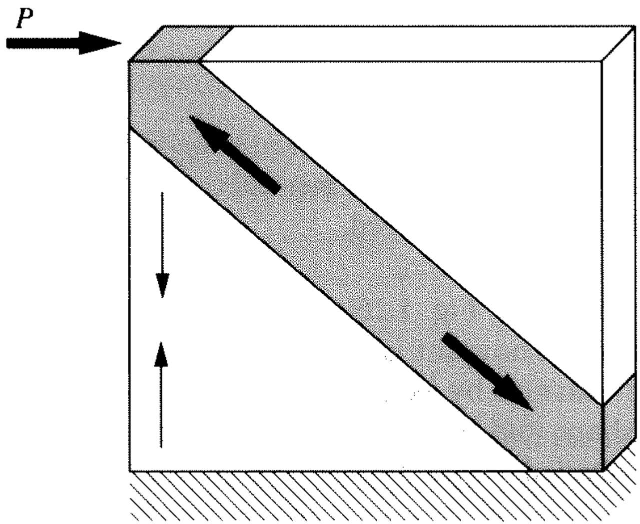
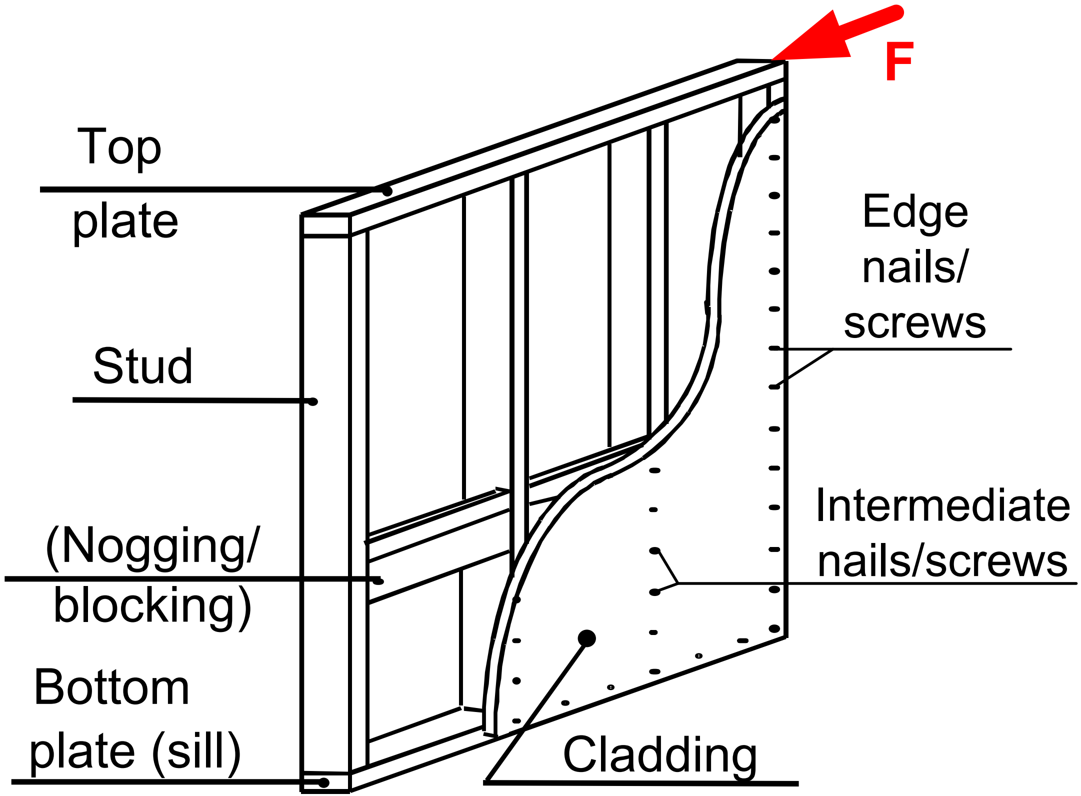
Shear panel

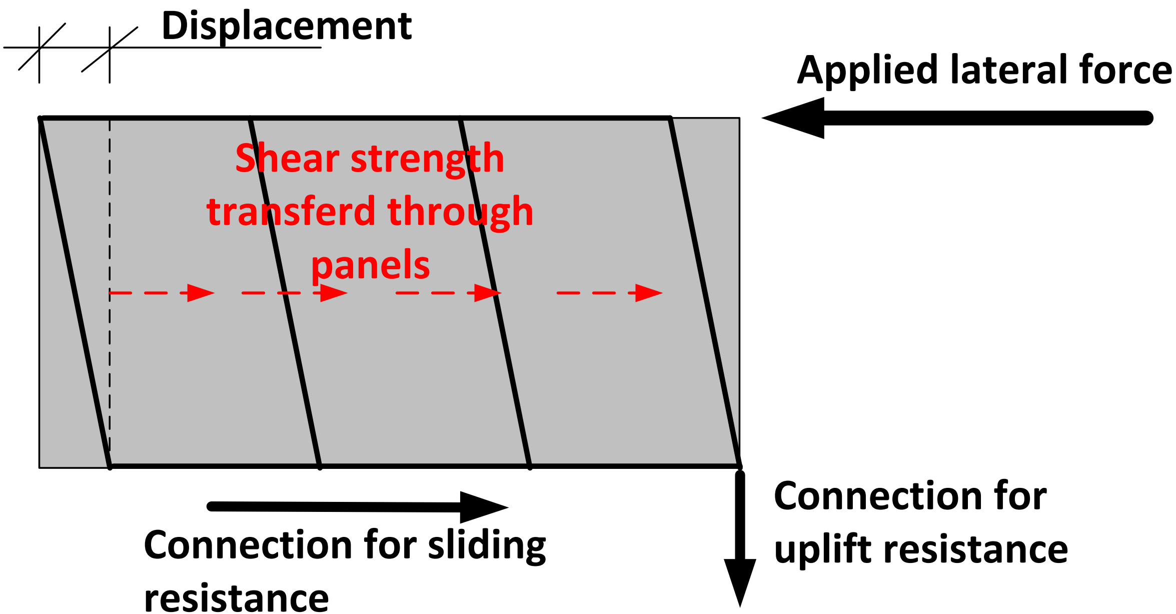


- Structurally, the shear wall can be regarded as a cantilevered diaphragm loaded by a concentrated force applied at the top plate

Light-timber-framed shear wall

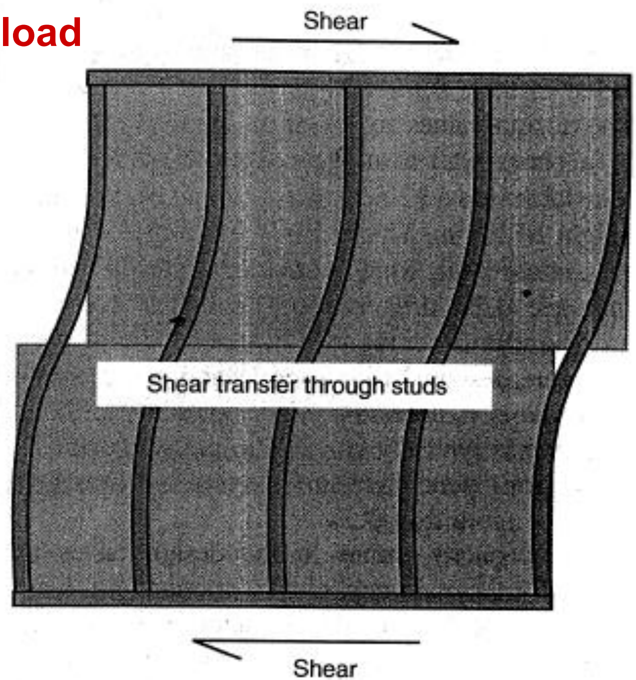


Shear wall provides stiffness and strength



Unblocked shear wall

Racking load



The main deformation occurs in the connectors

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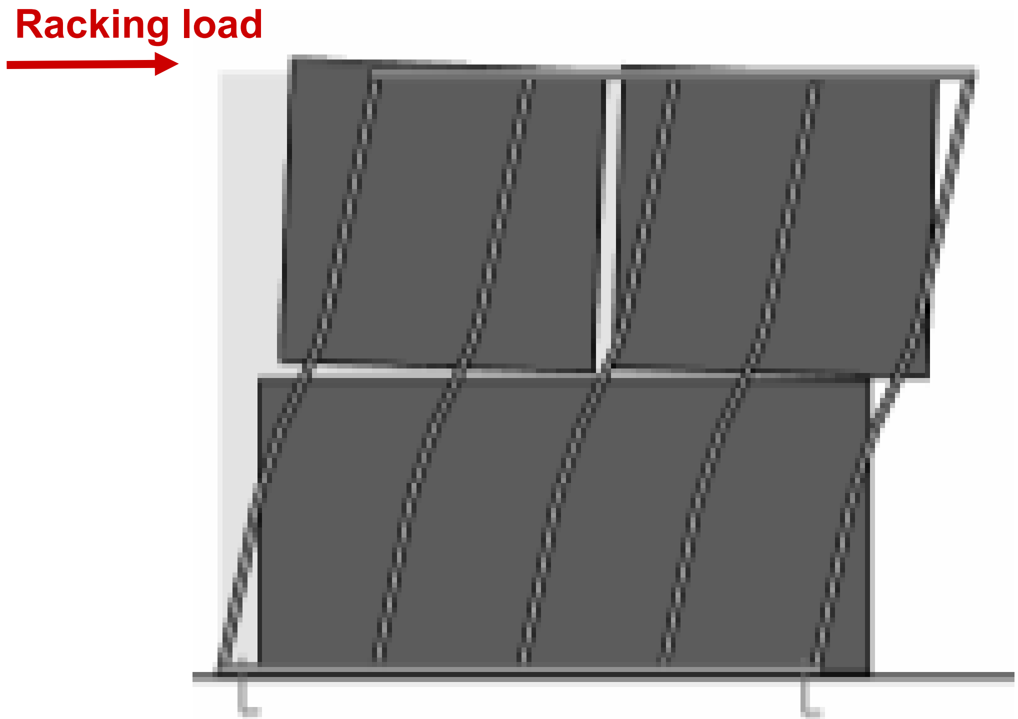
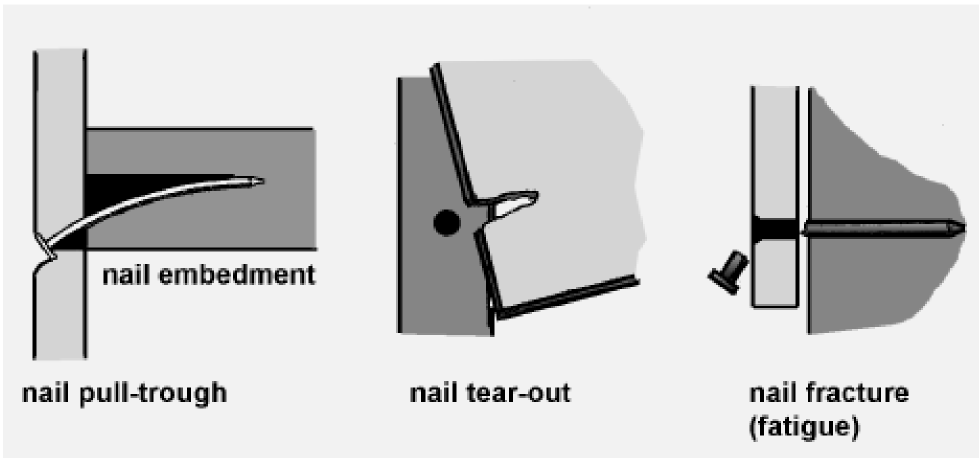
Shear wall

- Relative movement between panel and frame will create forces in the connectors



Shear wall - fasteners

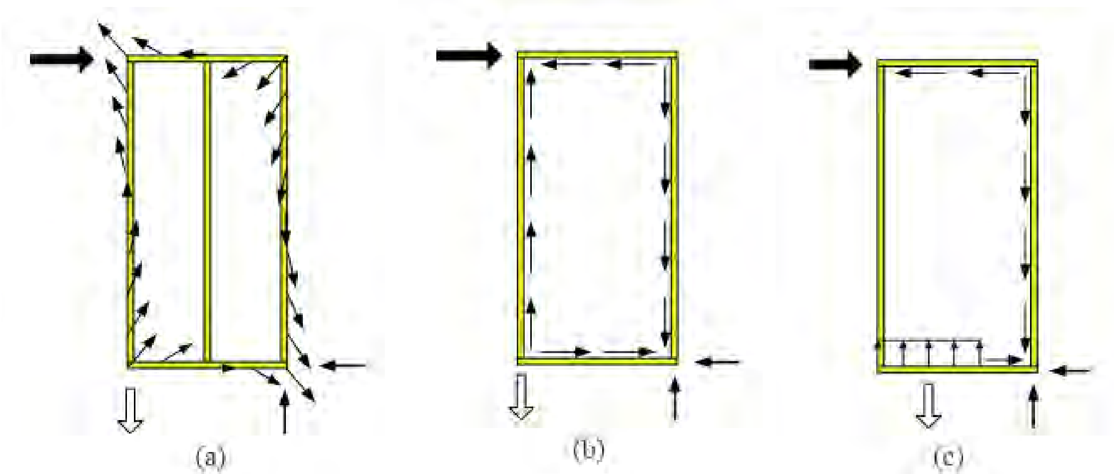
- The shear capacity of the connectors often determines the capacity of the shear wall



- Shear load -- failure mechanisms of nail connectors

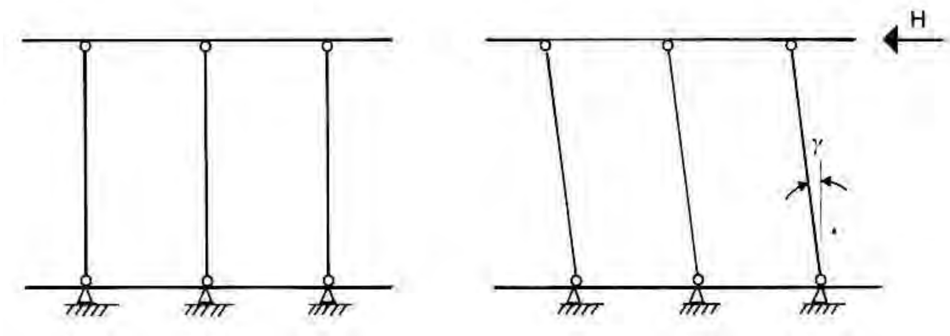
Design in shear wall

- Models taking into account force distribution on wall frame



- Assumptions:
    a) Elastic – complete anchorage of windward stud
    b) Plastic – complete anchorage of windward stud
    c) Plastic – windward stud not anchored but ground plate is anchored

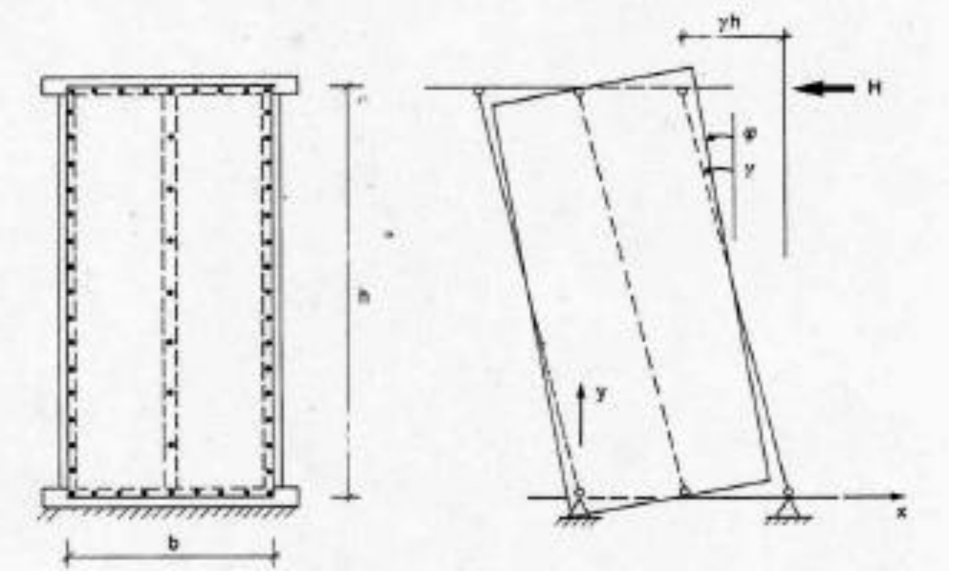
Design model for shear walls – elastic model



- Assumptions
  - Timber elements have pinned connections
  - Posts and beams are stiff and prevented to buckle
  - Small deformations
  - Fasteners behave in a linear-elastic manner

Design model for shear walls – elastic model

- Linear-elastic analysis – assumptions
  - The frame members and panels are regarded as rigid parts
  - Both framing timber and panels are hinged to each other
  - The load-displacement of the joints between the panel and the frame



The relative movements between panels and the frame determine forces in the connectors

Design model for shear walls – elastic model

Determination of fastener forces

1. Translate the force to center of gravity of joint
2. The vertical component of the force will be equally taken by each fastener, $F_{yi} = F/n$
3. The force due to moment in each fastener will be

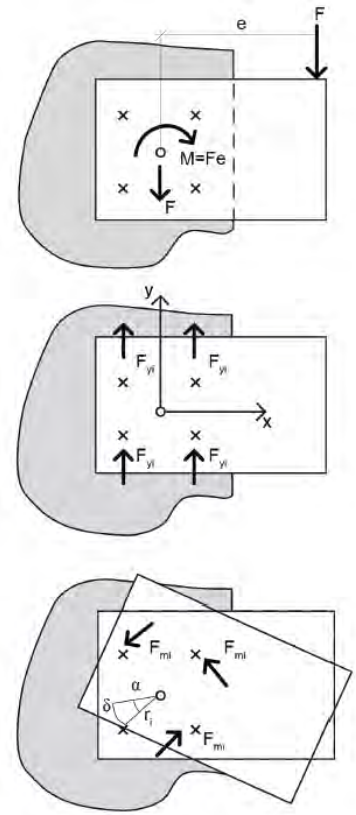
$$I_P = \sum r_i^2 = \sum \left(x_i^2 + y_i^2\right) \qquad F_{mi} = K \cdot \alpha \cdot r_i = \frac{M \cdot r_i}{I_p}$$

$$F_{mxi} = -\frac{M \cdot y_i}{I_p} \qquad F_{myi} = -\frac{M \cdot x_i}{I_p}$$

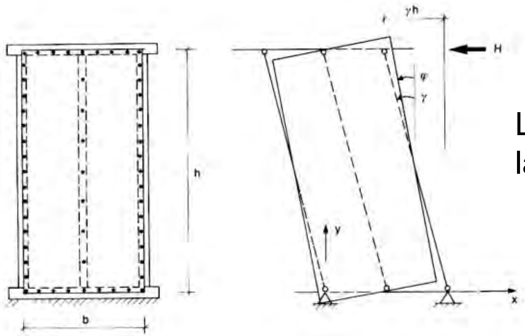
4. Vector summation gives

$$F_i = \sqrt{(F_{xi} + F_{mxi})^2 + \left(F_{yi} + F_{myi}\right)^2}$$

- Which should be compared with strength of a single fastener



Design model for shear walls – elastic model



Largest force to be found in fastener with largest distance from fastener group

$$F_{max} = \sqrt{F_{xi}^2 + F_{yi}^2} = Hh\sqrt{\left(\frac{x_{max}}{\Sigma x_i^2}\right)^2 + \left(\frac{y_{max}}{\Sigma y_i^2}\right)^2}$$

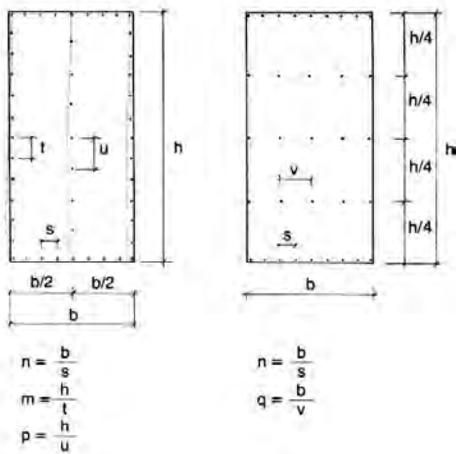
Design capacity for fastener F_{vd} defines the total capacity of the shear wall

Shear wall capacity (with regard to horizontal loading at top edge) is obtained by setting $F_{vd} = F_{max}$

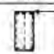
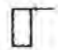
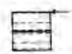
$$\boxed{H_{Rd} = \frac{F_{vd}}{h\sqrt{\left(\frac{x_{max}}{\Sigma x_i^2}\right)^2 + \left(\frac{y_{max}}{\Sigma y_i^2}\right)^2}}}$$

Σx_i^2 and Σy_i^2 in tables

Design model for shear walls – elastic model



Tabell 5.17. Approximativa uttryck för Σx_i^2 och Σy_i^2.

Nr	Typ av regelstomme	Σx_i^2	Σy_i^2
1		$\frac{b^2}{12}(2n + 6m)$	$\frac{h^2}{12}(6n + 2m + p - 3)$
2		$\frac{b^2}{12}(2n + 6m)$	$\frac{h^2}{12}(6n + 2m)$
3		$\frac{b^2}{12}(2n + 6)$	$\frac{h^2}{12}(6n + 6)$
4		$\frac{b^2}{12}(2n + 3q + 15)$	$\frac{h^2}{12}(6n + 1{,}5q + 7{,}5)$
5		$\frac{b^2}{12}(6m + 6)$	$\frac{h^2}{12}(2m + p + 9)$
6		$\frac{b^2}{12}(6m + 6)$	$\frac{h^2}{12}(2m + 6)$
7		$\frac{b^2}{12}(2n + q + 9)$	$\frac{h^2}{12}(6n + 6)$

$$H_{Rd} = \frac{F_{vd}}{h\sqrt{\left(\frac{x_{max}}{\Sigma x_i^2}\right)^2 + \left(\frac{y_{max}}{\Sigma y_i^2}\right)^2}}$$

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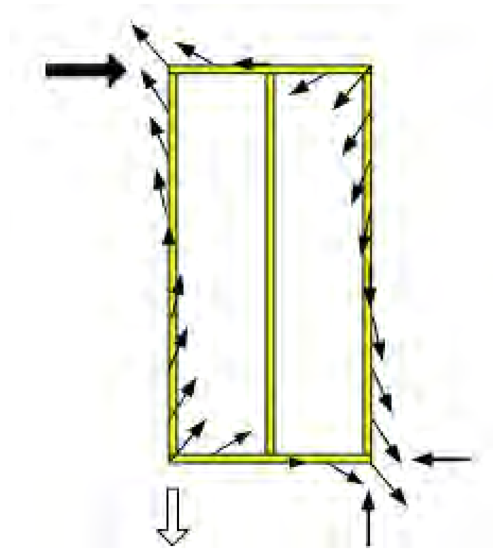
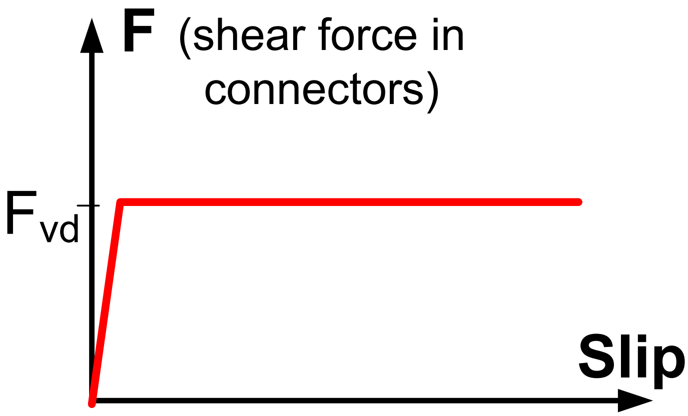
Comments on the elastic model

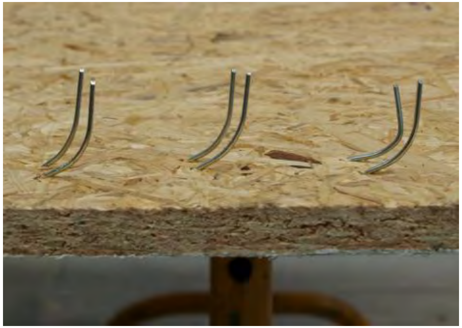
- Advantages
  - Simple to use
  - The flow of forces is described
  - Deformations can be estimated if the stiffness K of the connectors are known
- Disadvantage
  - Force redistribution due to plastic response of connectors in shear can not be utilised



Plastic model - assumptions

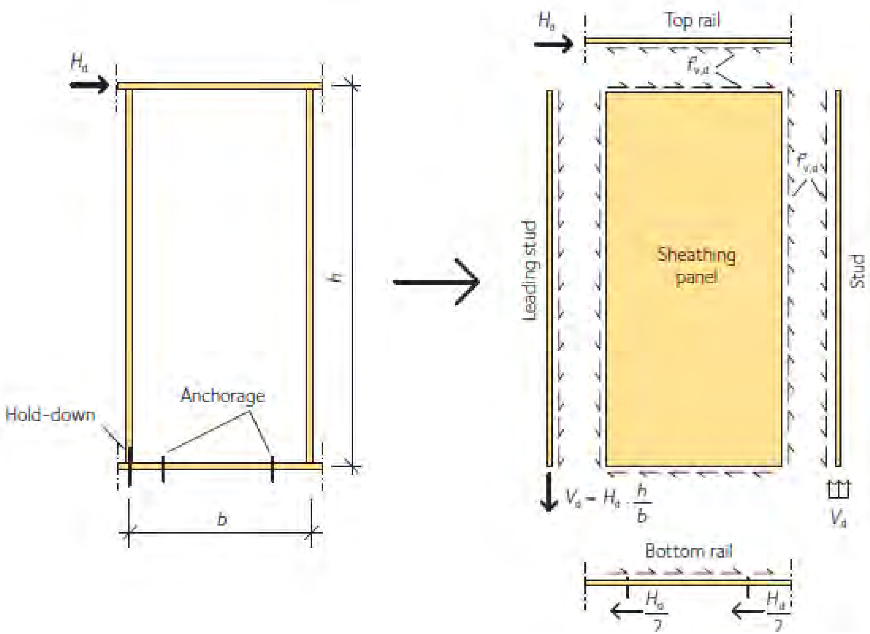
- Framing timber and panels are treated as rigid bodies
- The shear response of the connectors is considered ideally plastic



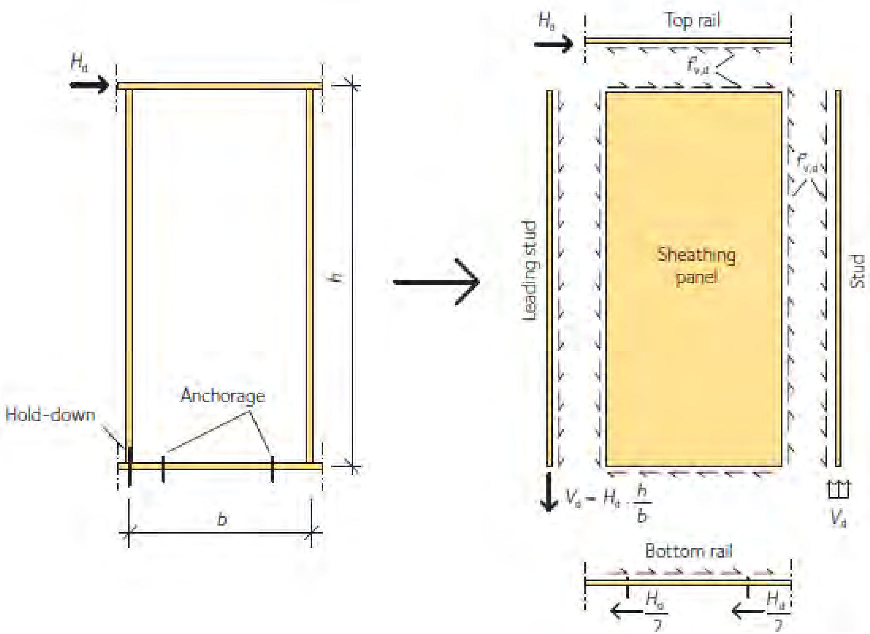


Picture: R. Steiger, Empa

Design model for shear walls – plastic model



Design model for shear walls – plastic model

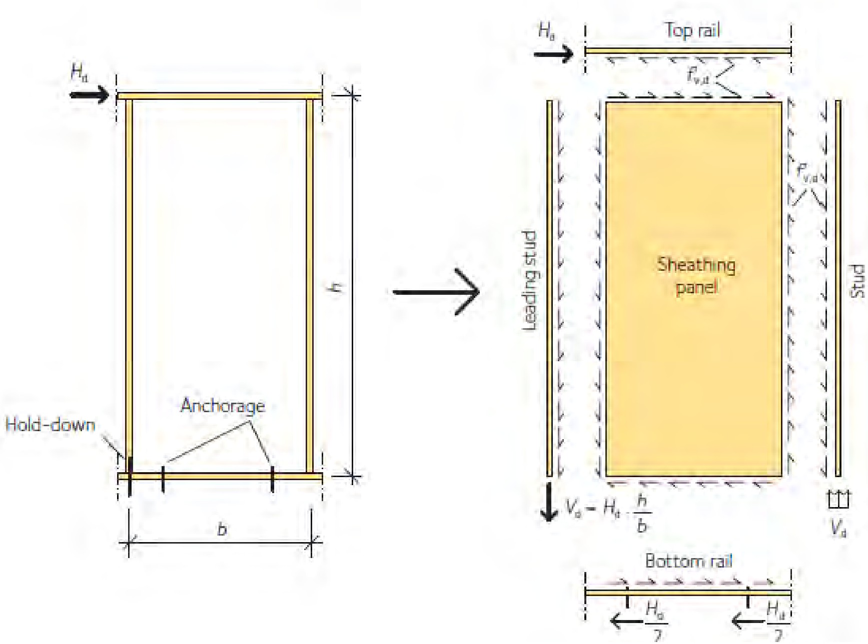


The racking capacity of the wall unit H_d can be determined from equilibrium of horizontal forces at the top rail:

$$H_d = f'_{v,d} \cdot b$$

where $f'_{v,d}$ is the shear flow strength (N/mm) at the sheathing-to-frame joint

Design model for shear walls – plastic model

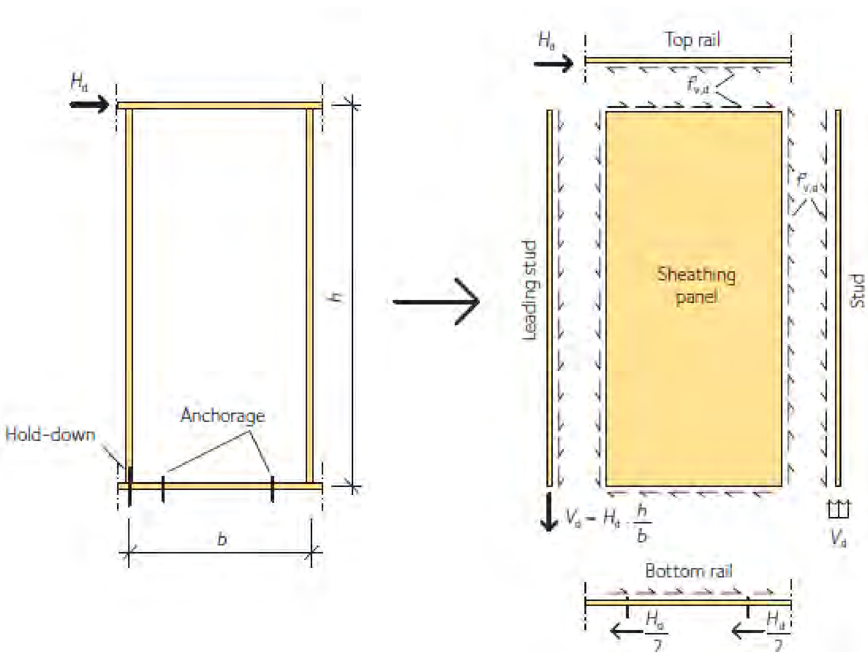


In reality, the shear between sheathing and frame is not continuous but punctual, since it is transmitted by the connectors – which are placed with a centre-to-centre spacing *s* (typically around *s* = 100 mm at the perimeter of the wall).

According to the plastic model all individual connectors carry the full design load $F_{v,d}$.

For equal spacing *s* between the connectors we get $f'_{v,d} = F_{v,d}/s$,

Design model for shear walls – plastic model



$$H_{\mathrm{d}} = f'_{\mathrm{v,d}} \cdot b$$

$$\Downarrow$$

$$f'_{\mathrm{v,d}} = F_{\mathrm{v,d}} / s$$

$$\Downarrow$$

$$H_{\mathrm{d}} = \frac{b}{s} \cdot F_{\mathrm{v,d}}$$

Racking capacity of the shear wall

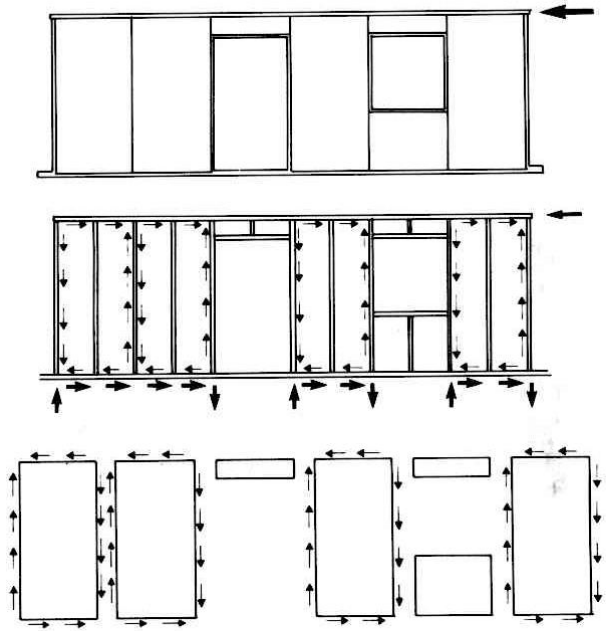
Load bearing capacity of single nail

Design of shear walls

- Small shear walls above doors and above/below windows are neglected

- Loads between neighbouring shear walls balance each other

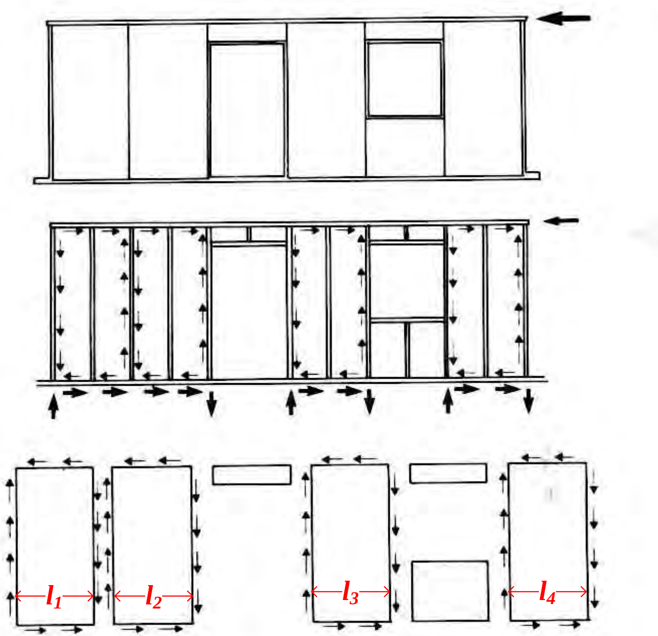
- The shear walls have to be connected to the underlying structure at both ends



Design of shear walls

- NB!
- The horizontal stiffness of the units:

$$k \propto \sum_i l_i$$



EC5 9.2.4

$$F_{v,Rd} = \sum F_{i,v,Rd}$$

- Method A – Simplified analysis of wall diaphragms
  - The recommended procedure
  - **Only whole sections** (no parts above openings)
  - Plastic design
- Method B – Simplified analysis
  - Recommended by BS std in the UK (STDtoEC5)
  - **Also smaller sections** (parts above openings)
  - Plastic design

EC5 9.2.4 Method A

$$F_{i,v,Rd} = \frac{F_{f,Rd} b_i c_i}{s}$$

Various **Principles 9.2.4.1** must be fulfilled:

- Each panel – secured against uplift!
- Width of each panel sheet is at least $h/4$
- Equal spacing of fasteners
- For fasteners along the edges of an individual sheet, the design lateral-carrying capacity $F_{v,Rk}$ should be increased by factor 1.2 cf.

$$F_{i,v,Rd} = \frac{k_{\mathrm{mod}} \cdot 1.2 \cdot F_{v,Rk}}{\gamma_M}$$

- For panels on both sides (same types sheets and fasteners) – the total racking load-capacity of the wall can be doubled.

Shear wall – summary

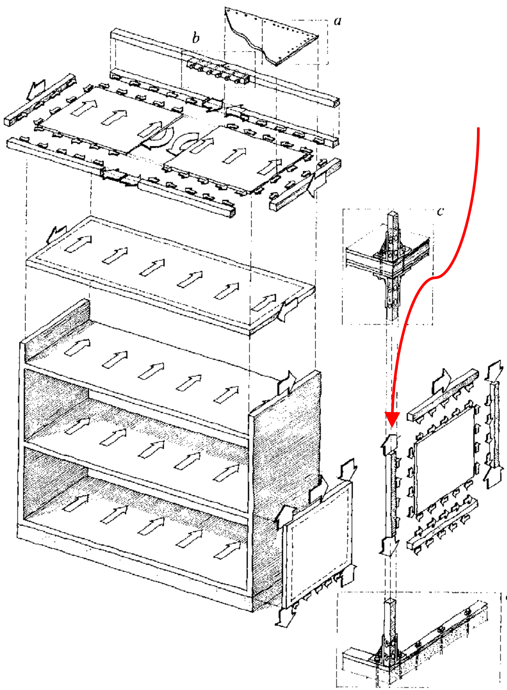
Shear wall – most efficient lateral load resisting system

- Nailed wood shear walls are highly redundant and are not governed by the weakest members
- Low grade timber provide a very reliable system
- The performance of the wall is mostly dependent on workmanship
- Shear walls are very ductile
- No special equipment is needed for construction and erection

Anchorage

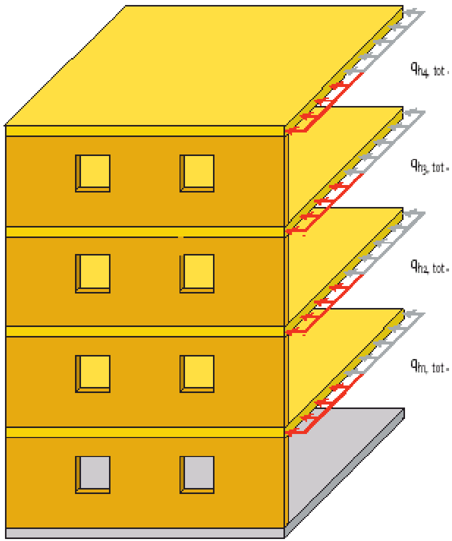
- Transmission of horizontal forces from floors to walls and to the ground

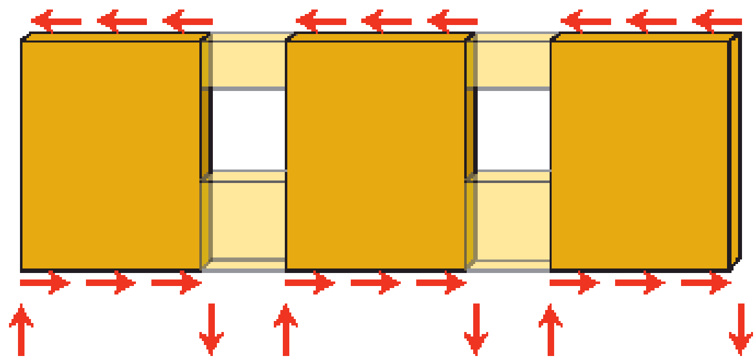
Uplift force.
How can we take care of that?



Anchorage of the shear wall

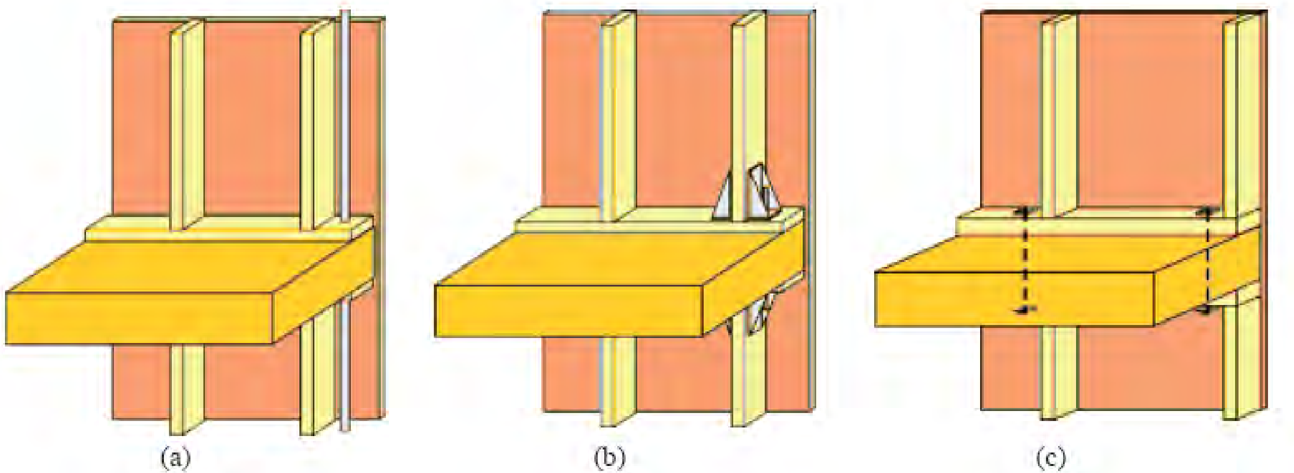
- Check the racking shear capacity of the load-bearing external wall





- Anchorage of the house/elements

Anchorage of the shear wall

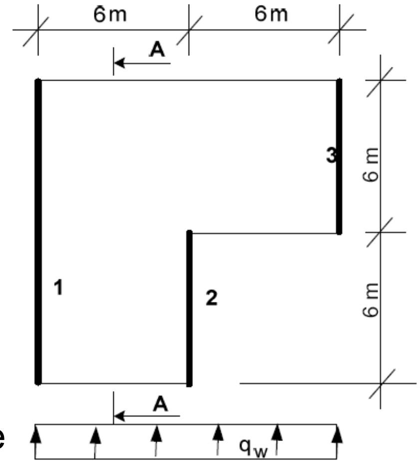


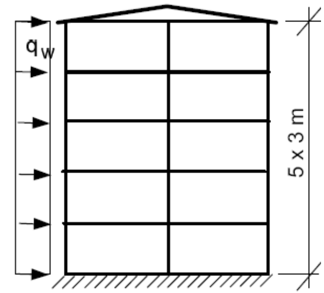
a) Complete anchorage of windward stud – steel rod throughout the entire house and fixed on each floor
b) Complete anchorage of windward stud
c) Ground and top plates are anchored

Källsner & Girhammar 2008

Example A1: Flexible diaphragm, stabilising walls

- Load: $q_{\mathrm{w,k}}$ = 0.93 kN/m^2
- Panels:
  - OSB t =24 mm
    1200 x 2600 mm
- Fasteners:
  - Screws 6 mm diameter
    Spacing 50 mm
  - $F_{\mathrm{v,Rd}}$ = 1.5 kN/shear plane
- Stabilising walls 1, 2, 3:
  - only 60% of the total length



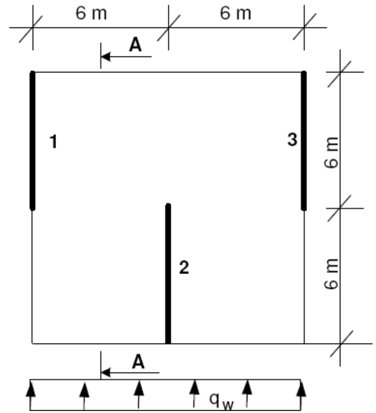


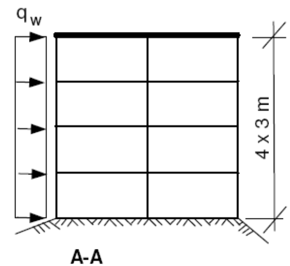
A-A

1. Determine the largest horizontal racking force (in kN) acting in the middle wall (no 2) on the bottom floor
2. Check the design of the shear wall (no 2) on the bottom floor by assuming that the connection has a plastic design. Is the resistance sufficient?

Example A2: Rigid diaphragm, stabilising walls

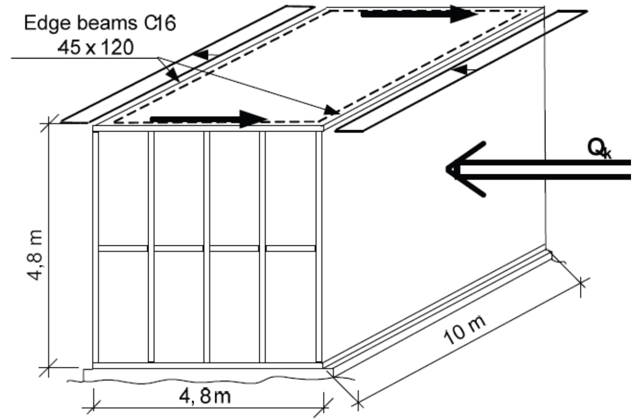
- Load: $q_{w,k}$ = 0.93 kN/m^2
- Panels:
  - OSB t =24 mm
    1200 x 2600 mm
- Fasteners:
  - Screws 6 mm diameter
    Spacing 60 mm
  - $F_{v,Rd}$ = 1.5 kN/shear plane
- Stabilising walls 1, 2, 3:
  - only 60% of the total length





1. Determine the largest horizontal racking force (in kN) acting in the middle wall (no 2) on the bottom floor
2. Check the design of the shear wall (no 2) on the bottom floor by assuming that the connection has a plastic design. Is the resistance sufficient?

Example A5: Roof diaphragm and wall diaphragm



- Load: $q_{w,k}$ = 0.8 kN/m^2
- SC2 Solid Timber C16
  Distance 1200 mm
- Panels:
  - Plywood P30, 1200 x 2400 mm
  - Walls t = 30 mm
  - Roof t = 24 mm
- Fasteners:
  - Wire nails 50 x 2, Spacing 50 mm

1. Check the capacity of the **roof diaphragm** with regard to load effect on nails due to shear in plywood, nail forces and the forces in the edge beams
2. Check the capacity of the **wall diaphragm** with regard to racking load.
3. Calculate the **lift forces** in the bottom rail.

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