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TIMBER ENGINEERING - VSM196

LECTURE 12 –

STABILITY- STABILIZING WALLS, TILTING AND HORIZONTAL STABILITY

SPRING 2020

Image: Valentin Jeck & Oliver Christen Architekten GmbH

Topic

- Stability
  - stabilizing walls
  - tilting
  - horizontal stability
- [DoTS: Chapter 6 & 8]

Content

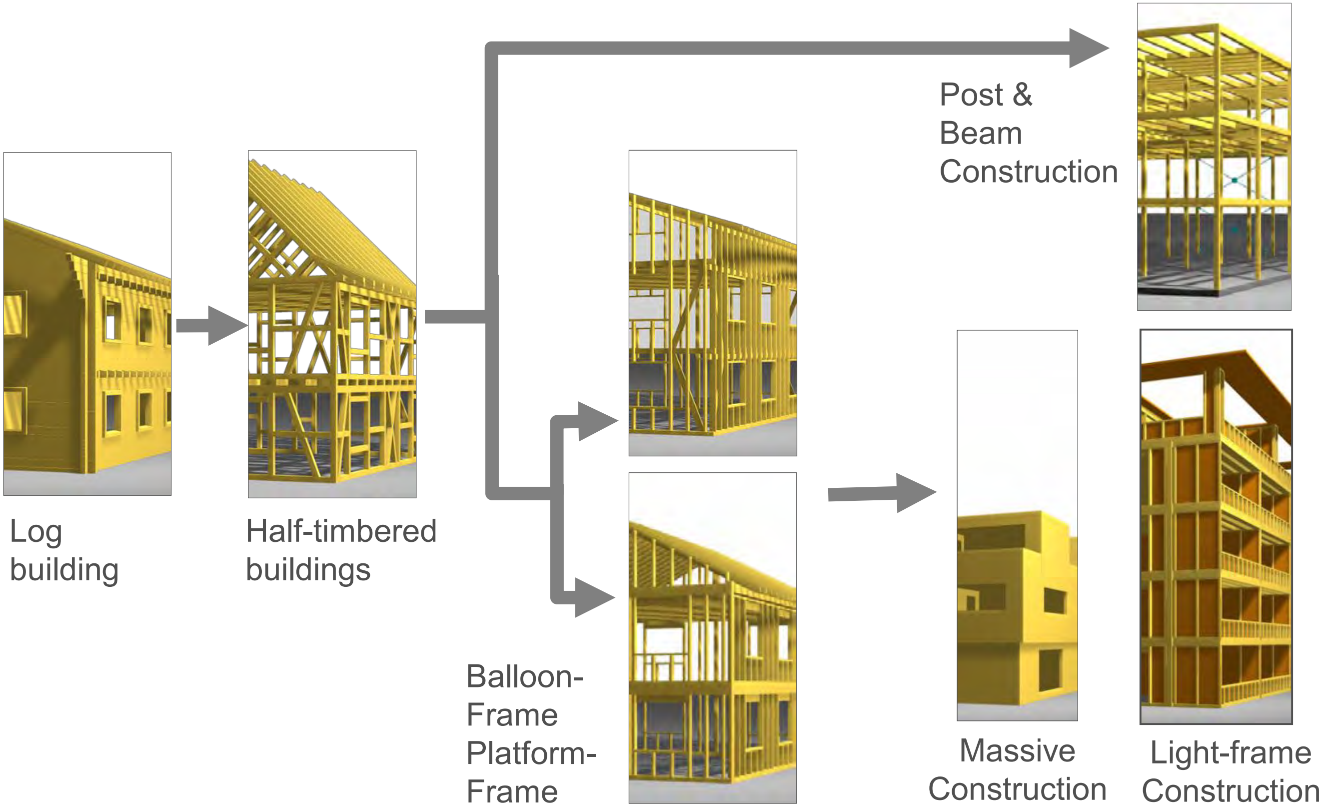
- Global stability of multi-storey timber building
- Bracing of structures – general issues

- Design examples A3

Intended Learning Outcomes of this lecture

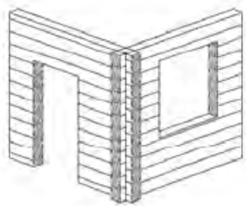
- You can evaluate the structural integrity of multi-storey timber buildings
- You can stabilize timber structures
- You understand bracing of structures
- You can choose and design stabilising systems for hall structures

Overview
Load-bearing systems in buildings

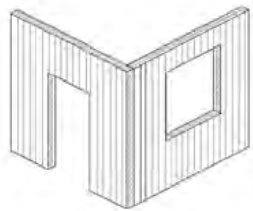

Post &
Beam
Construction
Log
building
Half-timbered
buildings
Balloon-
Frame
Platform-
Frame
Massive
Construction
Light-frame
Construction

Common load bearing systems

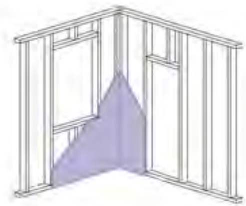
- Load-bearing walls



Log



CLT (or X-LAM)



Timber frame

- Post and beam system
  - typically used for multi-storey buildings

Load-bearing walls

- No columns are in the system, only the walls
- The walls carry both vertical and horizontal load
- Diaphragm action typically used for stabilization (bracing). (Sheathing, such as OSB, plywood or gypsum necessary in the case of timber frames)
- The sheathing material is also needed for fire resistance and sound insulation. Gypsum (inside) is the dominant material as both the fire, noise and resistance to be met.

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Post-and-beam system

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Post-and-beam system

- Timber wall bracing

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Post-and-beam system

- Concrete wall bracing

Stabilisation of multi-storey timber buildings

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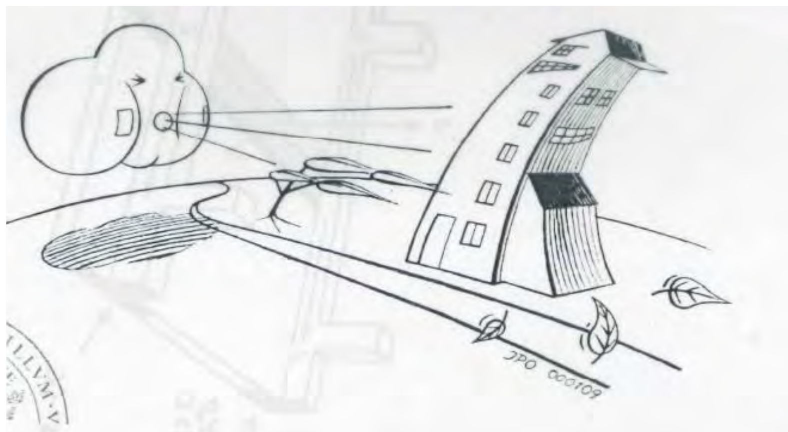
Stabilisation of multi-storey timber building

- Global stability (tilting & sliding)
- Bracing – general issues
- Transmission of forces between floors and walls

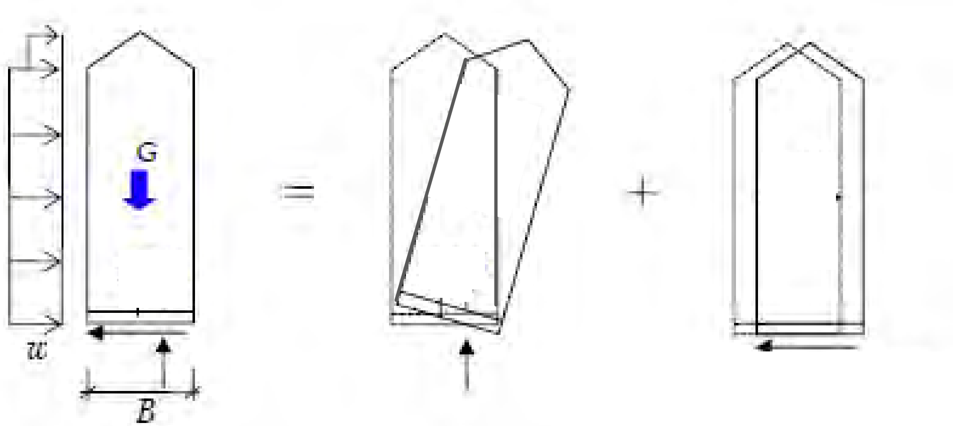


Global failure of a multi-storey building

Global failure of garage

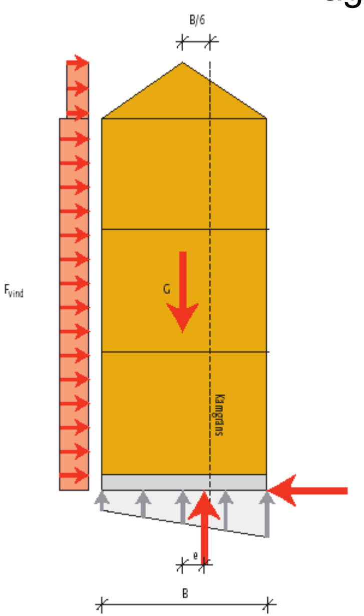
Global Stability: tilting and sliding

Tilting Sliding



Global Stability: tilting

- Always perform a *rough check* to determine whether safety against tilting may be considered satisfactory



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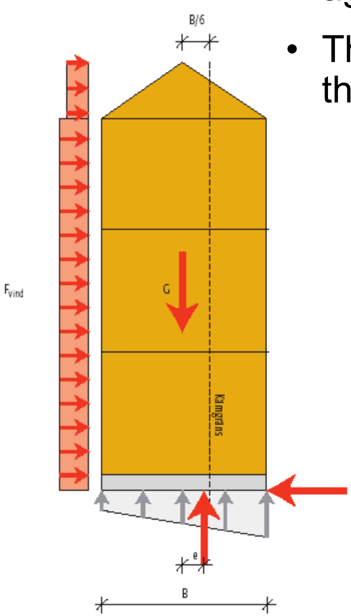
Global Stability: tilting



- Always perform a *rough check* to determine whether safety against tilting may be considered satisfactory
- This can be done by checking whether the load resultant of the vertical reaction ends up in the building's middle third.

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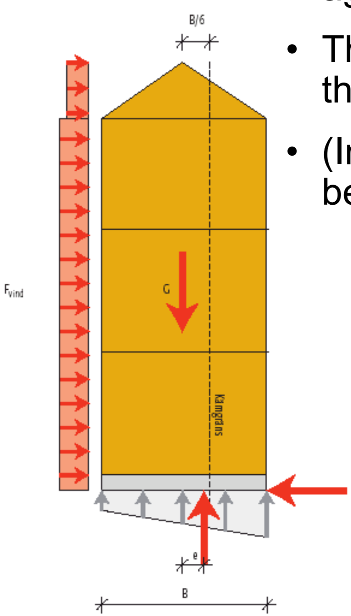
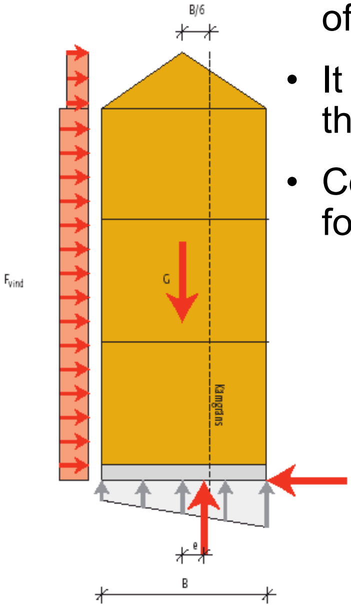
Global Stability: tilting

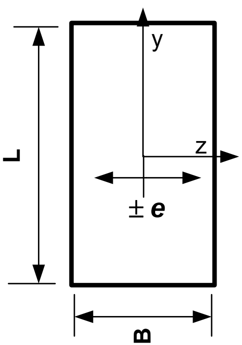


- Always perform a *rough check* to determine whether safety against tilting may be considered satisfactory
- This can be done by checking whether the load resultant of the vertical reaction ends up in the building's middle third.
- (In addition to the tilting check- of course - also ground bearing capacity must be controlled)

Global Stability: tilting

- The building is safe against tilting if the vertical resultant caused by all horizontal loads is within the border of the core ***e***.
- It means that there are no tensile stresses in the section of the foundation
- Consider a rectangular area of the foundation plate (Navier's formula):





Plan

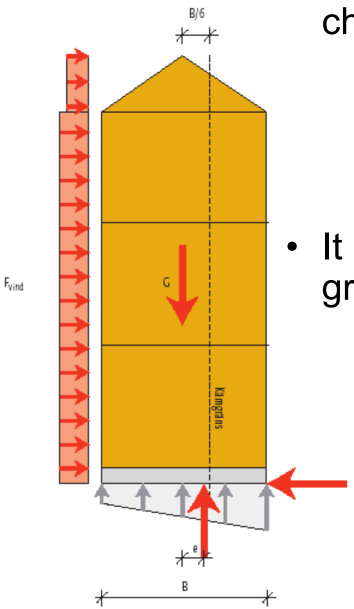
$$\sigma = 0 = \frac{N}{A} + \frac{M}{I} \cdot z_{max}$$

$$z_{max} = \frac{-N}{M} \cdot \frac{I}{A}$$

$$z_{max} = \frac{-N}{M} \cdot i^2 = \frac{-1}{e} \cdot i^2$$

$$e = \frac{i^2}{z_{max}} = \pm \frac{B^2/12}{B/2} = \frac{B}{6}$$

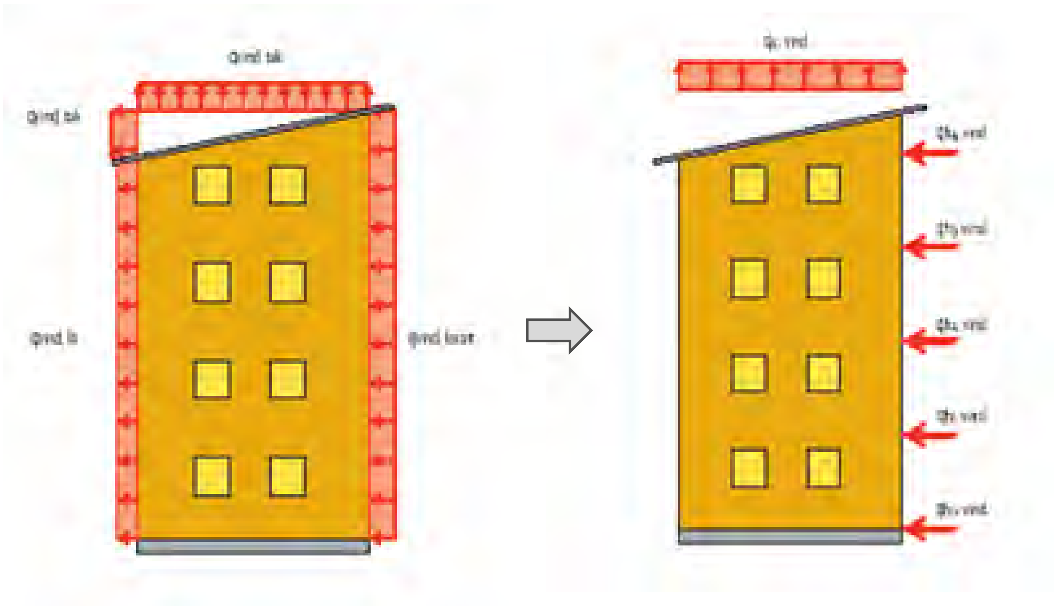
Global Stability: tilting



- If the self-weight of the building and its foundation are not sufficient to prevent tilting, the building design must be changed by, e.g.:
  - increasing the building's self-weight and/or
  - change the geometry.

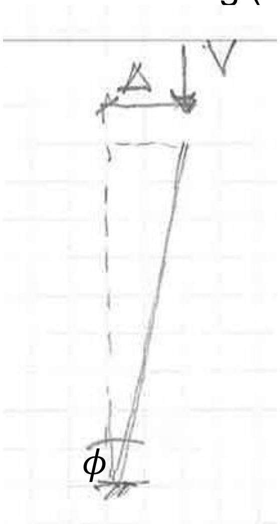
- It is also possible to anchor the bottom plate down into the ground – but often this is an expensive solution

Global Stability: equivalent (tributary) forces



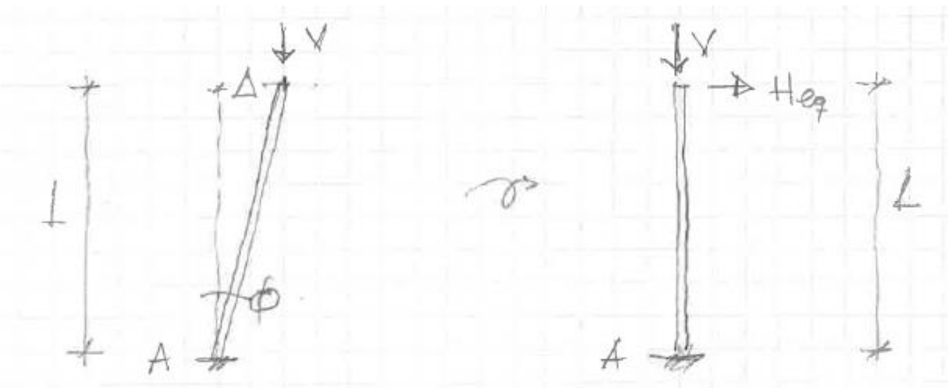
Global Stability: equivalent sway imperfections

- The equivalent (fictitious) horizontal forces occur due to accidental slope of the building (second order effects)



$$\begin{cases} \Delta \approx \dfrac{L}{300} \\ \phi = \dfrac{\Delta}{L} \end{cases} \Rightarrow \quad \phi = \frac{\Delta}{L} \approx \frac{1}{300}$$

Global Stability: equivalent sway imperfections



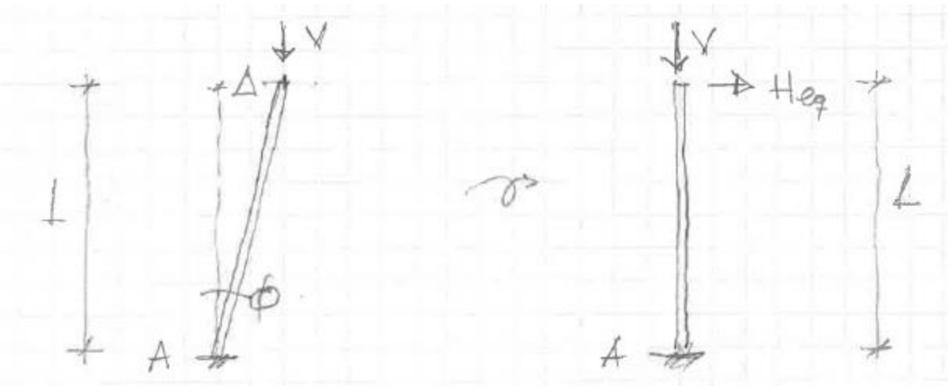
1. ”real” (exectued) structure

$$M_{A,1} = V \cdot \Delta = V \cdot L \cdot \phi$$

2. Simplified modell

$$M_{A,2} = H_{eq} \cdot L$$

Global Stability: equivalent sway imperfections



1. ”real” (exectued) structure

$$M_{A,1} = V \cdot \Delta = V \cdot L \cdot \phi$$

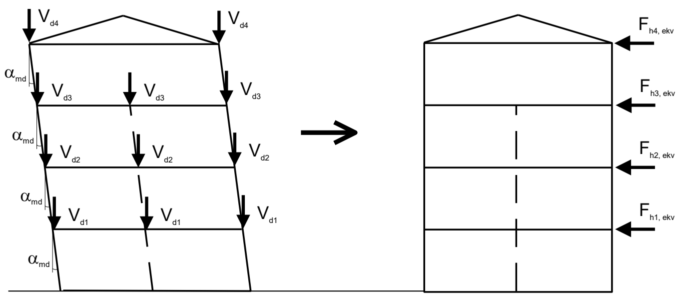
2. Simplified modell

$$M_{A,2} = H_{eq} \cdot L$$

$$M_{A,1} = M_{A,2} \quad \Rightarrow \quad H_{eq} = V \cdot \phi \ \left(\approx \frac{V}{300}\right)$$

Global Stability: equivalent sway imperfections

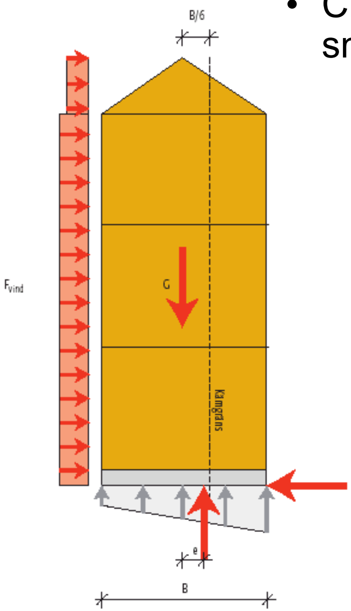
- The horizontal components as a result of unintended inclination forces on each floor are obtained by assuming that all the vertical loads (roof, self-weights of floors and walls) are transmitted through inclined walls



$F_{hi,eq} = V_{di} \cdot n \cdot \alpha_{md}$

- $\alpha_{md} = \alpha_0 + \alpha_d/\sqrt{n} = 0{,}003 + 0{,}012/\sqrt{n}$
- n - Number of supporting walls/columns in the system loaded with the vertical loads
- α_0 - Systematic part of inclination angle
- α_d - Random part of inclination angle

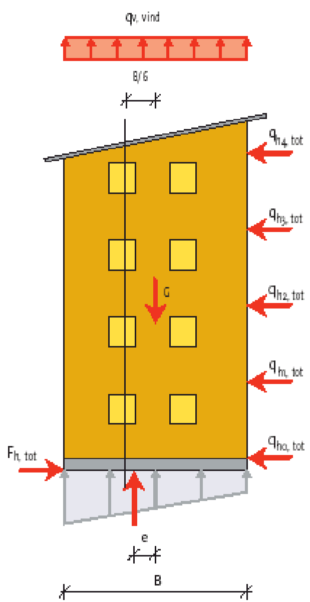
Global Stability: sliding



- Check that shear between concrete plate and ground is smaller that shear strength of ground material

Global Stability

- Control of the global stability of the building
  - against tilting moment
  - against horizontal reaction force



The building is safe against tilting
if the total self-weight (G) is sufficient to counteract the tilting moment
caused by total horizontal loads (caused by wind loads and contribution from unintended inclinations)

Global Stability

- Design values of actions (EC 1 or STDtoEC5)

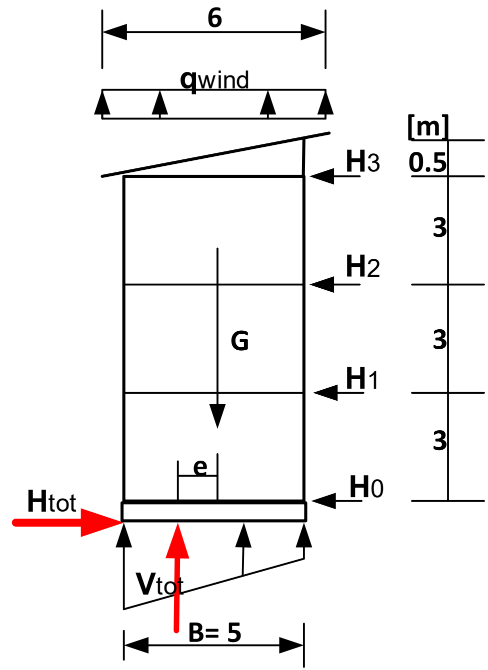
Table 2.8 Design values of actions for equilibrium (EQU) and strength (STR) limit states*

Ultimate limit state (under persistent and transient design situations – fundamental combinations)		Relevant equation in EC0	Permanent actions		Leading variable action	Accompanying variable actions	
			Unfavourable[‖]	Favourable[‖]		Main	Others
EQU	(a)[†]	*(6.10)*	$1.10G_{k,j,sup}$	$0.90G_{k,j,inf}$	$1.5Q_{k,1}$ (0 when favourable)	–	$1.5\psi_{0,i}Q_{k,i}$ (0 when favourable)
	(b)[‡] The highest design value from combination (i) or (ii)	(i) *(6.10)*	$1.35G_{k,j,sup}$	$1.15G_{k,j,inf}$	$1.5Q_{k,1}$ (0 when favourable)	–	$1.5\psi_{0,i}Q_{k,i}$ (0 when favourable)
		(ii) *(6.10)*	$1.0G_{k,j,sup}$	$1.0G_{k,j,inf}$	$1.5Q_{k,1}$ (0 when favourable)	–	$1.5\psi_{0,i}Q_{k,i}$ (0 when favourable)
STR[§] (not involving geotechnical actions)	(c)	(i) *(6.10)*	$1.35G_{k,j,sup}$	$1.0G_{k,j,inf}$	$1.5Q_{k,1}$ (0 when favourable)	–	$1.5\psi_{0,i}Q_{k,i}$ (0 when favourable)
	(d)	(ii) *(6.10a)*	$1.35G_{k,j,sup}$	$1.0G_{k,j,inf}$	–	$1.5\psi_{0,1}Q_{k,1}$	$1.5\psi_{0,i}Q_{k,i}$
		(iii) *(6.10b)*	$0.925 \times 1.35G_{k,j,sup}$	$1.0G_{k,j,inf}$	$1.5Q_{k,1}$	–	$1.5\psi_{0,i}Q_{k,i}$

EQU: to confirm that the structure or any part of it is not unstable

Example A3 Multi-storey timber house, horizontal stability

- **Check the horizontal stability of the building in ULS against tilting moment and against horizontal reaction force**
  for the case when the wind load is the main variable action acting on the long façade of this house.
- Wind loads:
  H_0 = 1.5 kN/m, $H_{1\text{-}2}$ = 2.5 kN/m H_3 = 2 kN/m,
  q_{wind} = 0.7 kN/m^2
- Self-weights are:
  external walls = 0.5 kN/m^2,
  roof = 0.4 kN/m^2,
  10 m (each flat) partition walls = 0.3 kN/m^2,
  loft floor 0.7 kN/m^2 and
  the total weight of the concrete slab is 18 kN
- Foundation is located on Friction soil with the design friction angle Φ_d = 30°



Stabilisation

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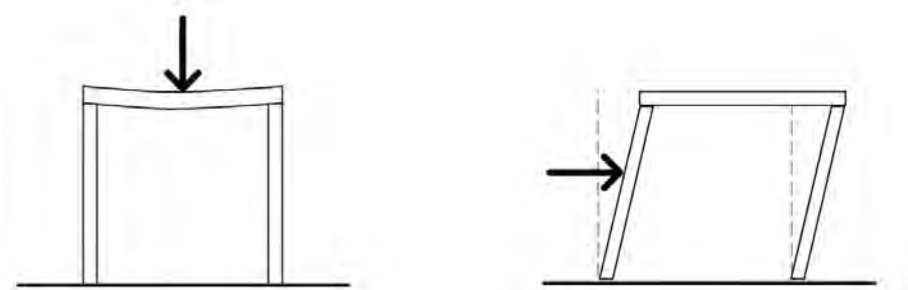
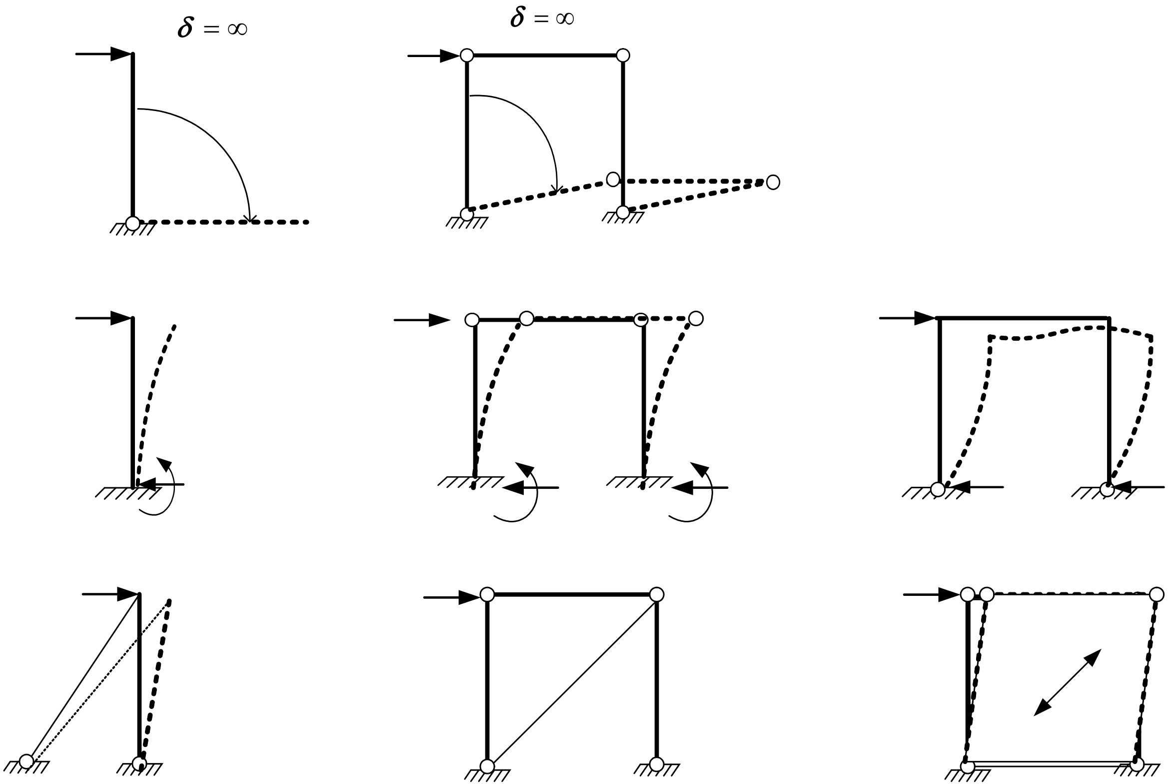
Stabilisation… what's it all about?

- The purpose behind stabilization of structures is to prevent (or reduce) deformations



Methods of achieving stability in a single-story building - principles



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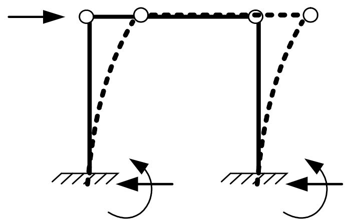
Methods of achieving stability in a single-story building

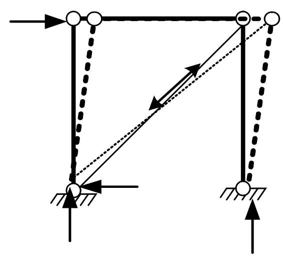
- Principles

- Portal frames



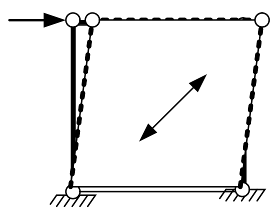
Relies on the bending stiffness of the framed elements

- Braced system



Relies on the axial stiffness of the bracing elements

- Shear panels

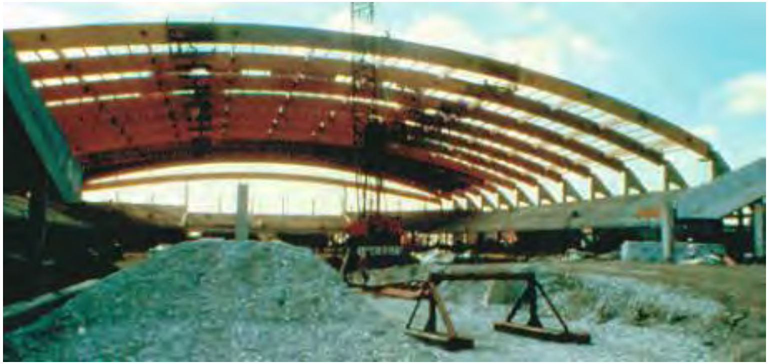


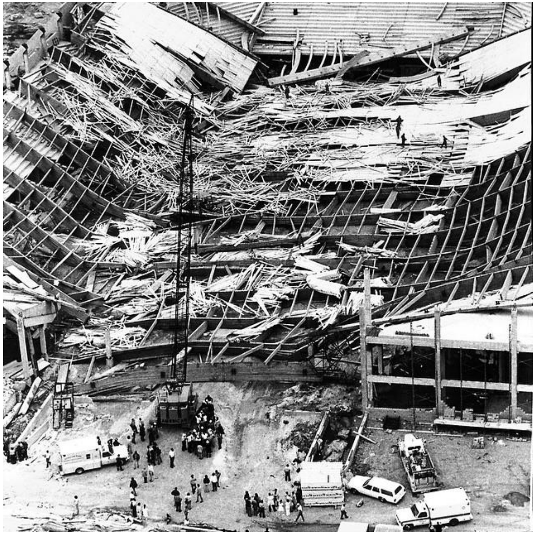
Relies on the shear stiffness of the panel

Apparently stable structures

Insufficient bracing during assembly

Insufficient bracing during assembly





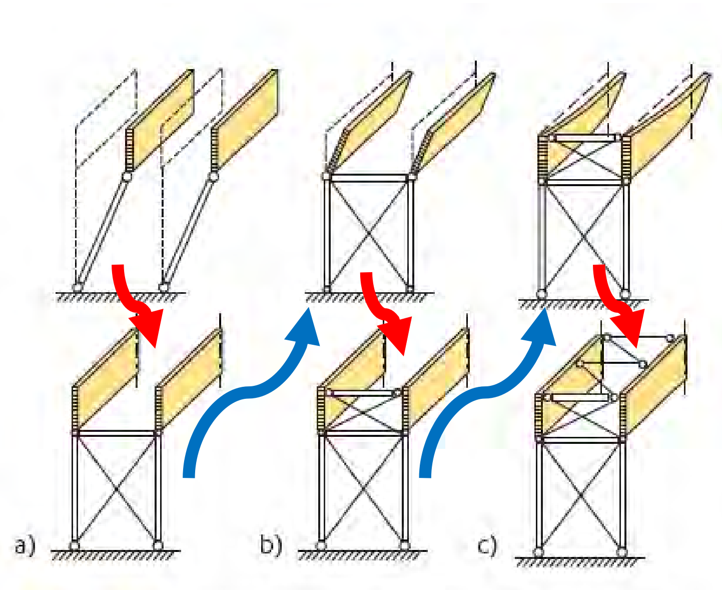
- Rosemont Horizon Stadium
- near Chicago, USA, 1979
- Konstruktion: Arches, approx. 90 m span
- (17 workers died at the collapse)
- Cause: insufficient bracing during construction phase

Insufficient bracing during assembly

Insufficient bracing during assembly

Edmonton, Canada, 2015

Complete Bracing of structures



Bracing of structures- what is bracing good for?

- Make unstable structures… stable, when these are subjected to horizontal loads

- Reduce lateral deformation

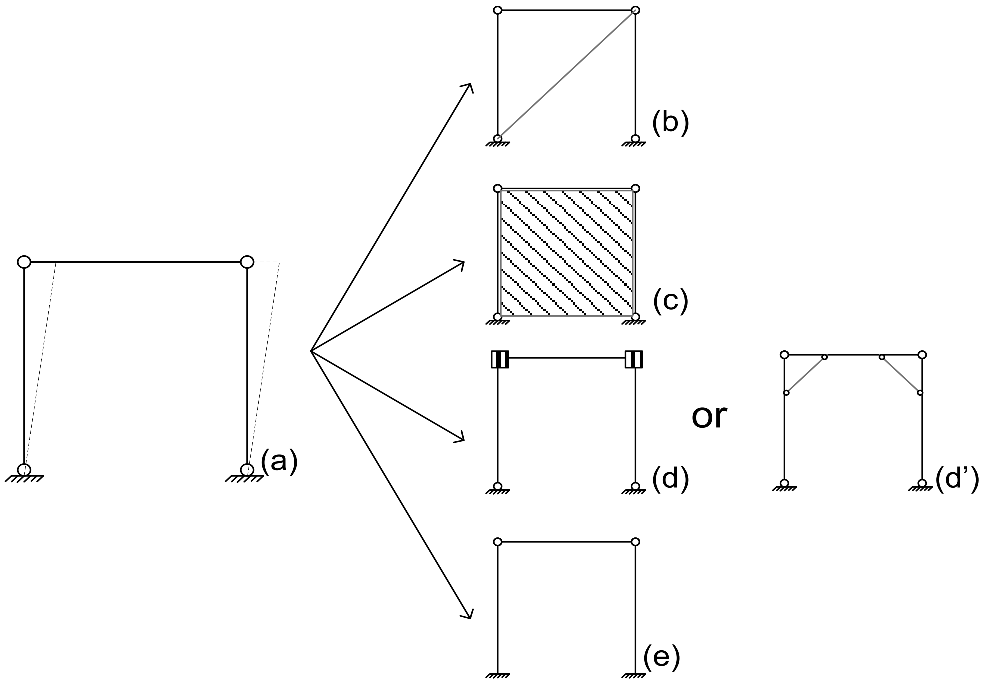
- Reduce buckling length of members
(e.g. LTB of beams and flexural buckling of columns)

- Facilitate the erection

Conversion of an unstable into a stable structure

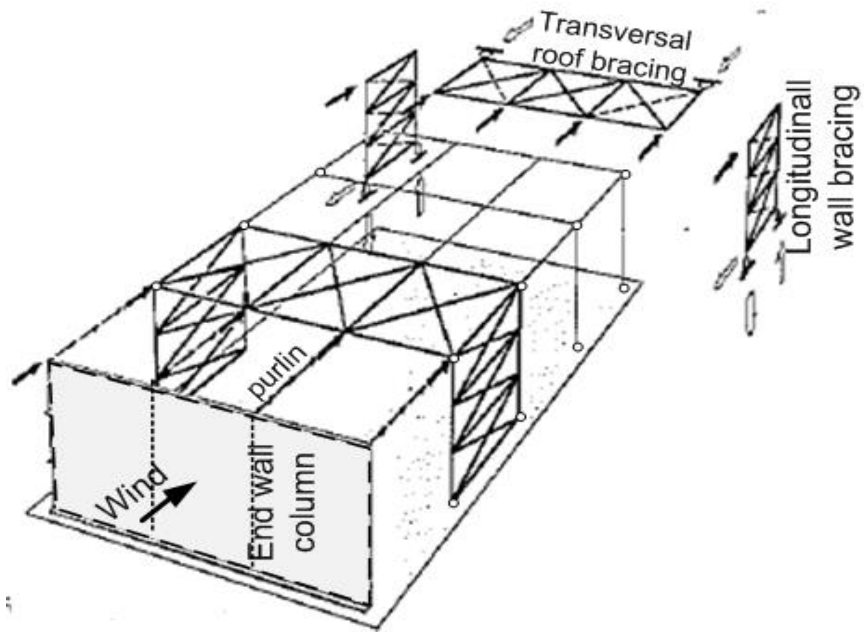
Unstable configuration

Stable configurations



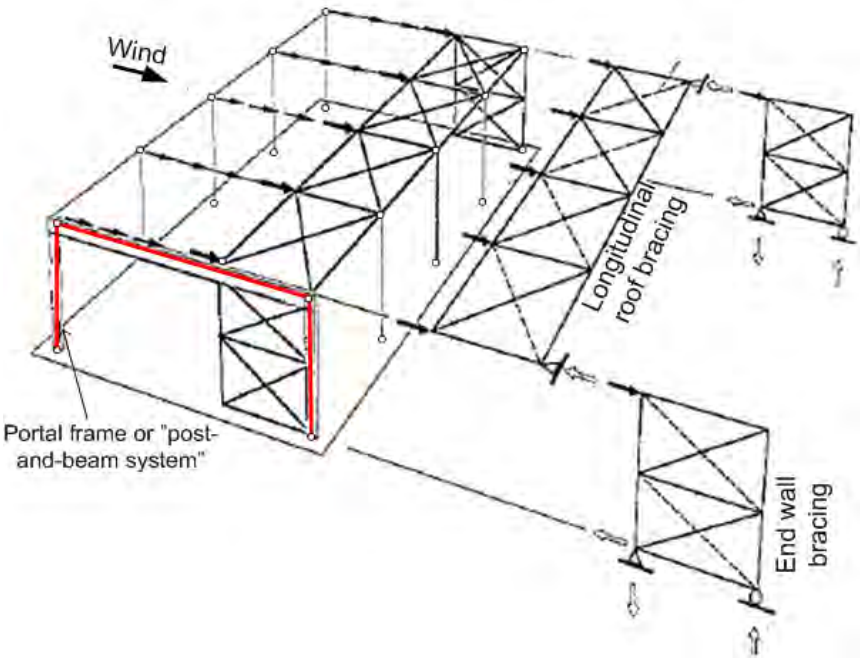
Transmission of horizontal loads

- Loads perpendicular to the end walls



Transmission of horizontal loads

- loads perpendicular to the longitudinal walls



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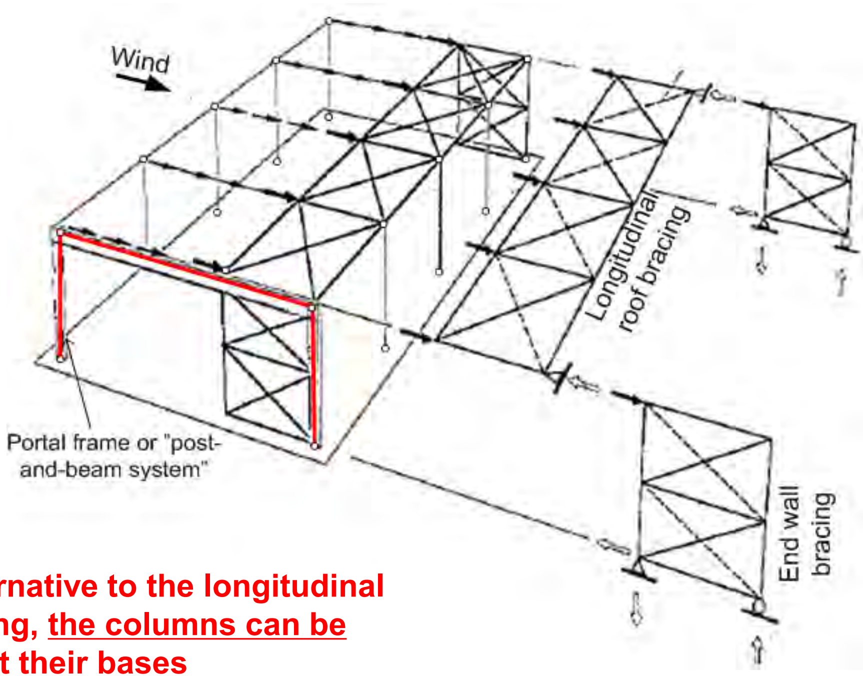
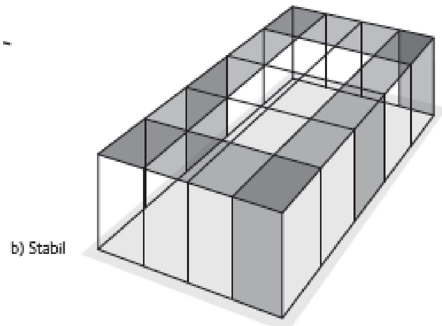
Transmission of horizontal loads

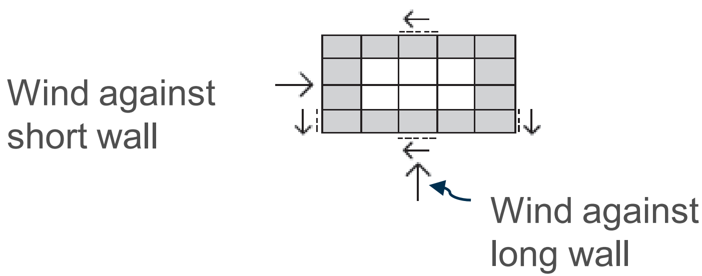
- loads perpendicular to the longitudinal walls



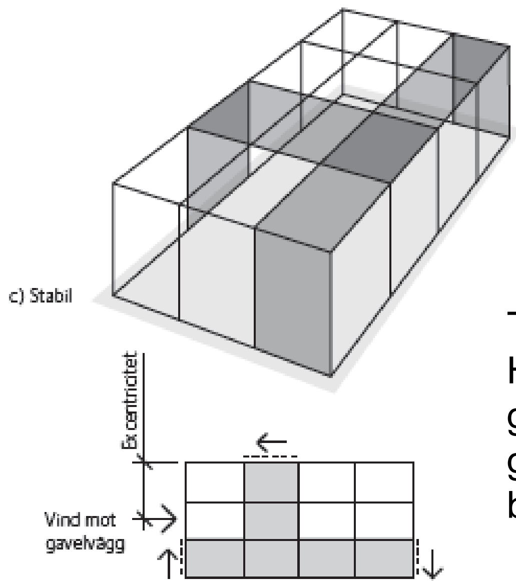
As an alternative to the longitudinal roof bracing, <u>the columns can be clamped at their bases</u>

Bracing of structures- examples of adequate bracing





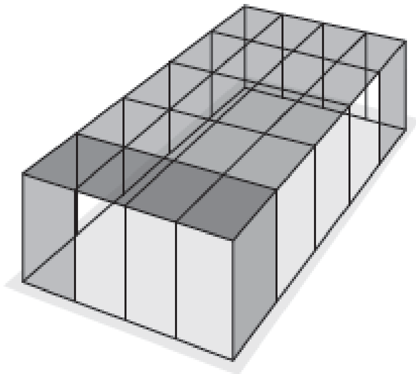
Bracing of structures- examples of adequate bracing

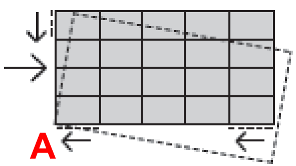


The system is stable. However, wind against gable gives rise to twist which in turn generates extra forces in the braces at the gables.

Bracing of structures- examples of inadequate bracing

d) Instabil





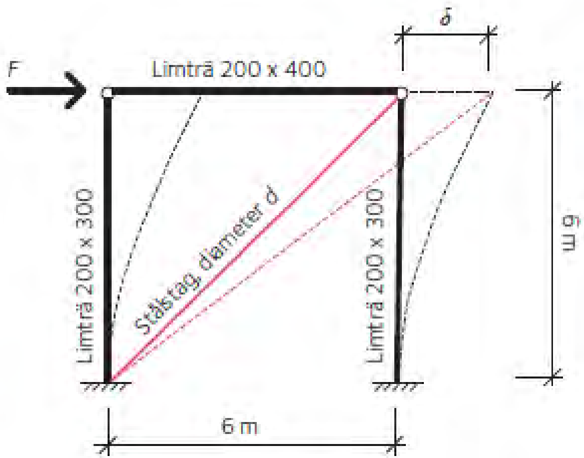
The system is unstable. Moments about point “A” are not in equilibrium.

Bracing of structures- what is bracing good for?

- Make unstable structures… stable, when these are subjected to horizontal loads
- Reduce lateral deformation
- Reduce buckling length of members (e.g. LTB of beams and flexural buckling of columns)
- Facilitate the erection

Reduction of lateral deformations

- wall bracing



Tabell 6.1

Diameter	Horisontalstyvhet $k = F/\delta$
Ingen diagonal	$k = k_0$
$d = 10$ mm	$k \approx 7 \cdot k_0$
$d = 20$ mm	$k \approx 25 \cdot k_0$
$d = 30$ mm	$k \approx 50 \cdot k_0$

Bracing of structures- what is bracing good for?

- Make unstable structures… stable, when these are subjected to horizontal loads

- Reduce lateral deformation

- Reduce buckling length of members
(e.g. LTB of beams and flexural buckling of columns)

- Facilitate the erection

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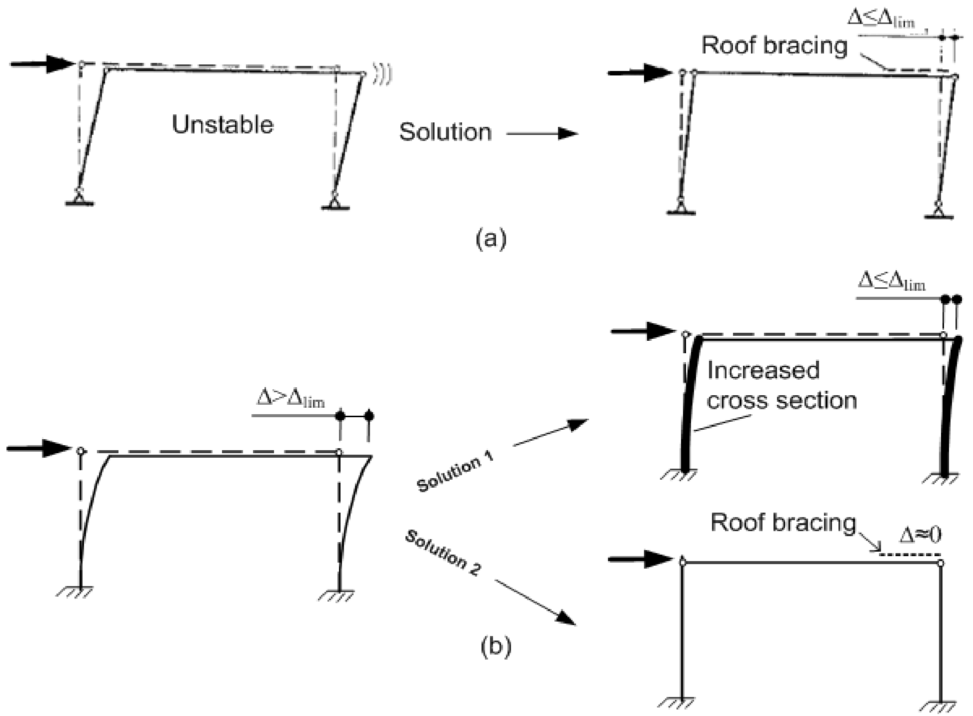
Reduction of lateral deformations

- roof bracing



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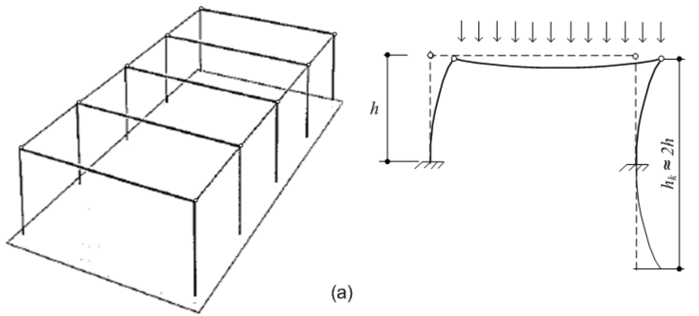
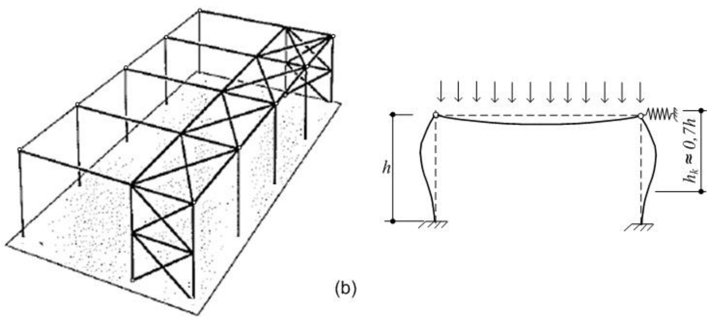
Enhancing buckling strength

- in-plane buckling



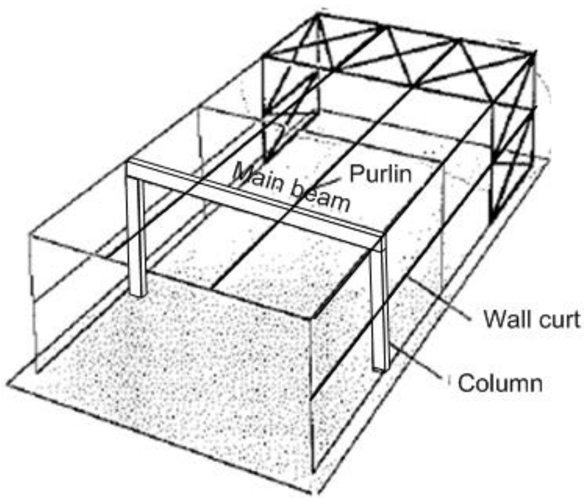
(a)

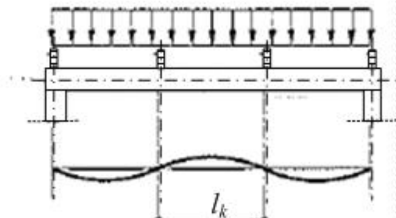


(b)

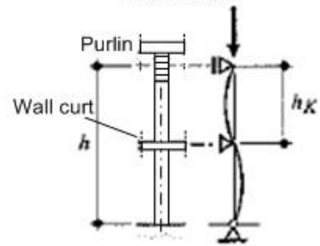
Enhancing buckling strength

- out-of-plane buckling





Lateral torsional buckling of main beam

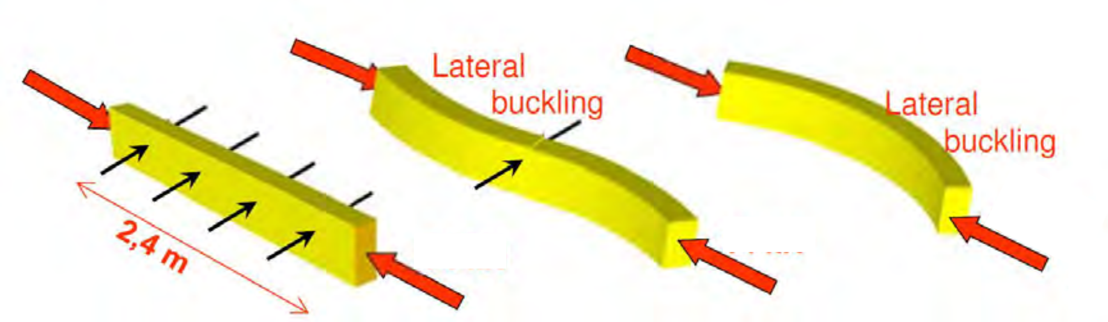


–Out-of plane buckling of column

Enhancing buckling strength

- out-of-plane buckling
  - Example:
    Compression in C24 member, 36 x 98 mm member 2,4 m long

  - Complete lateral bracing:
    $N_{c,0,k}$ = **74 kN**
  - One stiffener in the middle - lateral slenderness λ = 115:
    $N_{c,0,k}$ = **14,1 kN**
  - Unstiffened example - lateral slenderness λ = 230:
    $N_{c,0,k}$ = **3,7 kN**



Bracing of structures- what is bracing good for?

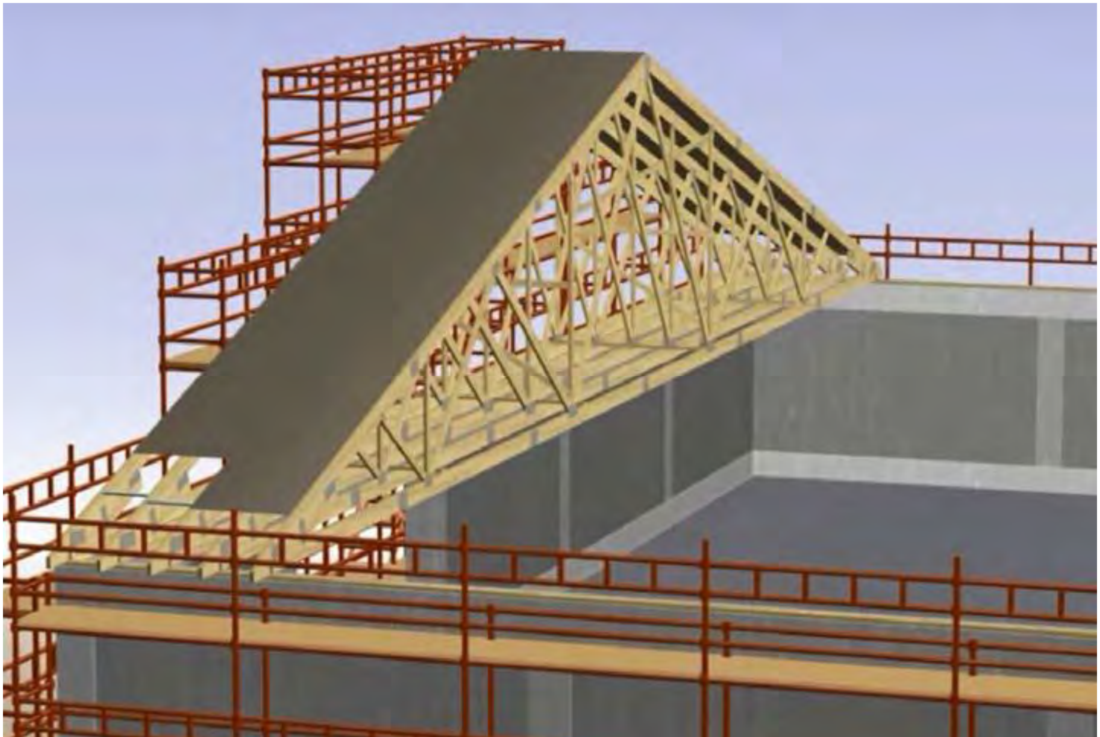
- Make unstable structures… stable, when these are subjected to horizontal loads

- Reduce lateral deformation

- Reduce buckling length of members (e.g. LTB of beams and flexural buckling of columns)

- Facilitate the erection

Facilitation of the erection



Failures during erection

- Generally, 3 main reasons for collapse of structures:
  1. Planning and design
  2. Construction / building phase
  3. Lack of maintenance, use and others
- Reasons No.1 and 2 are of about the same order, No.3 relatively less.
- About 60% of the failures occur during the building phase. Even if the problem is planning or design, the failure often occur during the building phase.
- Failures where people were killed or injured is relatively worse, 65-70% occurs during the building phase.

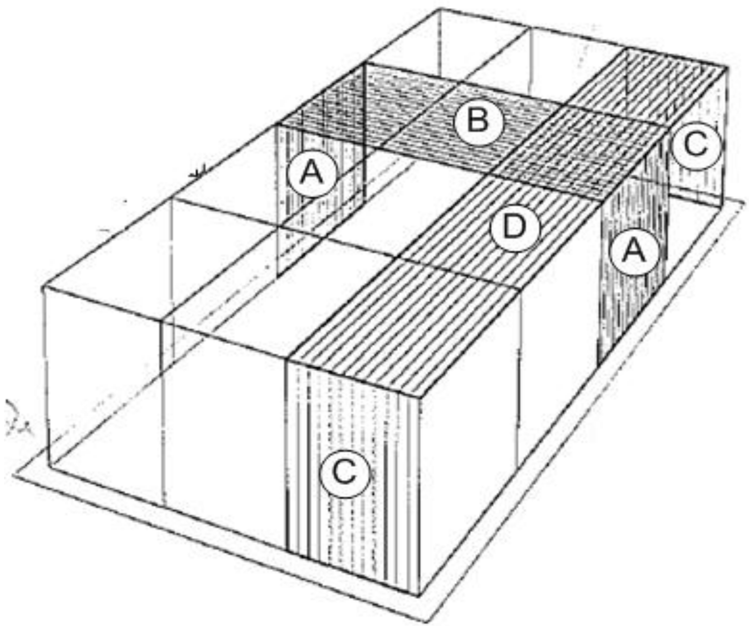
Design of safe timber structures – How can we learn from structural failures in concrete, steel and timber?
Frühwald et al., Lund Institute of Technology, 2007

Bracing elements

Bracing elements

- Wall bracing (C) & (A)

- Roof bracing (D) & (B)



Wall bracing

- Examples
  - Threaded Steel rods
  - Compression diagonal struts (normally timber members with nearly square cross section)
  - Frames
  - Shear walls

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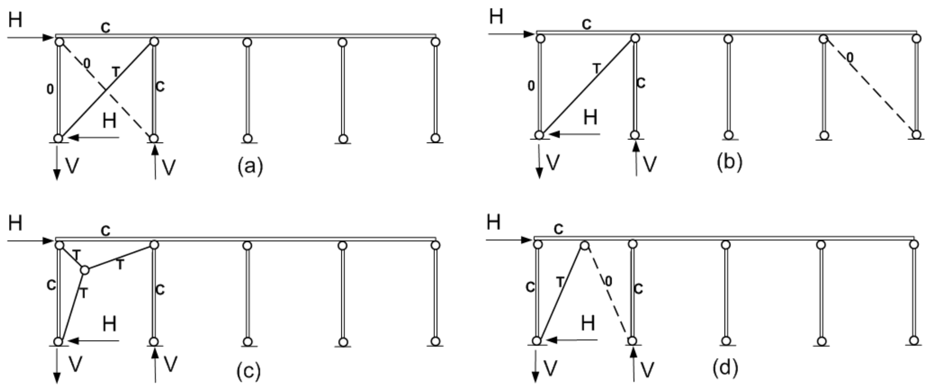
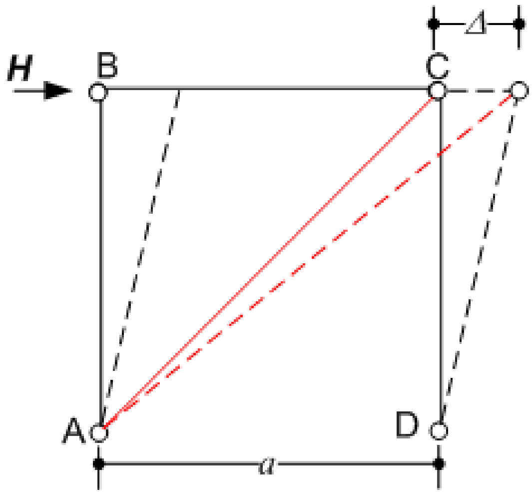
Wall bracing by steel rods



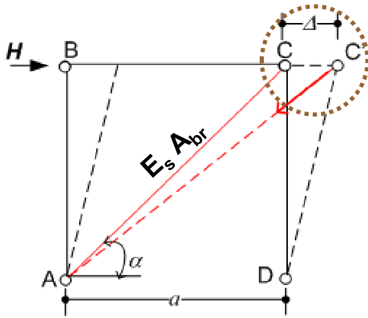
Brace stiffness

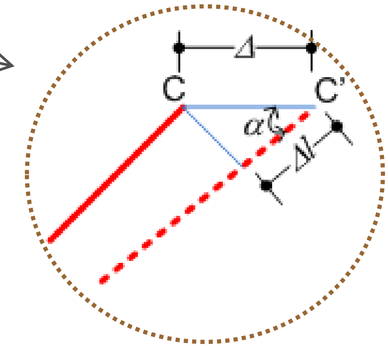


$$k_{br} = \frac{H}{\Delta}$$

Brace stiffness

- Assumption: the axial deformation of beam and column are nil





1. $N_{AC} = \dfrac{H}{\cos\alpha}$

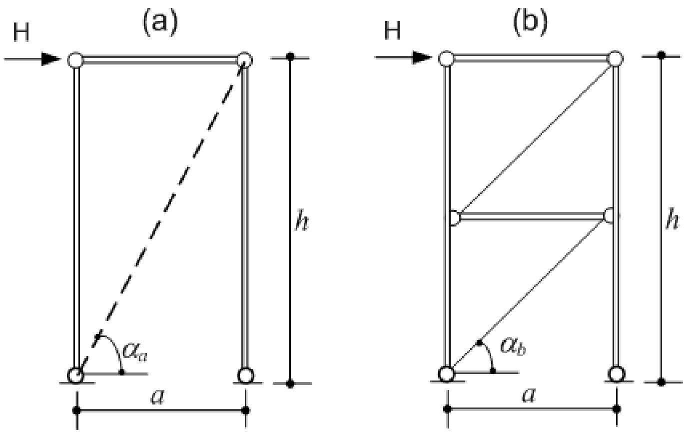
2. $\Delta l = \Delta \cdot \cos\alpha$

3. $\Delta l = \dfrac{N_{AC} \cdot l_{AC}}{E_s \cdot A_{br}}$

4. $k_{br} = \dfrac{H}{\Delta}$

$$\boxed{k_{br} = \frac{E_s A_{br} \cos^3 \alpha}{a}}$$

Bracing of high walls

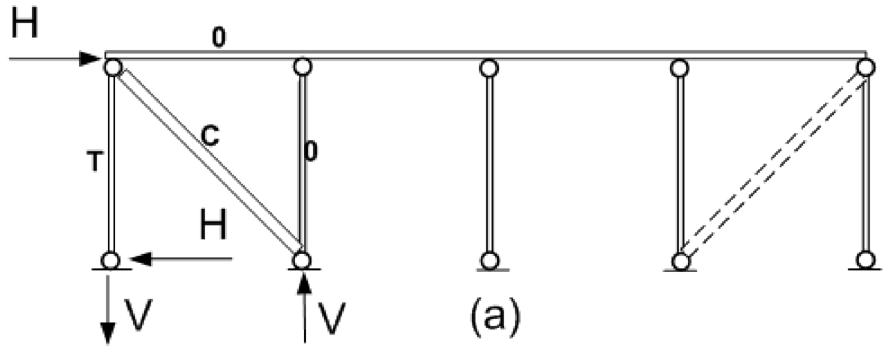


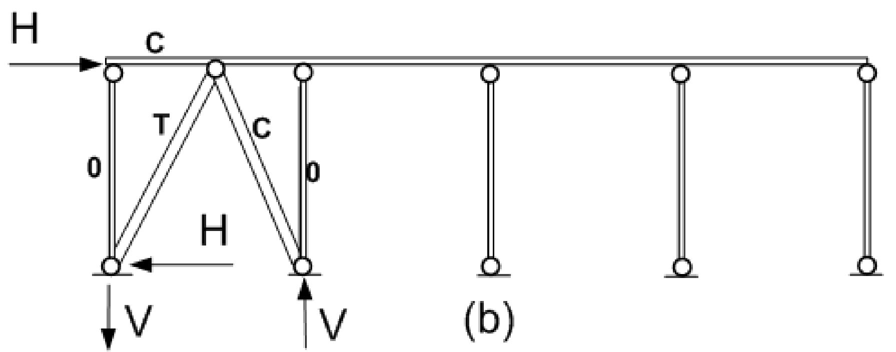
$$k_{br} = \frac{E_s A_{br} \cos^3 \alpha}{a}$$

- System (b) is in general more efficient than system (a), due to $\alpha_b < \alpha_a$
- System (b) is however more expensive than system (a)

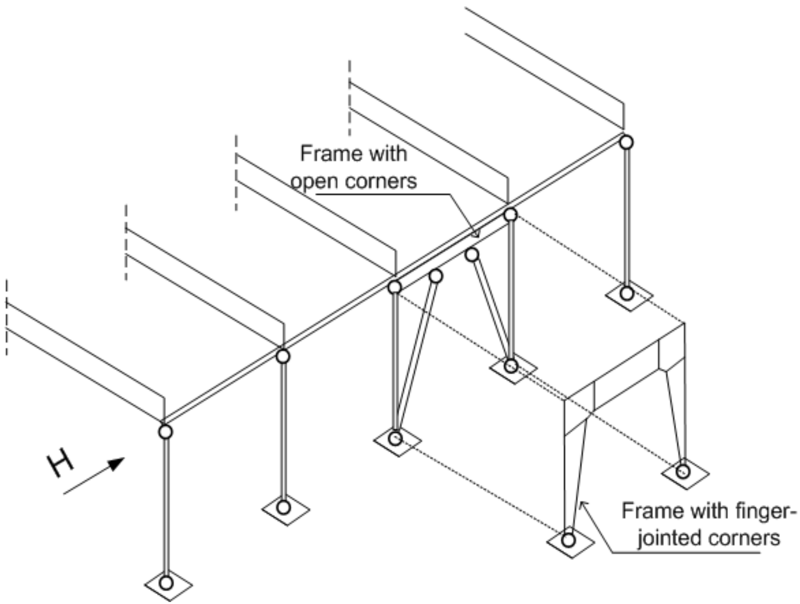
⇨ $40° < \alpha < 50°$ is a good compromise between economy and efficiency

Bracing by means of timber members

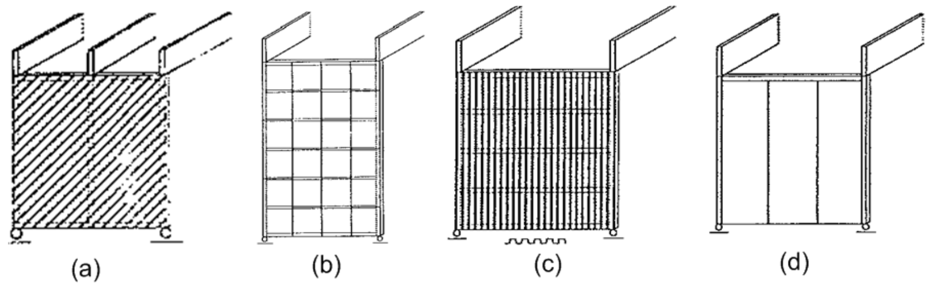




Bracing by means of frames



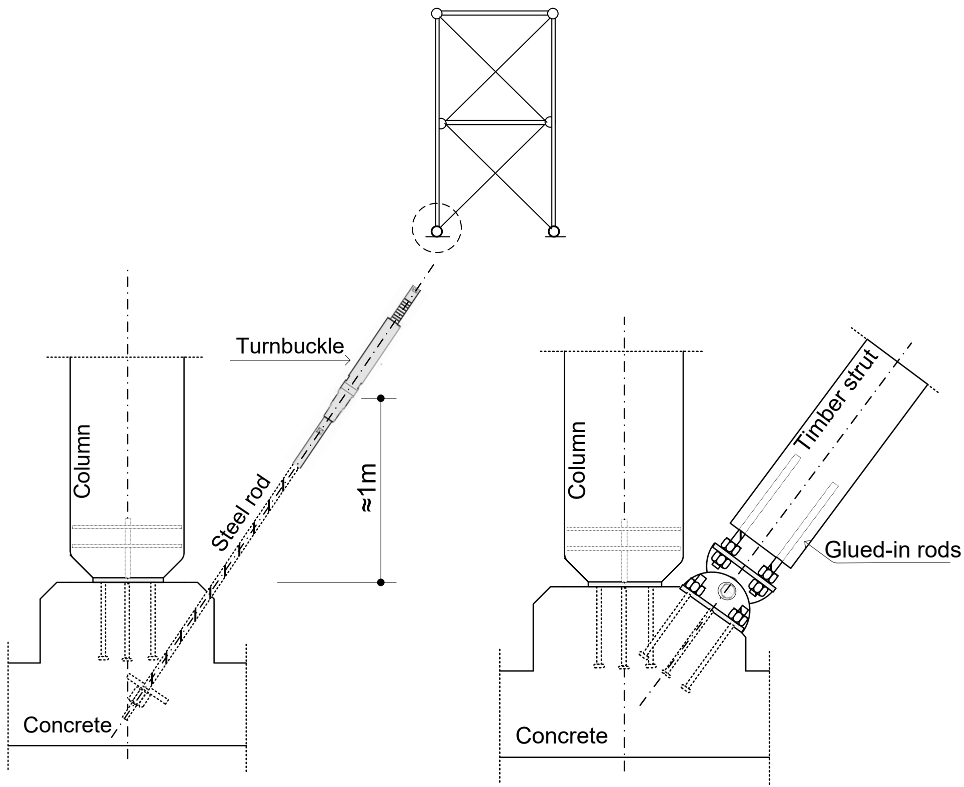
Bracing by means of shear walls



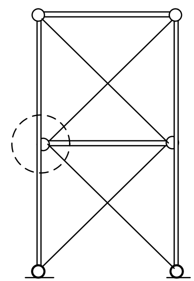
(a) Diagonal planks
(b) wood-based panels
(c) metal sheeting and
(d) concrete panels

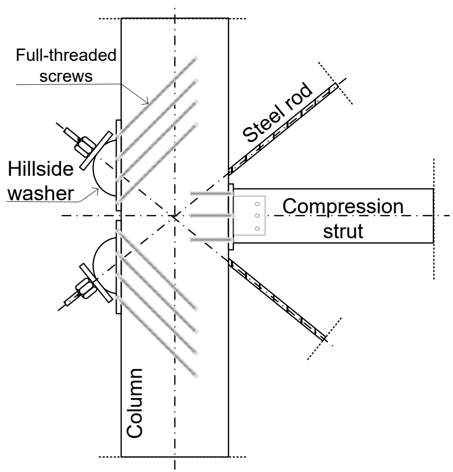
Examples of details for wall bracing

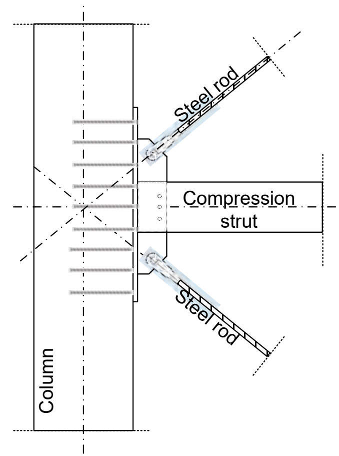
Connections of bracing diagonals to the concrete foundation



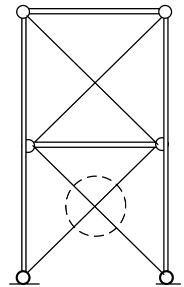
Connections of steel diagonals to a timber column

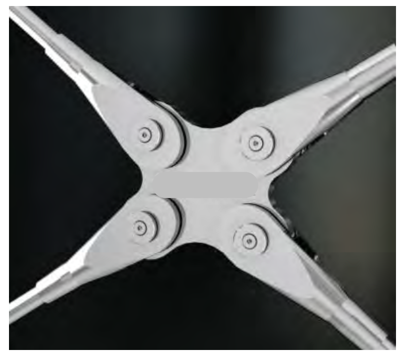






Connection at the intersection between steel rods



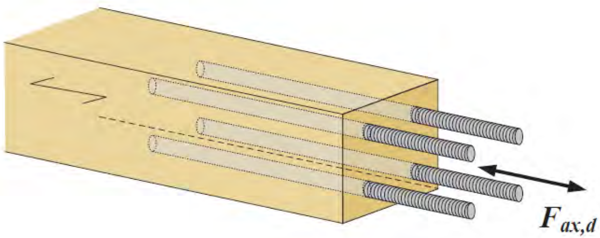


Diagonal bracing made of timber

Images: Valentin Jeck & Oliver Christen Architekten GmbH

Diagonal bracing made of timber

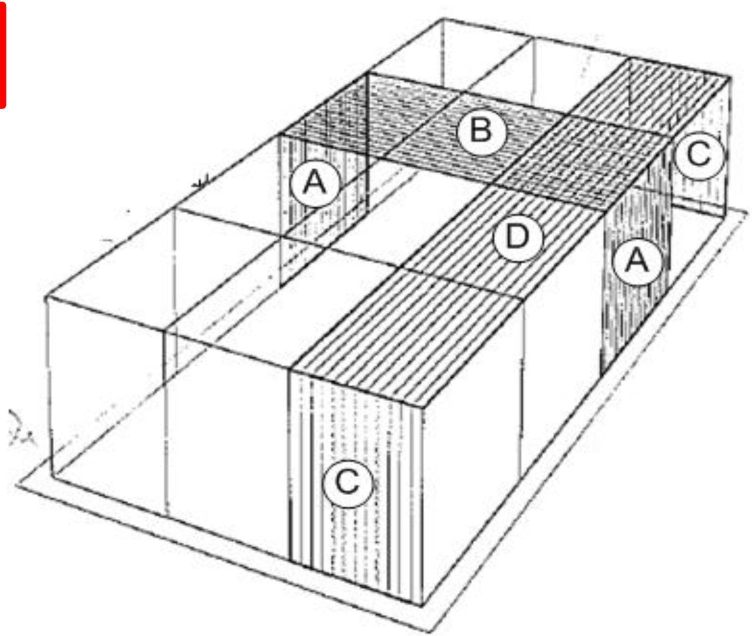
- Bracing by timber members with connections made of glued-in steel rods



Bracing elements

- Wall bracing (C) & (A)

- Roof bracing (D) & (B)



Roof bracing - bracing of trusses

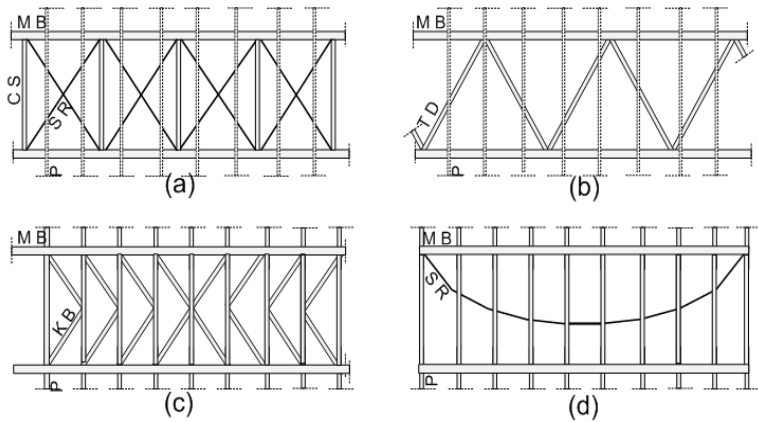
- Temporary Bracing
  is required during erection to enable the truss assembly to:
  - withstand the gravity forces of its own weight
  - resist wind loads during construction
  - support temporary construction dead loads such as the weight of sheathing and roofing materials
  - keep the trusses plumb
  - assure correct truss spacing

- Permanent Bracing
  is required to ensure that the trusses are integrated into the overall building structure to:
  - prevent buckling of web members loaded in compression
  - share loads between adjacent trusses
  - transfer lateral forces to diaphragms
  - restrains overall lateral displacements

Roof bracing

- Bracing by means of
  - Horizontal trusses in the roof
  - Diaphragm action of the roof by means of wood based panels or corrugated metal sheeting

Example of “horizontal trusses”



M B: Main Beam

P: Purlin

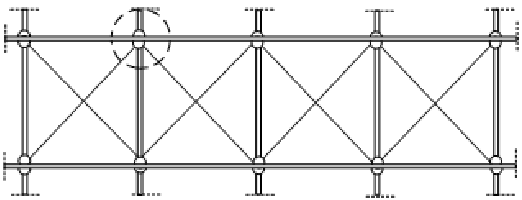
S R: Steel Rod

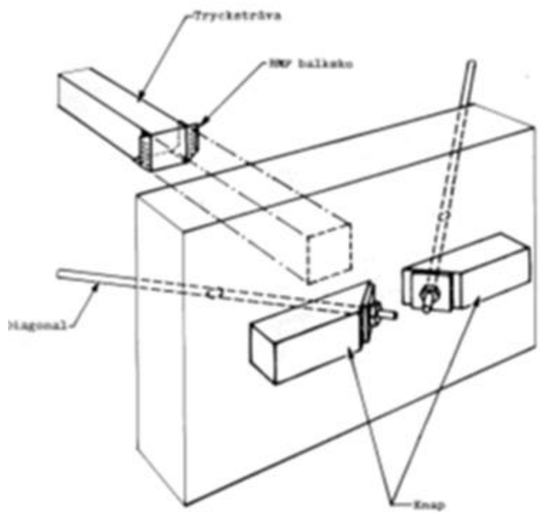
T D: Timber Diagonal

C S: Compression strut (timber)

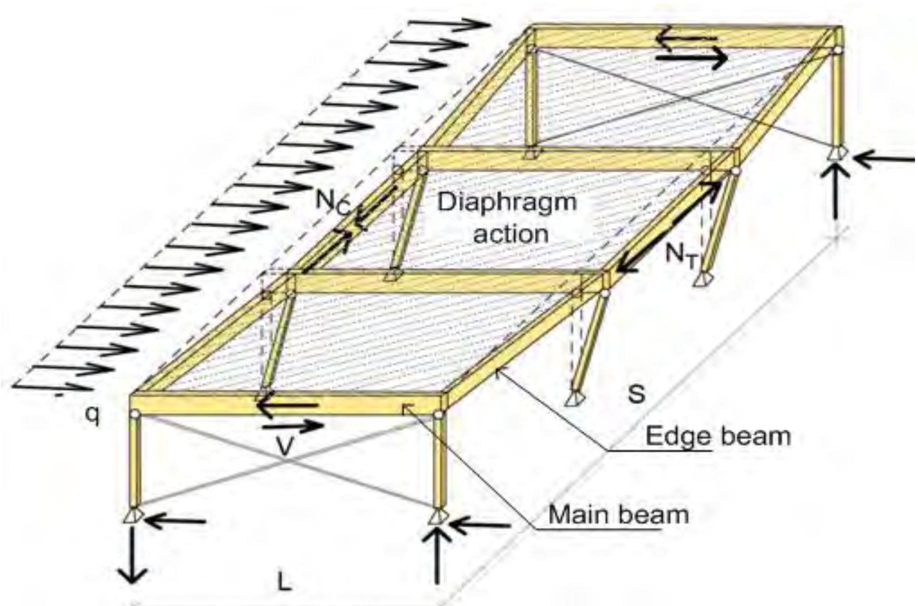
K B: K-Bracing element (timber).

Connections of bracing members to the main beam





Bracing by means of roof diaphragm action

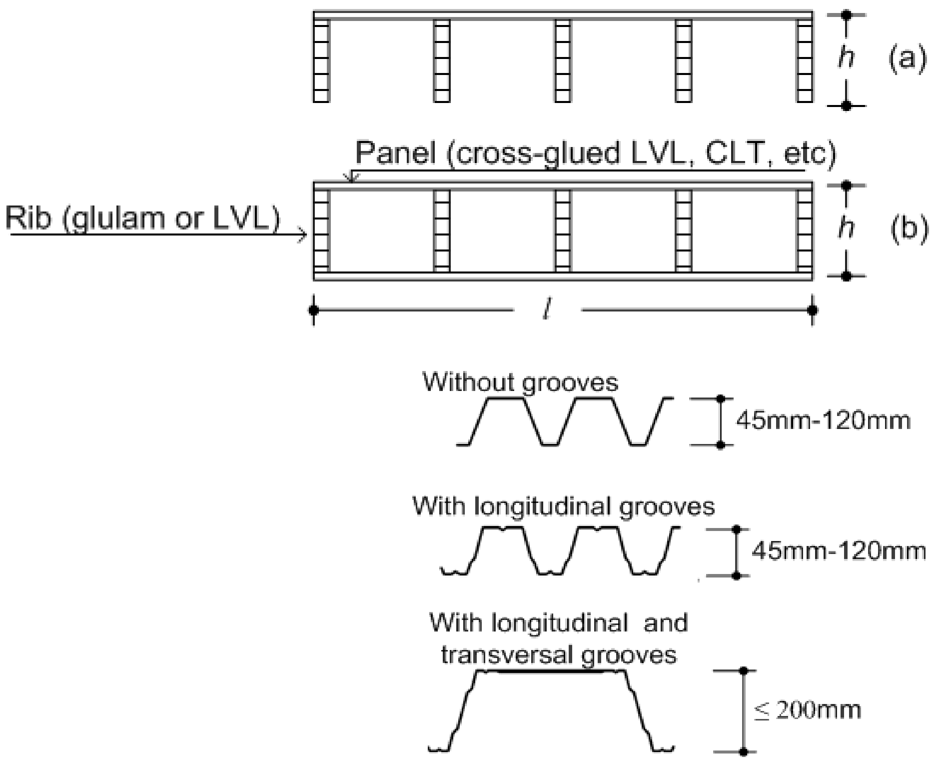


$$N_C = N_T = \frac{q \cdot s^2}{8 \cdot L}$$

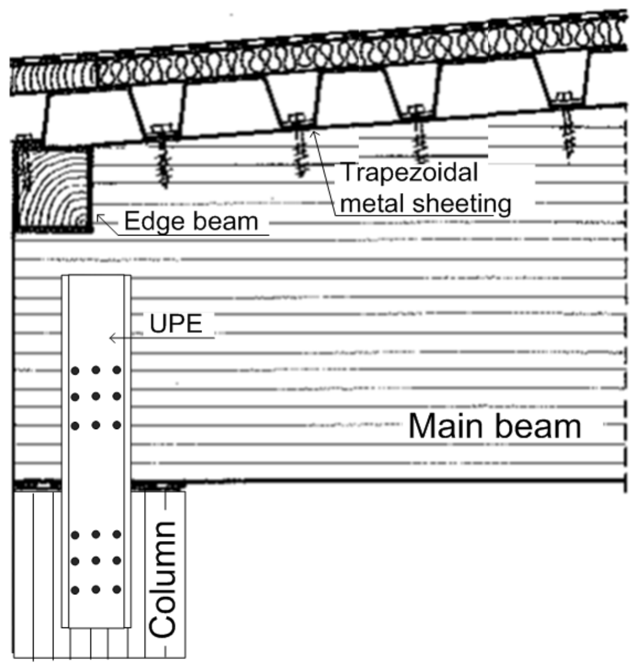
$$V = \frac{q \cdot s}{2}$$

$$v = \frac{V}{L}$$

Wood based and metal roof systems

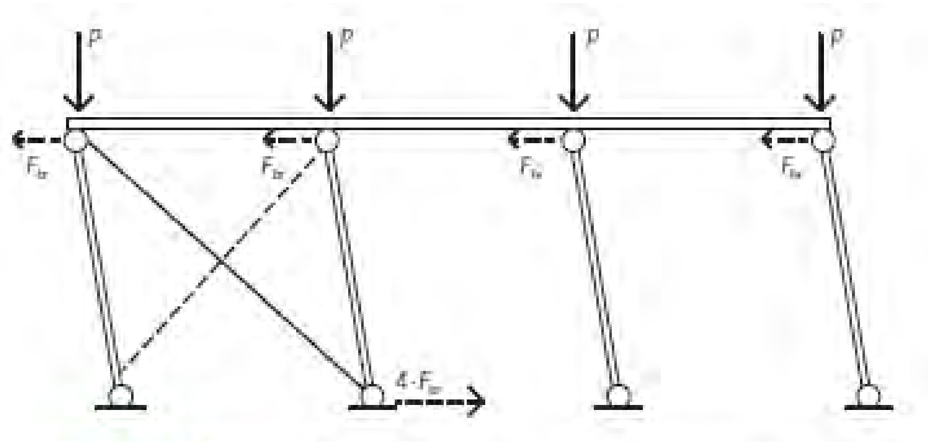


Connection of corrugated metal sheeting to the main beam



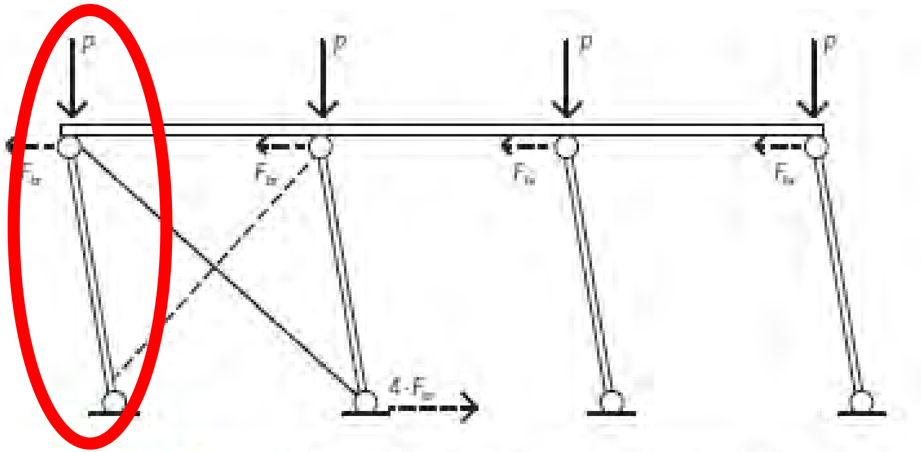
Strength and stiffness requirements for bracing systems

Stiffness of the bracing system

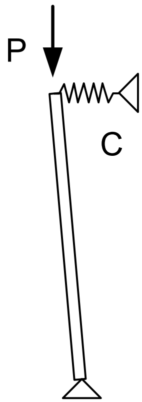


Figur 13.36 Stagningskraften som förorsakas av att pelarna inte är lodräta.

Stiffness of the bracing system

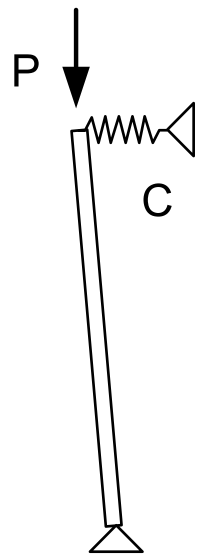


Figur 13.36 Stagningskraften som förorsakas av att pelarna inte är lodräta.



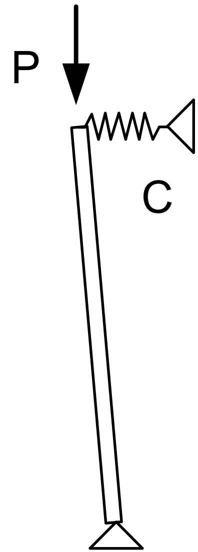
Stiffness of the bracing system

- What is the minimum stiffness “C” to prevent lateral Sway of the system?



Stiffness of the bracing system

- What is the minimum stiffness “C” to prevent lateral Sway of the system?



Shown on the board!

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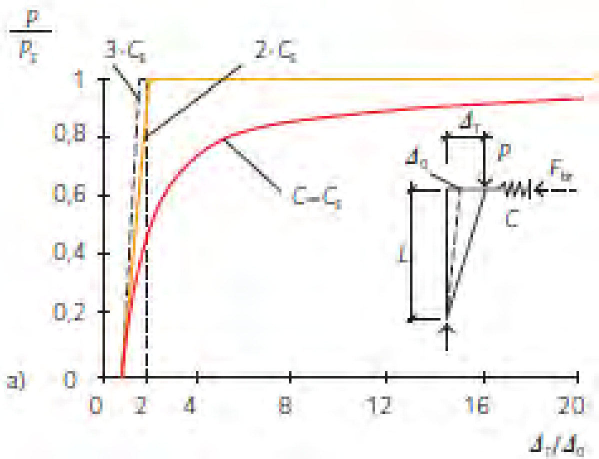
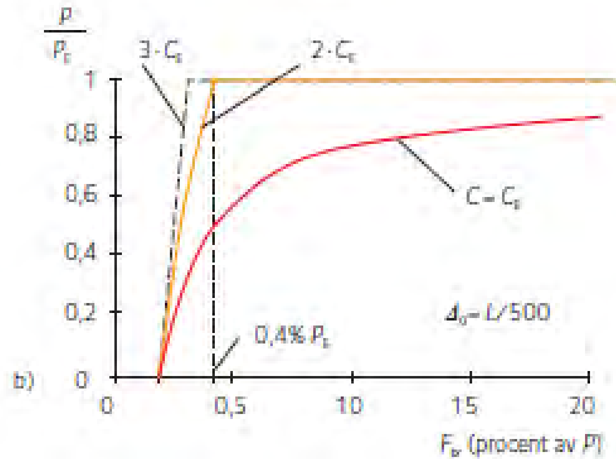
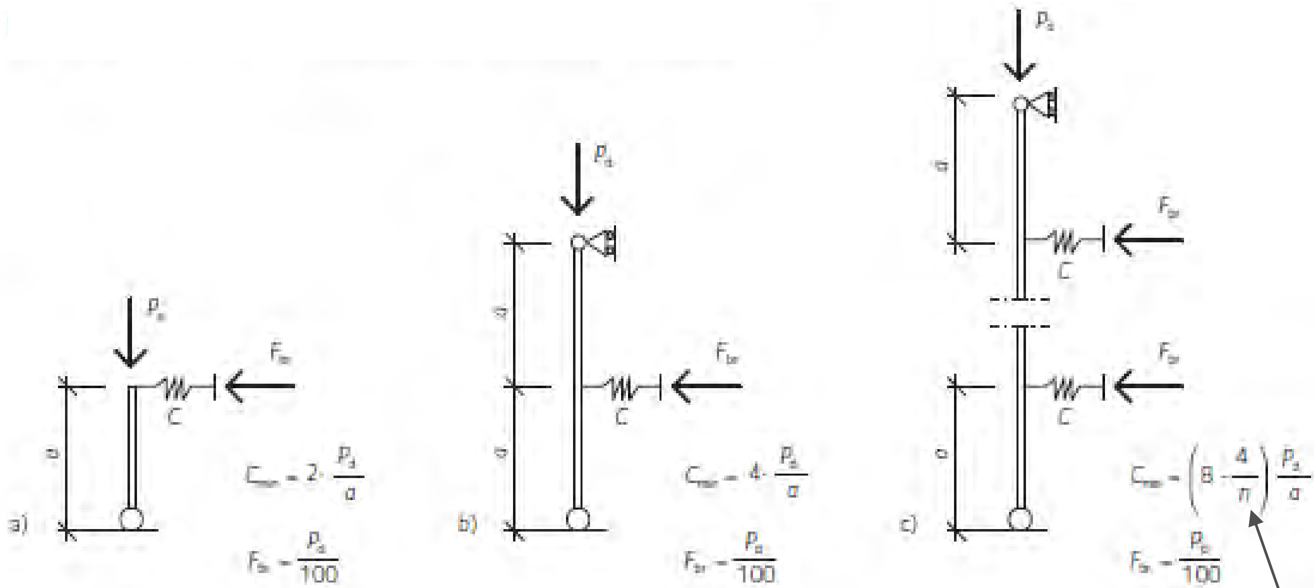
Brace stiffness and brace force



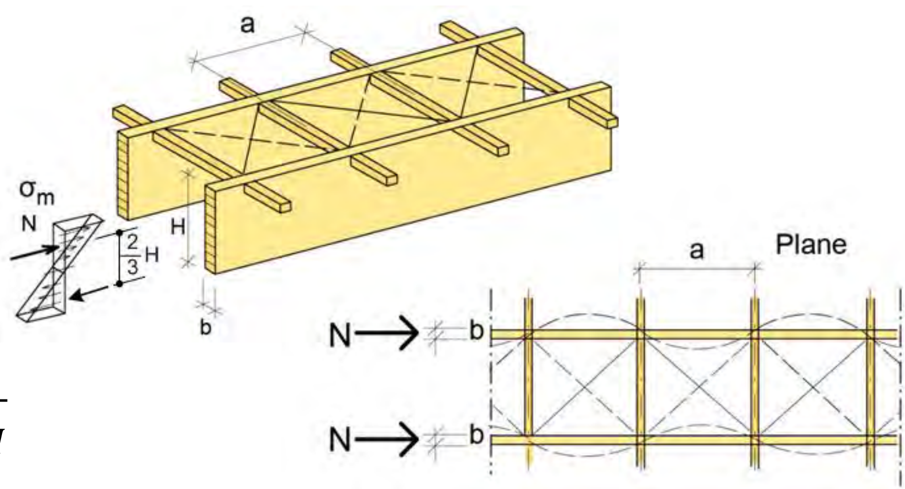


Brace stiffness and brace force



n is the number of brace points

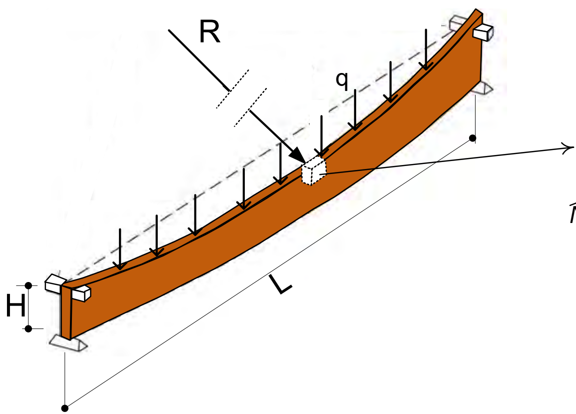
Beam bracing

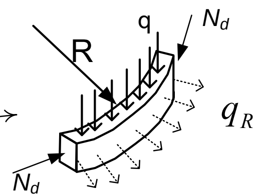


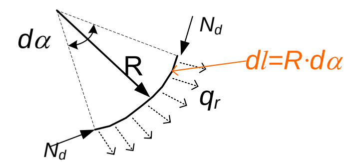
$$N_d \approx \frac{M_d}{\frac{2}{3} \cdot H}$$

Beam bracing

- Model for lateral forces in beams



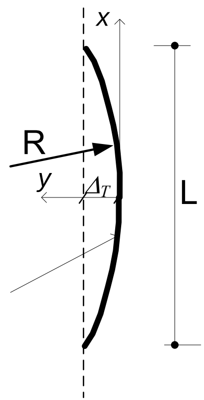




$$N_d \cdot d\alpha = q_r \cdot R \cdot d\alpha \Rightarrow q_r = \frac{N_d}{R}$$

Beam bracing

- Assumed final out-of-plane deflection of the beam: parabolic shape



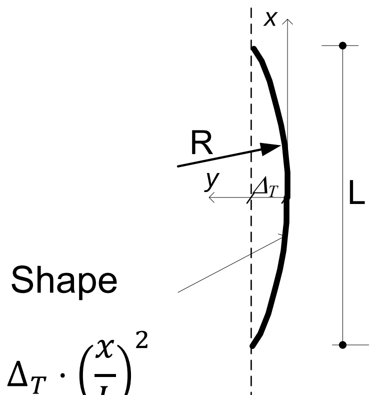
Shape

$$y = 4 \cdot \Delta_T \cdot \left(\frac{x}{L}\right)^2$$

How can we obtain R?

Beam bracing

- Assumed initial deformation: parabolic shape



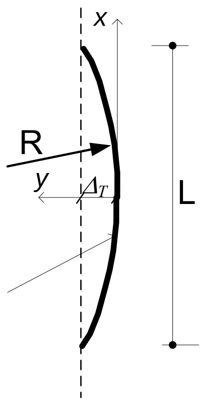
$$y = 4 \cdot \Delta_T \cdot \left(\frac{x}{L}\right)^2$$

How can we obtain R?

$$\frac{1}{R} = \frac{d^2y}{dx^2}$$

Beam bracing

- Assumed initial deformation: parabolic shape



Shape

$$y = 4 \cdot \Delta_T \cdot \left(\frac{x}{L}\right)^2$$

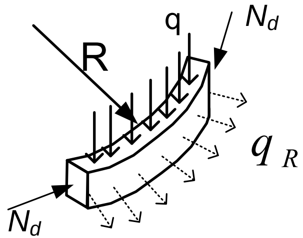
How can we obtain R?

$$\frac{1}{R} = \frac{d^2y}{dx^2}$$

$$\frac{1}{R} = \frac{d^2y}{dx^2} = \frac{d^2}{dx^2}\left(4 \cdot \Delta_T \cdot \left(\frac{x}{L}\right)^2\right) = \frac{8 \cdot \Delta_T}{L^2}$$

Beam bracing

- Lateral forces



$$q_r = \frac{N_d}{R} \quad \& \quad \frac{1}{R} = \frac{8 \cdot \Delta_T}{L^2}$$

$$\Downarrow$$

$$q_r = \frac{8 \cdot N \cdot \Delta_T}{L^2}$$

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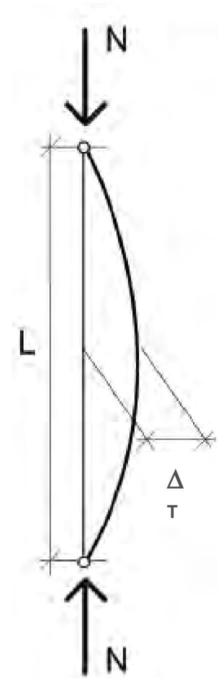
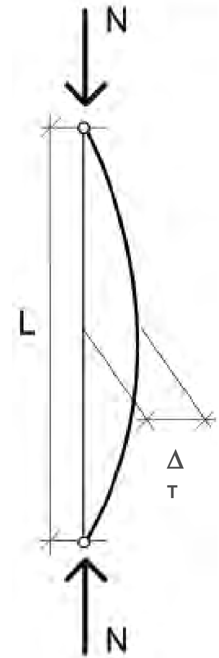
Beam bracing

- A simpler model:
  - Find an equivalent simply supported beam subjected to uniformly distributed load



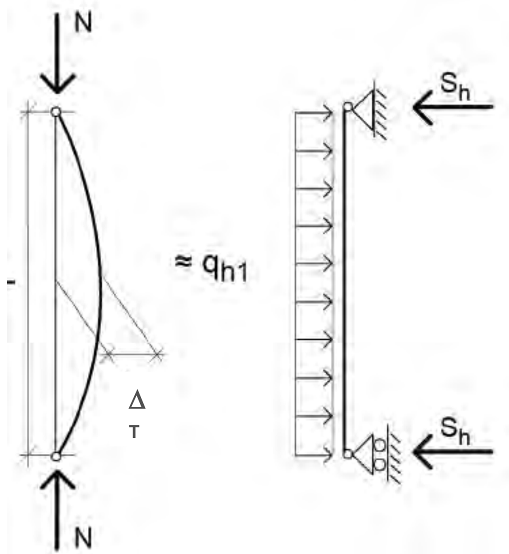
Beam bracing

- A simpler model:
  - Find an equivalent simply supported beam subjected to uniformly distributed load
  - The bending moment at mid-span for the two equivalent systems shall be the same



Beam bracing

- A simpler model:



$$N \cdot \Delta_T = q_{h1} \cdot \frac{L^2}{8} \quad \Rightarrow \quad q_{h1} = \frac{8 \cdot N \cdot \Delta_T}{L^2}$$

Same equation as before

Estimation of lateral loads for glulam structures

- Initial out-of-straightness: $\Delta_0 = L/500$

Estimation of lateral loads for glulam structures

- Initial out-of-straightness: $\Delta_0 = L/500$
- Additional deformation Δ (e.g. due to wind load) shall not exceed $L/500$

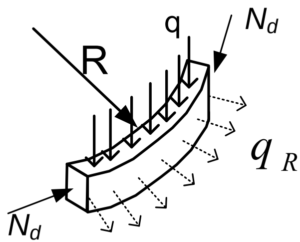
Estimation of lateral loads for glulam structures

- Initial out-of-straightness: $\Delta_0 = L/500$
- Additional deformation Δ (e.g. due to wind load) shall not exceed $L/500$
- This means that the final deformation shall be (maximum value)

$$\Delta_T = (\Delta_0 + \Delta) = \frac{L}{250}$$

Beam bracing

- Lateral forces



$$N_d = \frac{M_d}{\left(\frac{2}{3} \cdot H\right)}$$

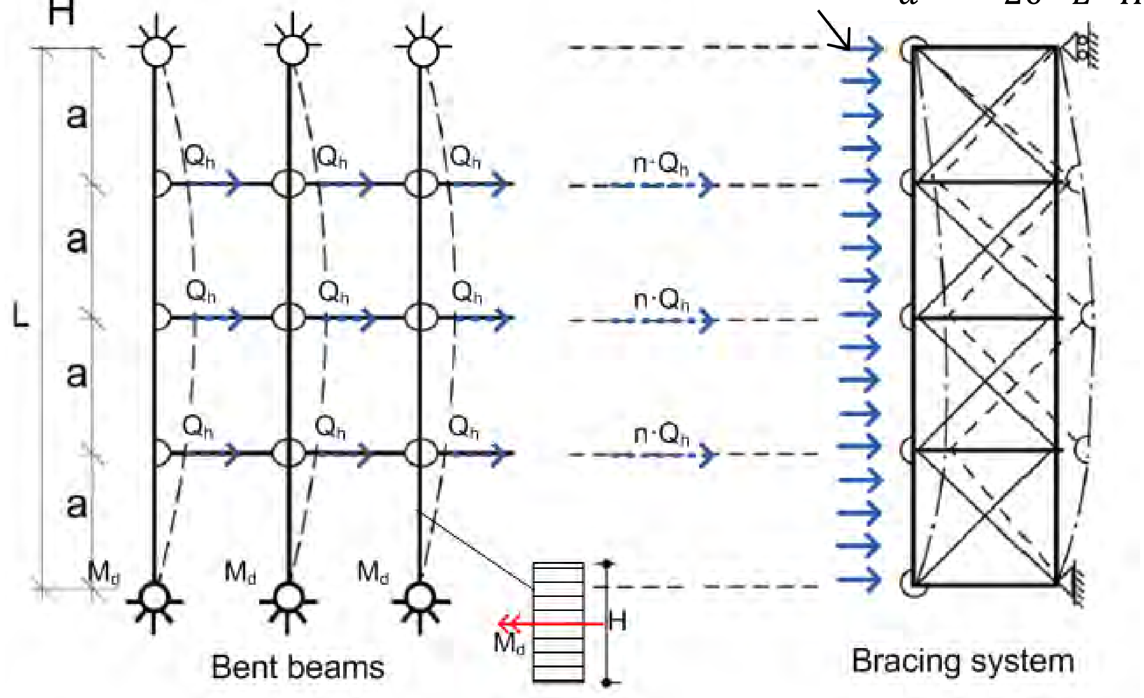
$$q_{h1} = \frac{8 \cdot N \cdot \Delta_T}{L^2}$$

$$\Delta_T = \frac{L}{250}$$

$$\Rightarrow \quad q_r \approx \frac{M_d}{20 \cdot L \cdot H}$$

Brace forces for a series of bent members

$$q_h = \frac{n \cdot Q_h}{a} \approx \frac{n \cdot M_d}{20 \cdot L \cdot H}$$

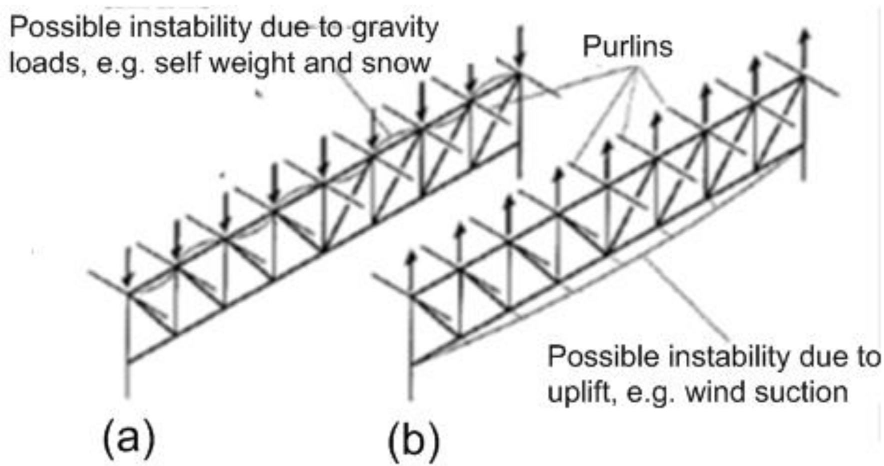


EC5 approach

$$q_h = n \cdot \frac{M_d}{k_{f,3} \cdot H \cdot L} \cdot (1 - k_{crit})$$

M_d	design moment in the beam
H	depth of beam
L	span of the beam
n	number of laterally braced beams
$k_{f,3}$	modification factor ($k_{f,3}$ = 30 - 80)
k_{crit}	reduction factor for lateral buckling when the beam is unbraced

Timber members subjected to compression at their unrestrained side



Timber members subjected to compression at their unrestrained side

- Rosvallahallen, collapsed winter 2009

Continuous beam

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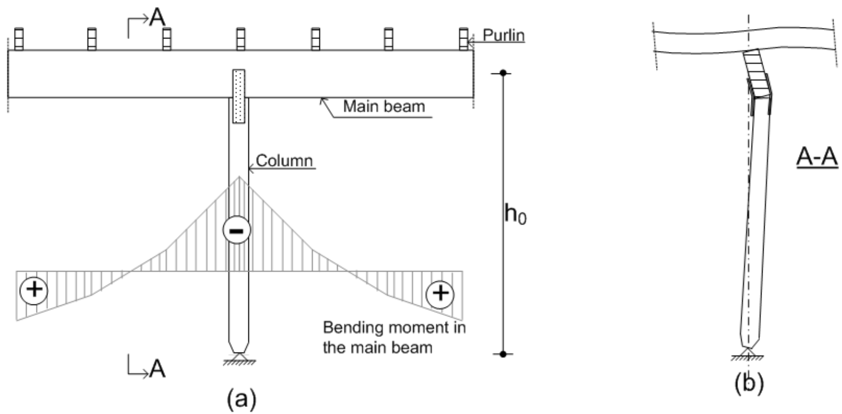
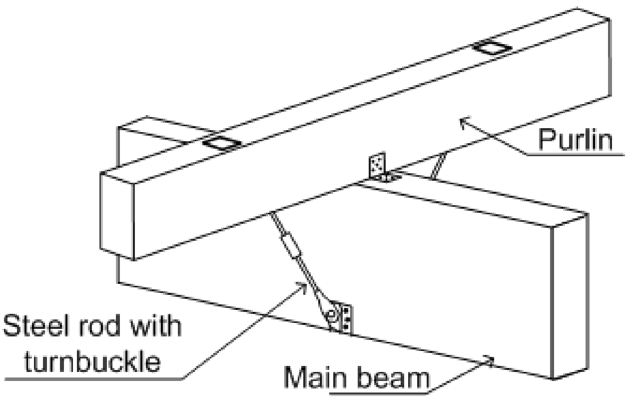
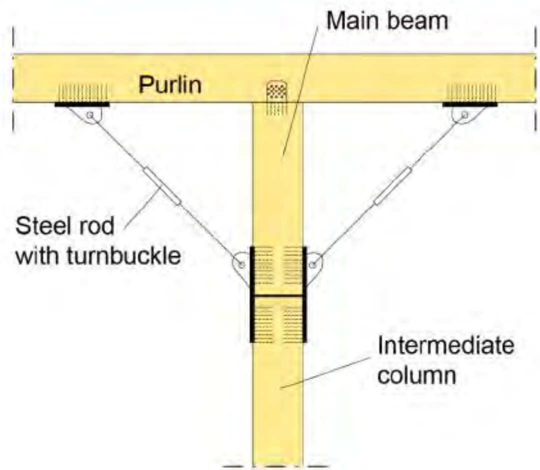
Timber members subjected to compression at their unrestrained side



Possible solutions



(a)



(b)

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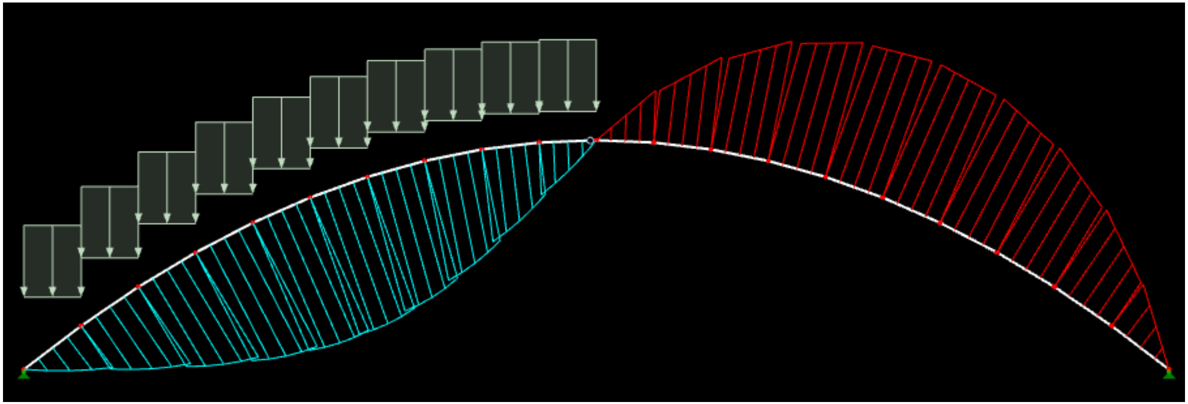
Arches

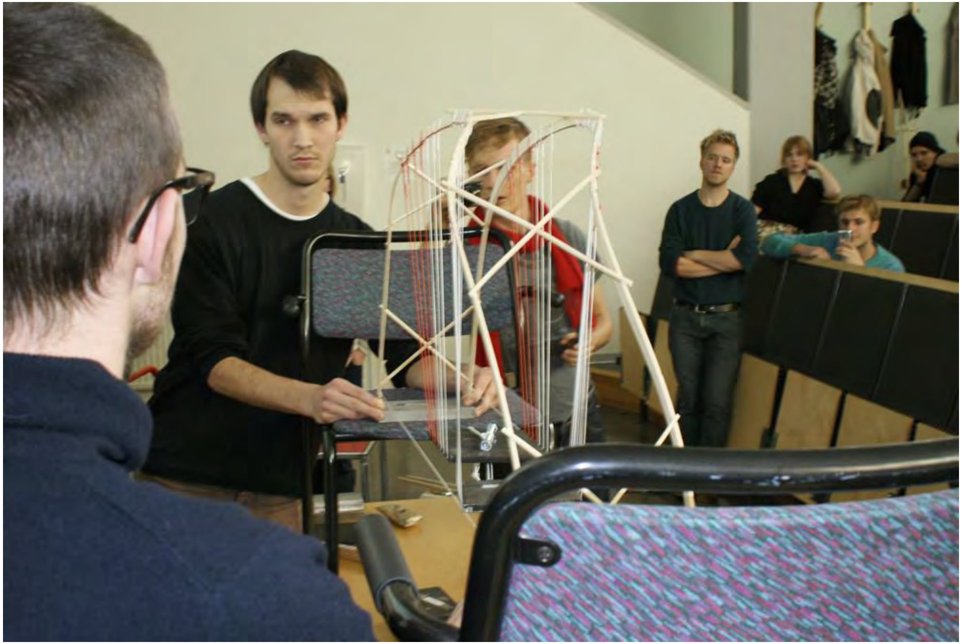
Arches loaded in bending



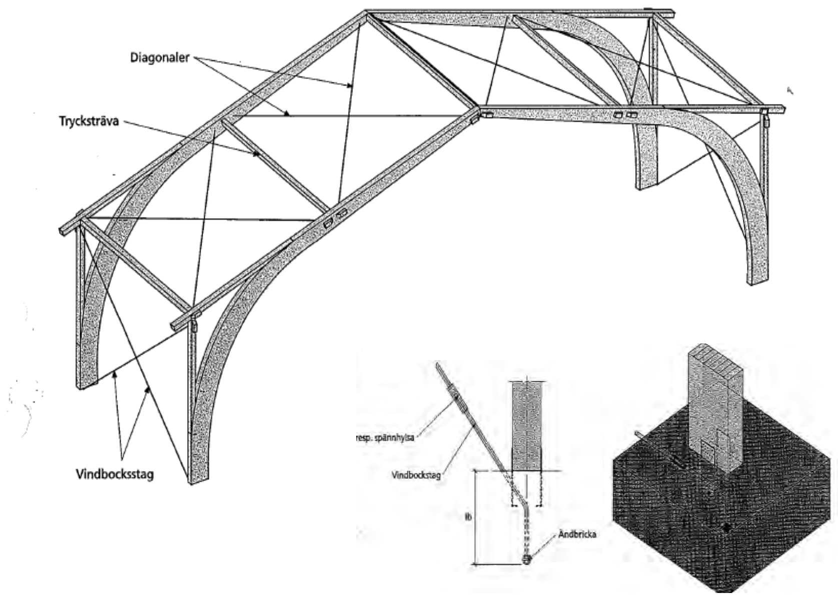
- Asymmetric load fall:
    - Negative bending moment gives pressure to the underside of the higher arch half

Arches

- Bracing of the bottom part of the arch



Bracing of three pin portals



Bracing

- Timber struts as bracing system

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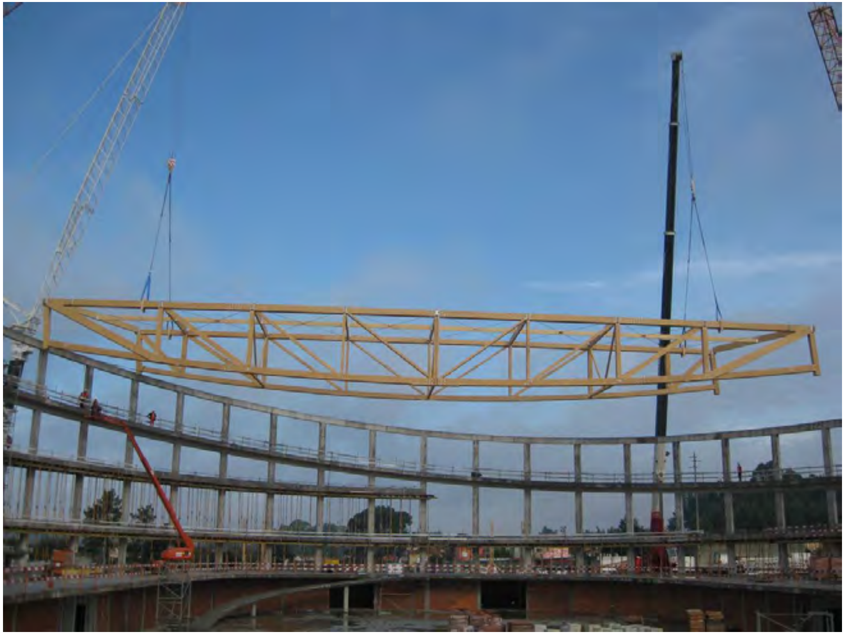
Bracing

- Erection: pair of fully braced trusses



Conclusion

- Temporary Bracing is required during erection to enable the assembly of the structure to:
  - withstand the gravity forces of its own weight
  - resist wind loads during construction
  - support temporary construction dead loads such as the weight of sheathing and roofing materials
  - keep the trusses plumb
  - assure correct truss spacing

- Permanent Bracing is required to ensure that the structure is integrated into the overall building to:
  - prevent buckling of members loaded in compression
  - share loads between adjacent trusses
  - transfer lateral forces to diaphragms
  - restrains overall lateral displacements

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