Additional literature:
Glulam handbook
http://www.svensktlimtra.se/en/limHTML/

Structural systems

Lecture 7: 2020-02-05 **[DoTS: (3.2.4) 3.4 and 3.5]**

Content

Timber building system
Glulam: background and history
Beam and columns
Various beam types & application
Three-pin trusses (with rods)
Arches
Portals
Cantilevers
Glulam system
Orthogonal grid

Some parts are based on lectures by Prof. Roberto Crocetti, KTH

Timber building systems

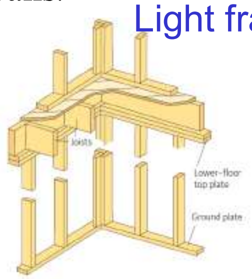
- Timber-framed and panel systems
- Modular systems
- Post and beam system

Timber-framed and panel systems:

are based on planar building elements, for example walls or floors. These systems utilize either light frames or solid wood elements as their basic technology.

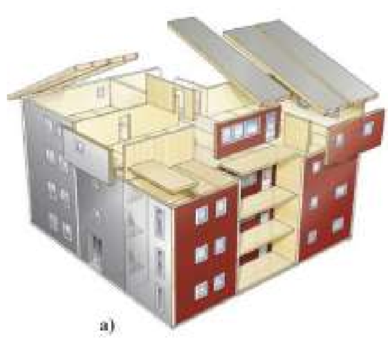
The panels can be full size or partitioned in widths of 1 200 mm for ease of transportation. Floor elements are not suitable for long-span structures, the limitation in span length is about 8 – 10 m. Roof elements however, can have longer spans.

Light frame system

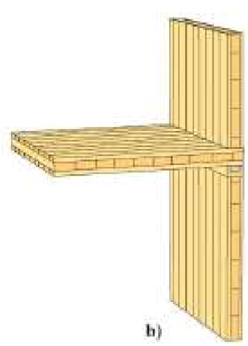


Panel systems

Solid wood system (CLT)



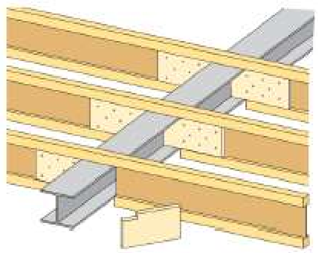
a)

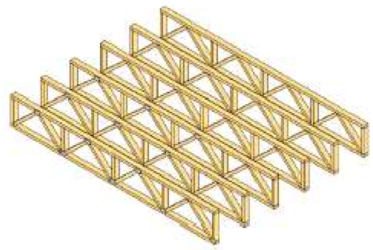


b)

Panel systems

Engineered wood products


I-joists


Floor truss elements

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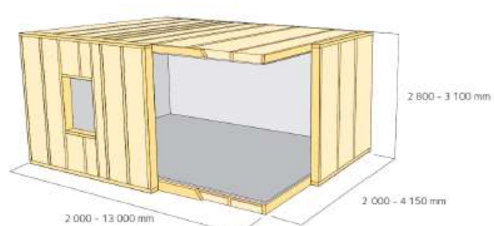
Modular systems (volumetric modules):

utilize the light frame system mainly, but examples exist where solid wood elements apply. The main principle is that the entire volumetric box consisting of walls, floor and ceiling, as well as inner claddings and all services are assembled in a factory and delivered to the building site for erection. Modular systems are not suitable for long-span structures, limitations on span is about 4 m due to transportation limitations.

Light frame modular system



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Modular systems (volumetric modules):

CLT modular system

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Post and beam systems:

sometimes named big frame structures and are very common for industrial and commercial buildings. The post and beam system is a system based on a structural grid of beams and columns, typically with pinned connections. The structure is instead stabilized through diagonal bracing or shear walls.

Post and beam systems are most suitable for long-span structures and are used for arenas.

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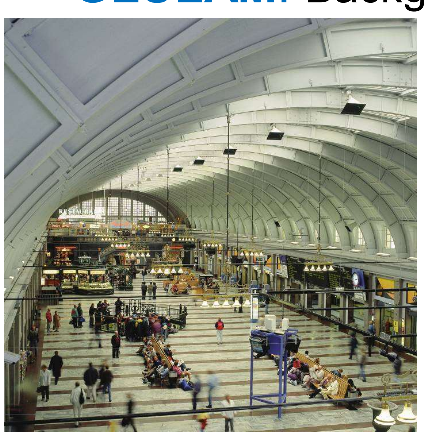
Post and beam systems:

Short span structures

Long span structures

GLULAM: Background and history



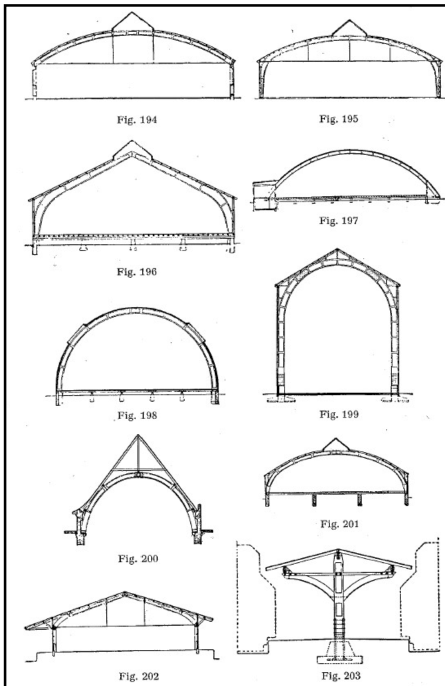
Railway station in Stockholm,1925

Railway station in Malmö, 1923

Typical platform roof

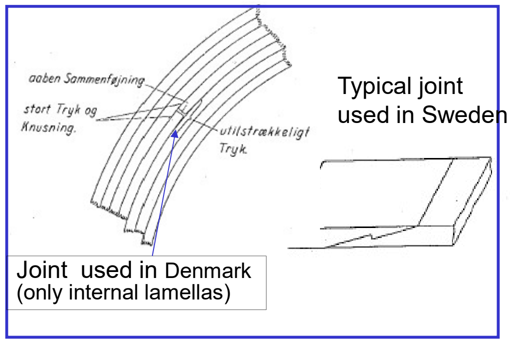
Water vapor – metal corrosion
Glulam marked for rail track

The company started manufacturing glulam back in 1919 in Töreboda, a small village that lies approx. 180 km north-est of Göteborg by the Göta Canal. *A/B Fribärande Träkonstruktioner, Töreboda*, was the first glulam factory in Scandinavia. (Glulam patent, by Hetzer 1906. Germany)



Typical glulam structures from the first half of the 20th century.

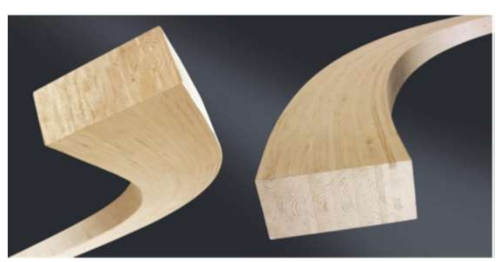
Note that these structures are mainly subjected to compression, due to the fact that the joint between the lamellas were not suitable to resist tensile stresses (finger joint technique was not known at that time)



Common glulam shapes

Straight beams:
Finger-jointed lamellas,
thickness 45 mm

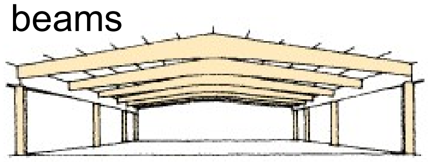
Curved beams:
Finger-jointed lamellas,
thickness 10-33 mm

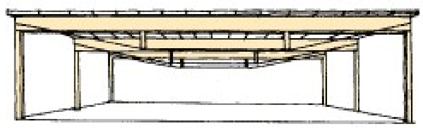


Beam and column system

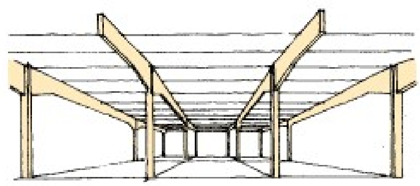
Pitched or tapered beams

Simply-supported beams





Cantilever beams



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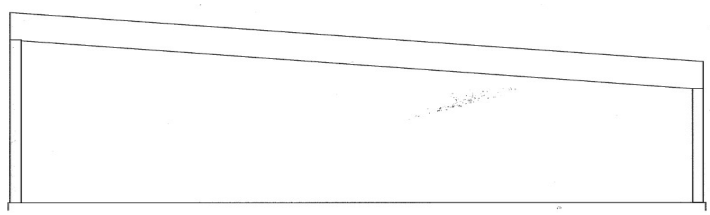
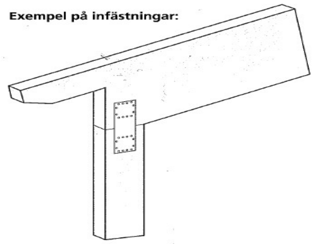
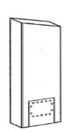
Straight beam, L_{max} = 30 m



Exempel på infästningar:



Exempel på skärning av takfotstass och infästning med spikningsplåt och ankarspik.



Pelarinfästning med ingjutna spikningsplåtar och ankarspik.

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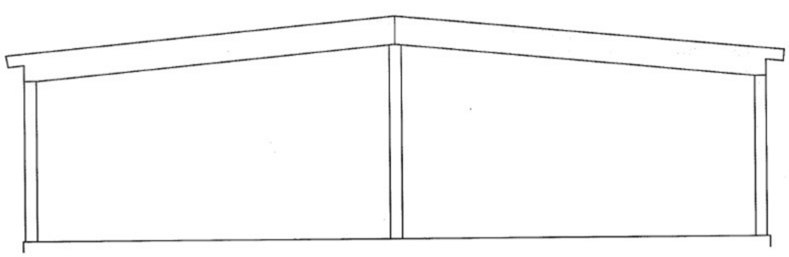
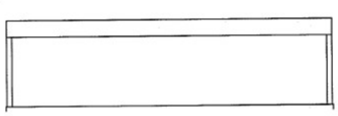
Storage building - Haparanda

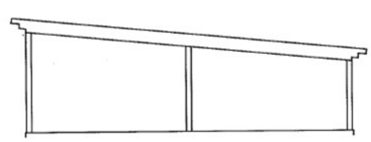
Some examples of straight beam applications



Exempel på sadeltak uppbyggt av raka balkar på pelare.

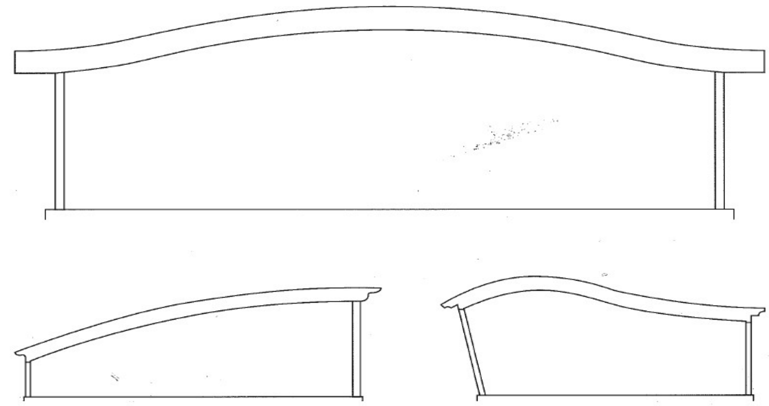


Exempel på horisontellt monterad bärlina.

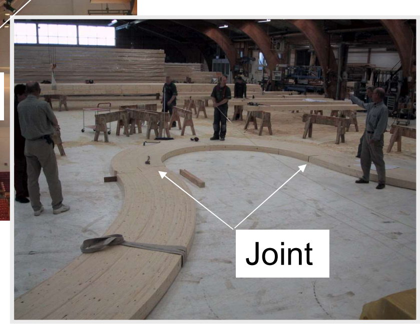


Flerstödsuppläggning ger mindre spännvidder och därmed slanka dimensioner.

Curved beam: the maximum span depends on the radius of curvature



Dunkers house - Helsingborg

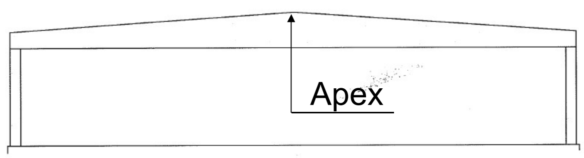


Radius: 1,5 m

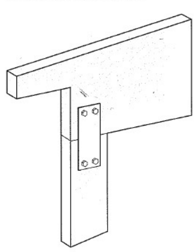
Thickness of lamellas = 10 mm!

“ Building for wedding ceremonies” - Israel

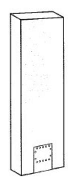
Tapered beams L_{max} = 30 m, roof slope <15°



Exempel på infästningar:



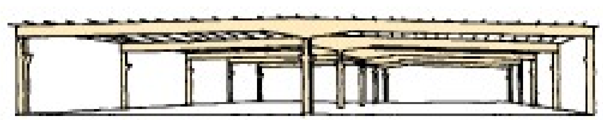
Exempel på skärning av takfotstass och infästning med plattstål och genomgående bult.

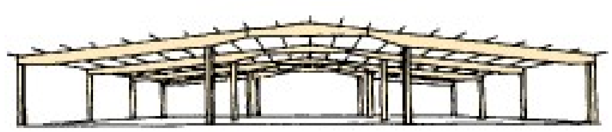


Pelarinfästning med ingjuten spikningsplåt och ankarspik.

Tapered beams

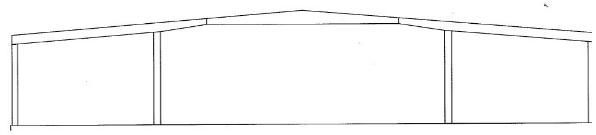
Continuous beams



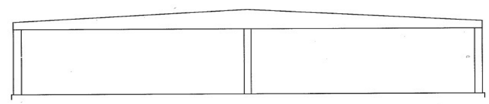


The degree of utilisation can be further increased by increasing the depth of the beam at the inner supports

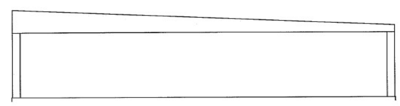
Some examples of tapered beam applications



Kombination av raka balkar och sadelbalk som tillsammans ger mycket gynnsam totalkostnad för stommen. Lämplig konstruktion för industrihallar, virkesmagasin och liknande. Husbredd upp till 75 m.



När sadelbalken läggs upp på tre stöd blir den extremt materialbesparande och kostnadseffektiv. För husbredder upp till 30 m.



Pulpetbalken är en variant för tak med lutning i endast en riktning. Denna konstruktion är inte lika materialeffektiv som sadelbalk med motsvarande spännvidd.

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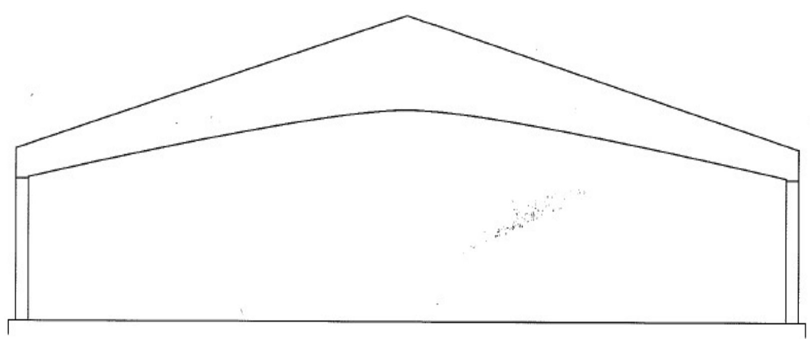
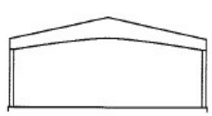
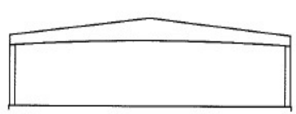
Pitched cambered beams, $L_{max} \approx 20m$, roof slope $<15^o$







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Pitched cambered beams

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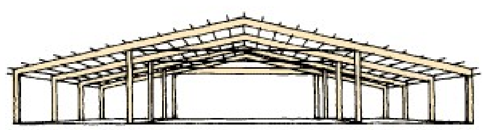
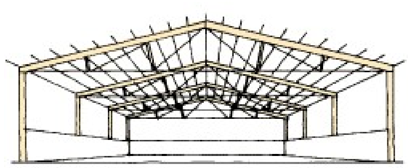
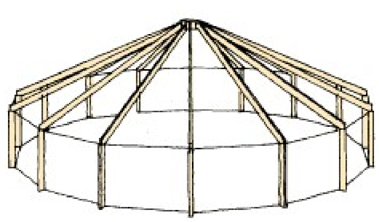
Three-pin trusses







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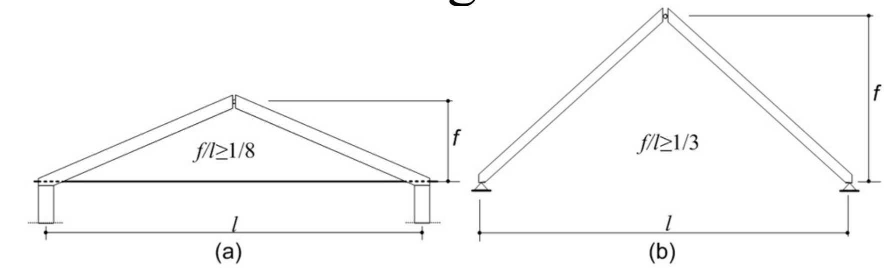
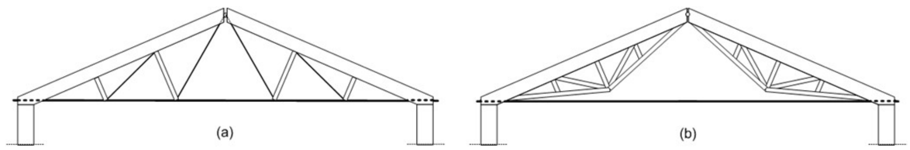
Three-hinged trusses



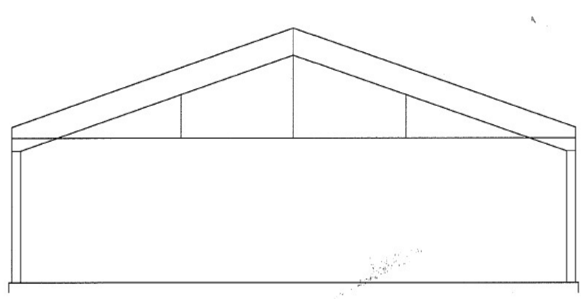
(a) on columns **(b) on ground supports**



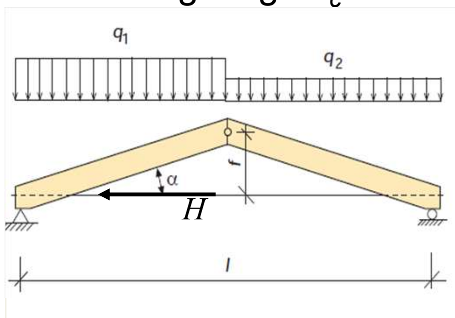
a) with timber struts and steel ties
b) with underlying timber truss **(trussed rafter)**

Three pin frame with tie rod,

L_{max}≈50 m, roof slope >14°



In buckling perpendicular to the plane of the roof, the buckling length l_c is:



$$l_c = \frac{l}{2 \cdot \cos\alpha}$$

Force in the tension tie:

$$H = \frac{(q_1 + q_2) \cdot l^2}{16 \cdot f}$$

Maximum moment *M* and corresponding normal force *N* in rafter:

$$M = \frac{q_1 \cdot l^2}{32} \qquad N = \frac{(q_1 + q_2) \cdot l}{8 \cdot \sin\alpha}$$

Maximum shear forces in the rafter V_1 and in the ridge V_2

$$V_1 = \frac{q_1 \cdot l}{4} \cdot \cos\alpha \qquad V_2 = \frac{(q_1 - q_2) \cdot l}{8}$$

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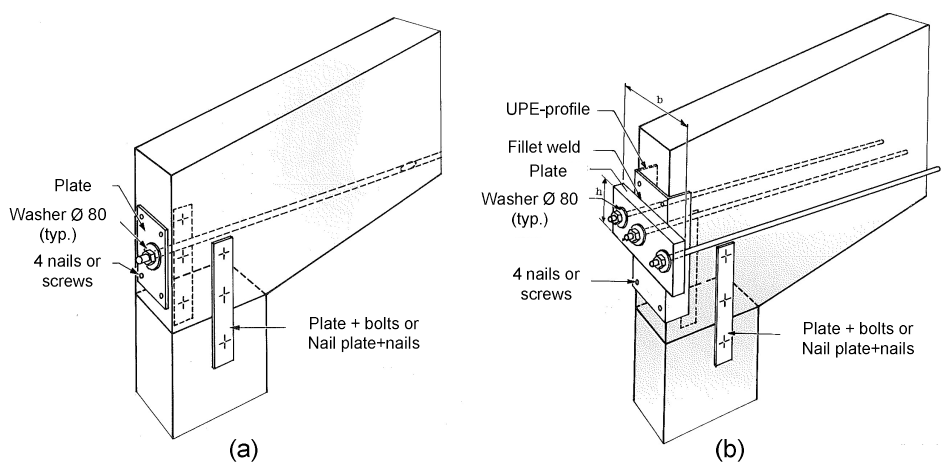
Some details



(a) Detail suitable for moderate tension forces
(b) Detail suitable for large tension forces

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Some details

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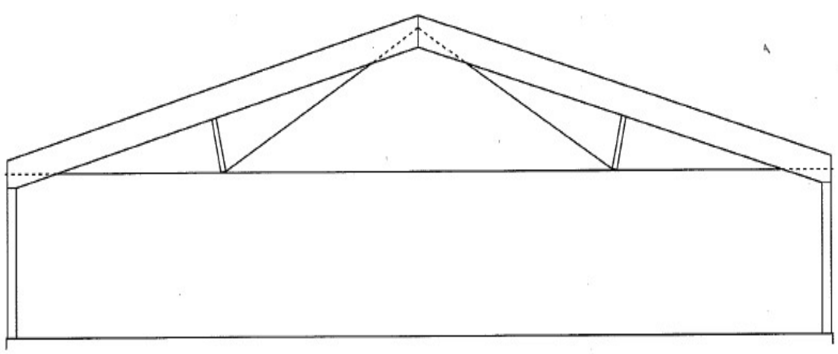
Truss with timber struts and steel ties, L_{max}≈60 m, roof slope >14°



Variant av dragbandstakstol där de båda mellanstöttorna ger minskade takbalksdimensioner. Kan användas för spännvidder upp mot 60 m.

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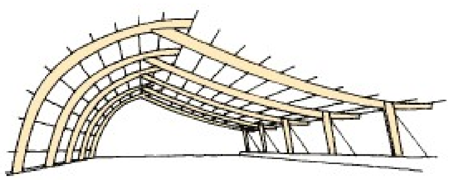
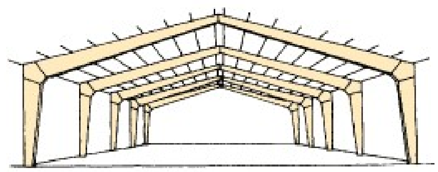
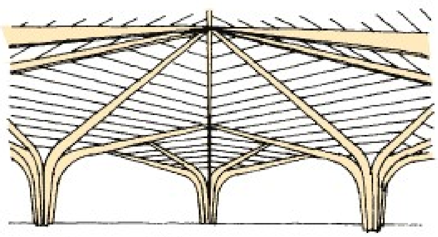
Portal frames



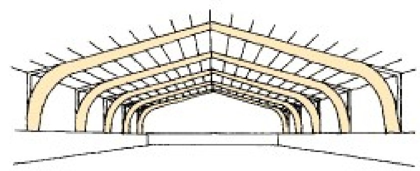
Combination of differently curved frames



Finger jointed haunches

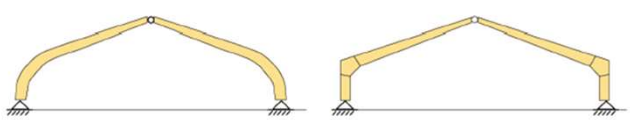


Three-dimensional frames



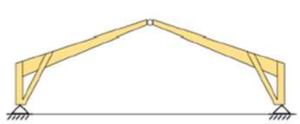
Curved haunches

Examples of three-hinged portal frames:
a) Frame with curved frames
b) Frame with finger-jointed haunches



(a) (b)

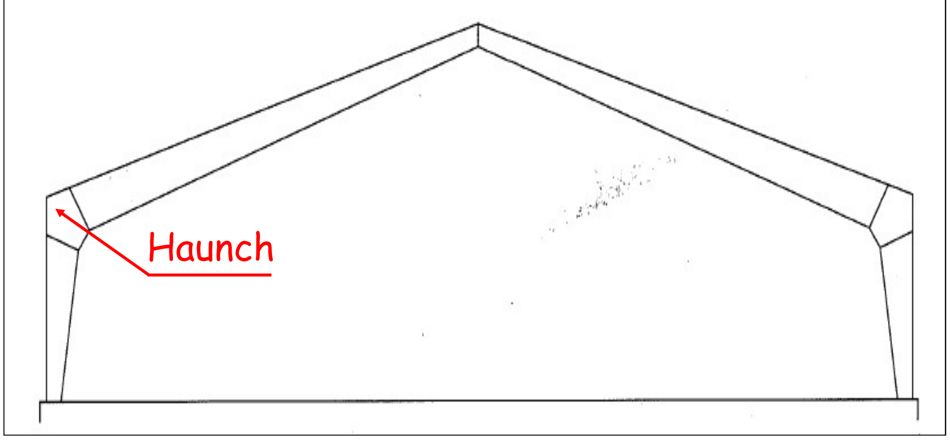
c) Built-up frame (knee-braced frame)



(c)

DoTS, Chapter 3.4, Fig. 3.39

Finger-jointed portal, $L_{max} \approx 25$ m, roof slope >14°



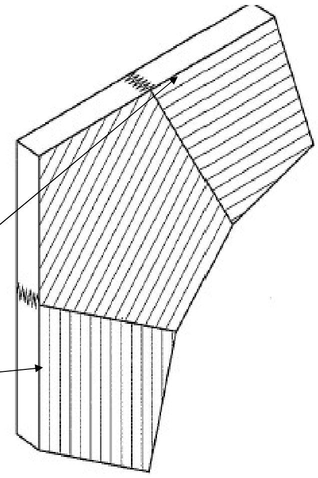
Finger-jointed portals

The design of finger-jointed portals is conducted in a very similar manner as in curved haunch portal

The main difference is the **design of the haunch**

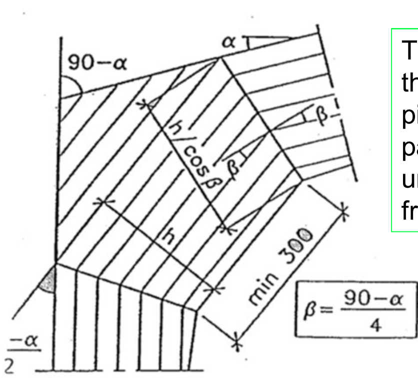
Finger-jointed haunch

This is the most common finger jointed haunch



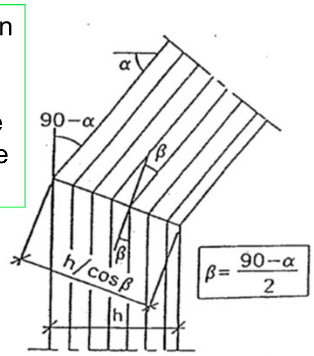
It is common that laminates are placed parallel to the upper side of the frame. This is favorable for negative bending moment (self-weight + snow)

Finger-jointed haunch



with jointing piece

The laminates in the jointing piece shall be parallel with the underside of the frame.



without jointing piece

Advantage of using a jointing piece

Finger-jointed haunches are usually designed with a jointing piece. The angle between the force and the grain at the joints is limited, which is favourable for the loading capacity of the haunch.

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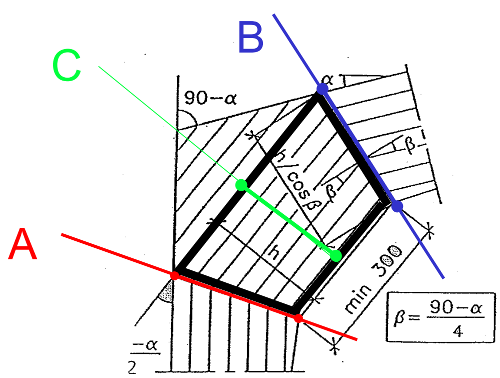
Design of the finger-jointed haunch



Sections A and B

Check the strength of the finger joint

Section C

Check the material with consideration of compression buckling and lateral torsional buckling

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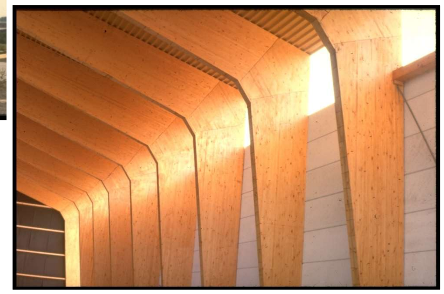

Finger jointed portals

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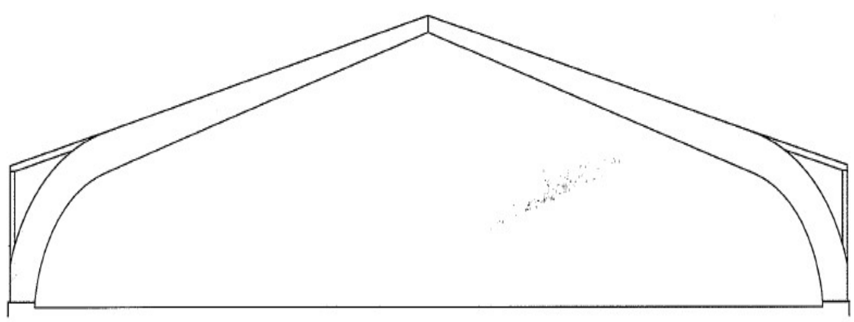
Three-pin portal with curved haunch, $L_{max} \approx 50$ m, roof slope >14°



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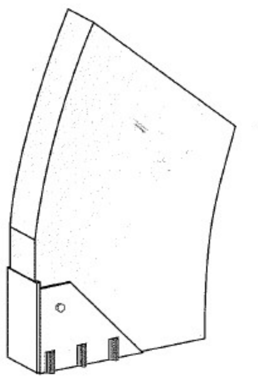
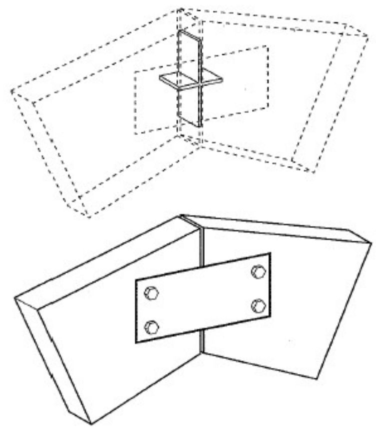
Some details

Exempel på infästnings- och anslutningsdetaljer:



Pelarfotsinfästning till grund med ingjutet specialbeslag och genomgående bult.

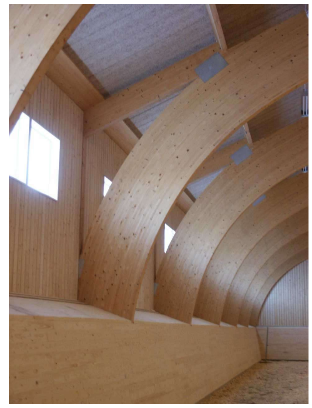
Hinged support



Nockförbindning med plattstål och genomgående bult.

Hinged connection at the apex

Riding hall, Töreboda

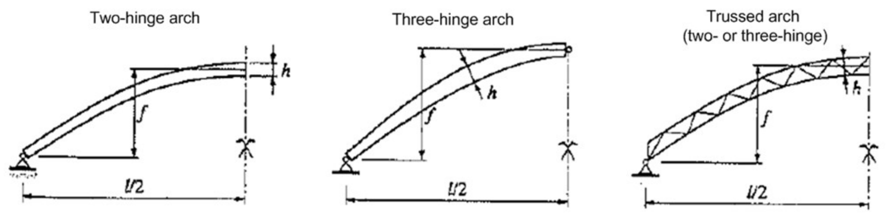



Riding hall, Töreboda

Church in Ireland

Arches - conceptual design

Some “rules of thumb” concerning depth-to-span ratios



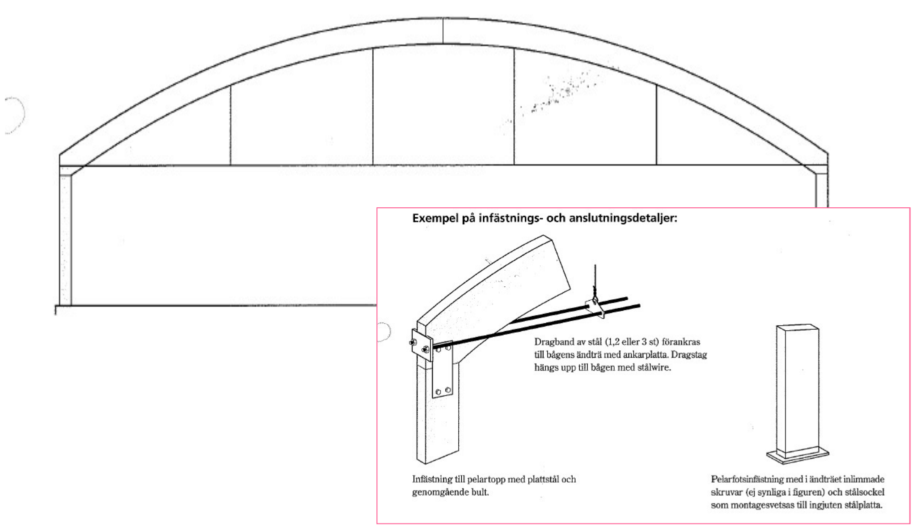
$l = 30\text{-}100$ m ; $h = l/50\text{-}l/30$; $f \geq l/10$
(a)

$l = 30\text{-}100$ m ; $h = l/50\text{-}l/30$; $f \geq l/7$
(b)

$l = 50\text{-}120$ m ; $h = l/40\text{-}l/20$; $f \geq l/8$
(c)

Three or two-pin arch with or without tie rod,

$L_{max} \approx 80\text{-}90$ m, $f\,/\,l > 0{,}144$



Two-pin arch with tie rod

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Three-pin arch without tie rod

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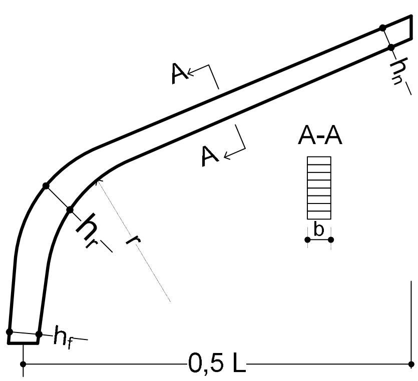
Design of 3-hinged frame

- The shape of the frame should be as close as possible to thrust line of the main load combination (usually: self-weight + snow)
- For roof slopes $\alpha \leq 15^{o}$, frame sizes are governed by self-weight + snow loads. The design of the apex and its connection is normally governed by uneven snow loads.
- For slopes $\alpha > 15^{o}$, frame size may be governed by wind loads

Preliminary dimensions



$h_r \sim 0,03$ L

$h_f \sim 0,09\ h_r$

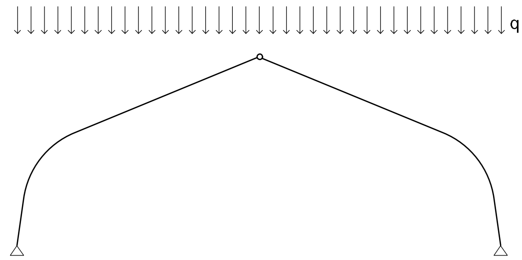
$h_n \sim 0,\cancel{5}\ h_r$ ($\geq$ 250mm) 0,3

$b \sim 0,15\ h_r - 0,20\ h_r$

$r \geq \cancel{5}$ m 8 m

Radius of curvature
- -r= 5,6 m; if t=33mm
- -r= 4,7 m; if t=28mm
- -r= 3,7 m; if t=22mm

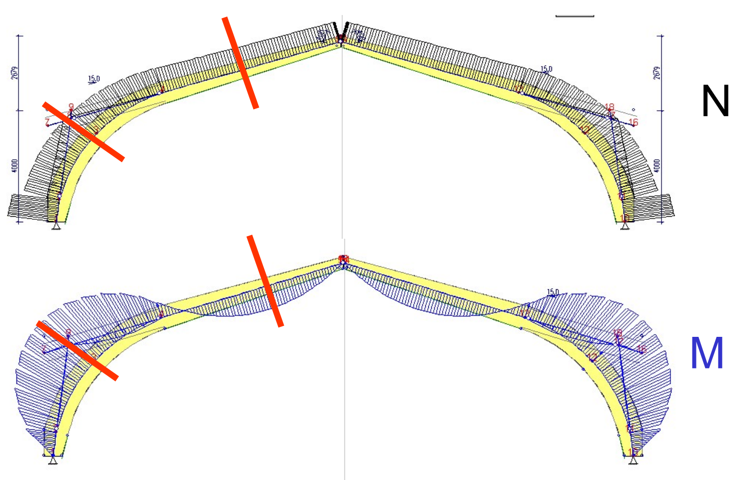
Example: Frame with curved haunches



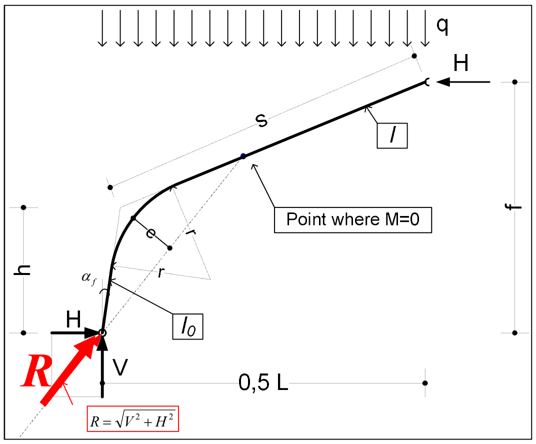
In this example we disregard the effect of wind load, which could produce increase of positive bending moment at the curved haunch, and, as a result, a potential risk for tension perpendicular to the grain

Ref: DoTS, Chapter 3.2.4

Cross sections to be checked

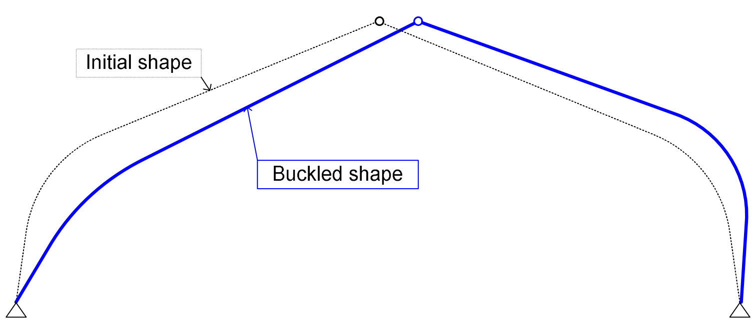


A first approach to determine the bending moment at the curved haunch



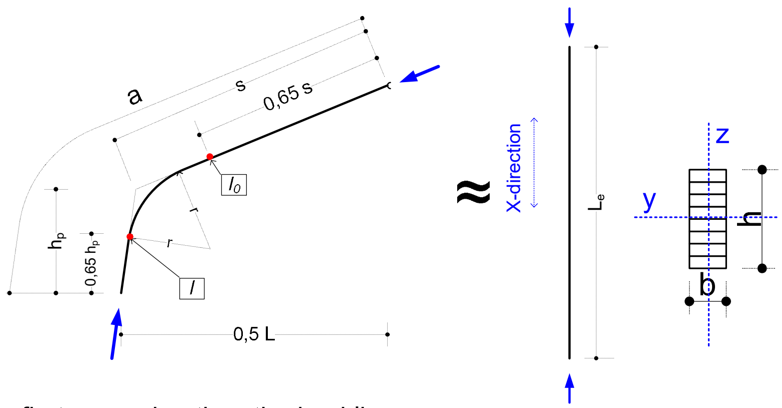
$$M_{haunch} \approx R \cdot e$$

In-plane buckling



How do we estimate the buckling length?

Estimation of buckling length – in-plane buckling



As a first approximation, the buckling length of the frame can be assumed as: $L_e \approx 1.25 \cdot a$

German code, DIN 1052: $L_e \approx h_p \sqrt{4 + 1{,}6 \cdot \frac{I_0}{I} \cdot \frac{2 \cdot s}{h_p}}$

Determination of buckling parameters – in plane buckling

- Determine the slenderness

$$\lambda_y = \frac{L_e \cdot \sqrt{12}}{h}$$

h is the depth of the beam at the haunch zone

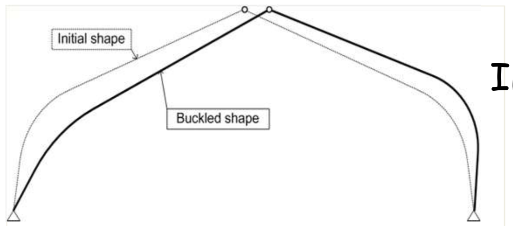
Bending about y-axis!! (i.e. about the strong axis)

- Determine the slenderness ratio

$$\lambda_{rel,y} = \frac{\lambda}{\pi} \sqrt{\frac{f_{c0,k}}{E_{0,05}}}$$

Frame with curved haunches

Linear buckling analysis as for beam-columns



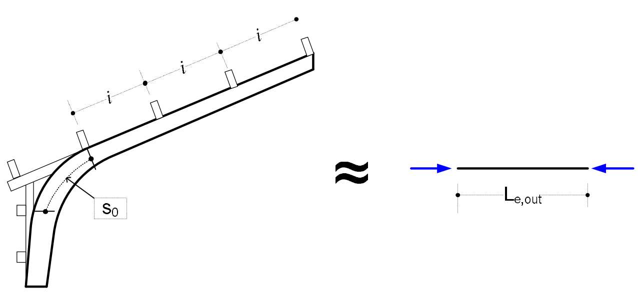
In-plane buckling

The design criterion:

$$\frac{\sigma_{m,y,d}}{k_r \cdot f_{m,y,d}} + \frac{\sigma_{c,0,d}}{k_{c,y} \cdot f_{c,d}} \leq 1$$

Coefficient k_r, see lecture 10

Estimation of buckling length – out-of-plane buckling



$$L_{e,out} \approx \begin{cases} i \rightarrow \textit{for check of the straight part} \\ s_0 \rightarrow \textit{for check of the curved part} \end{cases}$$

Frames – general considerations

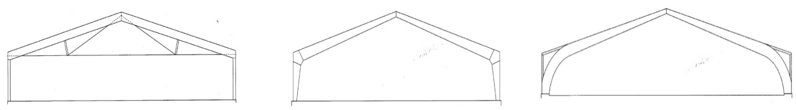
- Three-pin (or hinged) frames are the most common type of frames, mainly due to timber moisture-induced deformations and possibly ground settlements.
- Three-hinged frames are statically determinate structure, therefore they are not affected by uneven ground settlements or unforeseen deformations at the connections
- Three-hinged frames allows for relatively simple foundations due to the fact that they do not transmit moments at the supports
- Three-hinged frames are stable in the plane of the frame

Frames – general considerations

- **Roof slope** should **not be less than 14°**, in order to avoid too large deformation at the apex
- In situations where **ground has low strength, horizontal forces can be carried by tie rods** hidden in the floor between supports. In this way, the ground under the foundation will be subjected only to vertical loading.
- **Common spans are 15-50 m**. Larger spans would imply difficulties for transportation

Rehearsal question

B6. All these structural systems below for the glulam are used for buildings with roof angle > 14°.
What maximum spans can they offer?
What are the critical details which have to be specially considered by a designer?



B7. In frames and arches, as in columns, the buckling resistance must be verified by stability checks.
What is the principle when design for out-of-plane buckling?

Tynset bridge, Norway

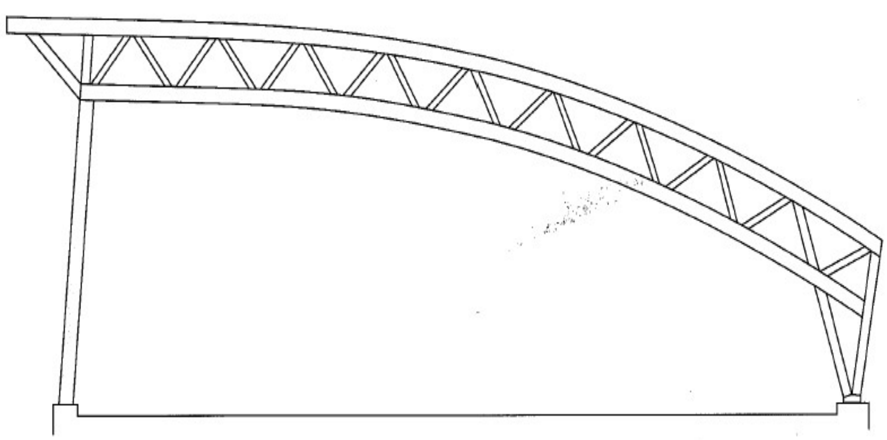
Production of trussed arch

Three arches, main span 70 m

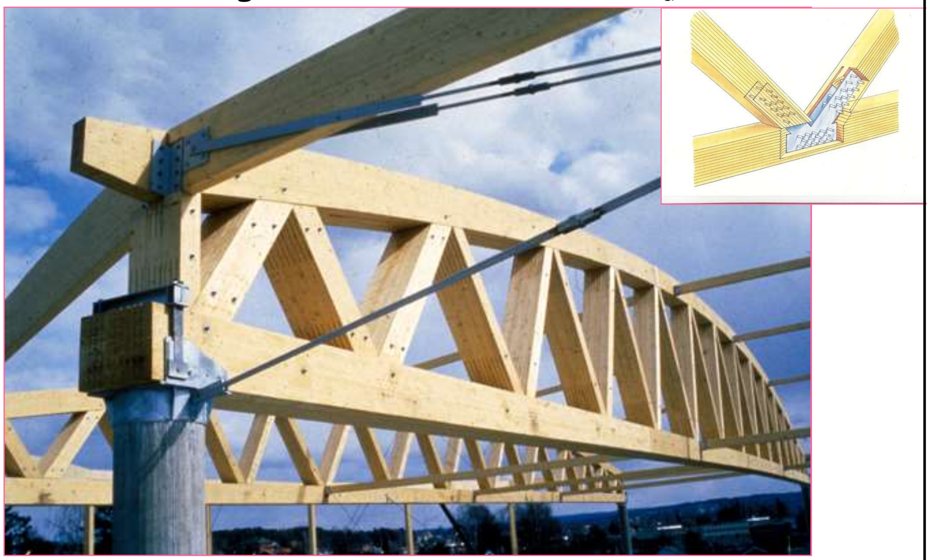
Road bridge in Hägernäs

Total length: 42m, arch span: 34m

Trusses $L_{max} \approx 100$ m



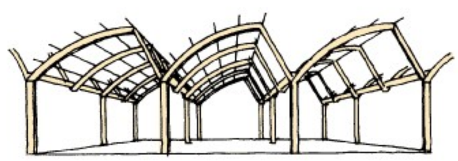
Olympic hall in Hamar, 1994 L=71m, The lower chord is designed for a tensile load F_d=7000kN



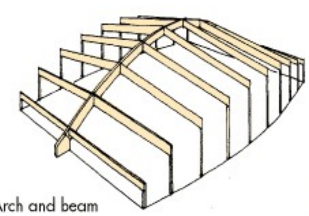
Elmia, Jönköping's fair

Elmia, Jönköping's fair

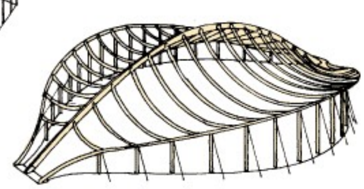
Composite systems



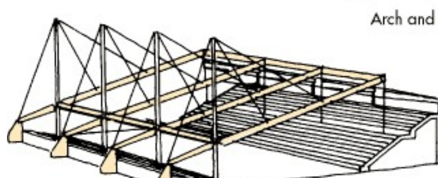
Saw-tooth roof



Arch and beam

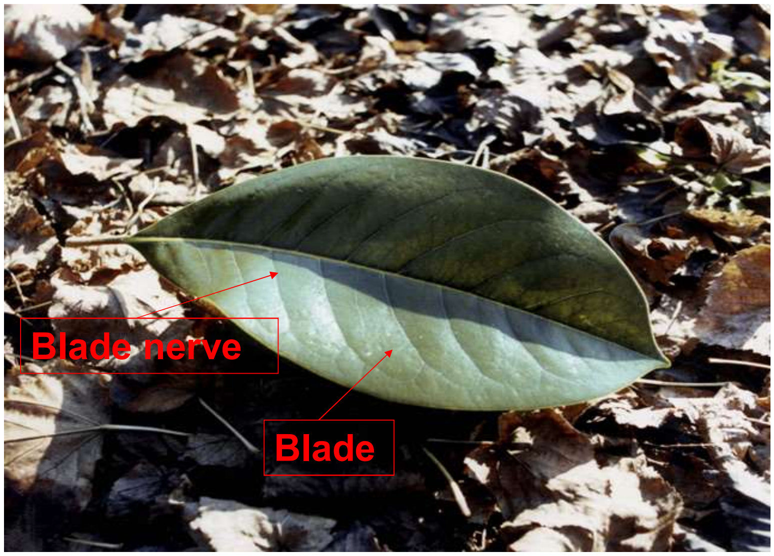


Arch and beam



Cable stayed roof

Inspiration..



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The idea

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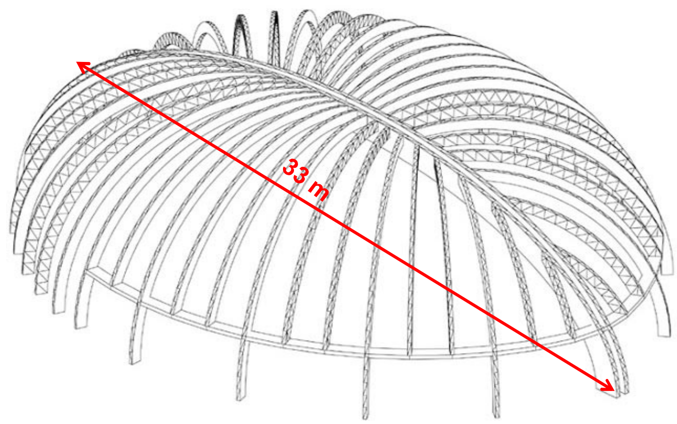
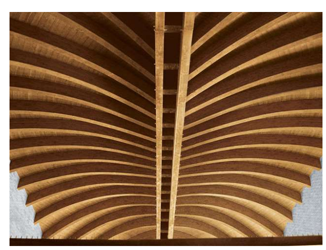


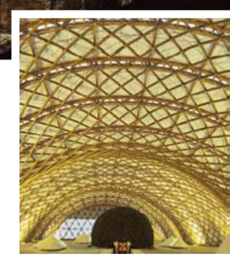
A theater in Rimini



"Blade nerve"

"Blade plate"

Expo 2000, Hannover- the Japanese stand



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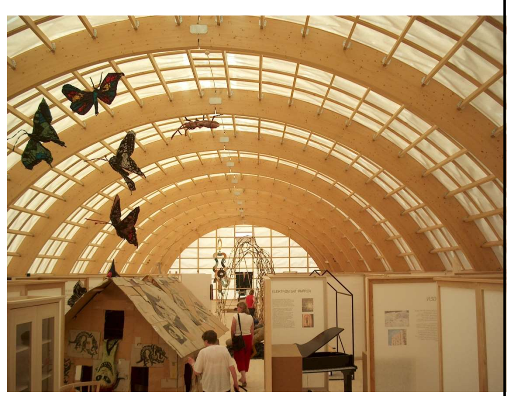
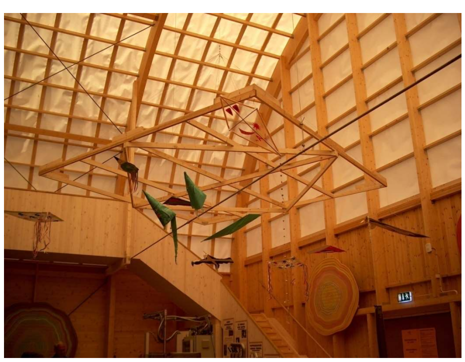
Show rum in Virserum





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Composite structures: timber glas

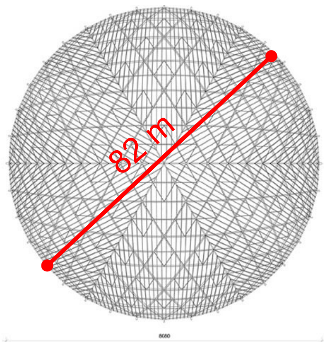
Auflager der HGV-Trägers im Hotel Palafitte, Monruz

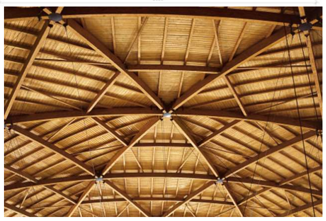
Auskragendes Ende des HGV-Trägers, Palafitte

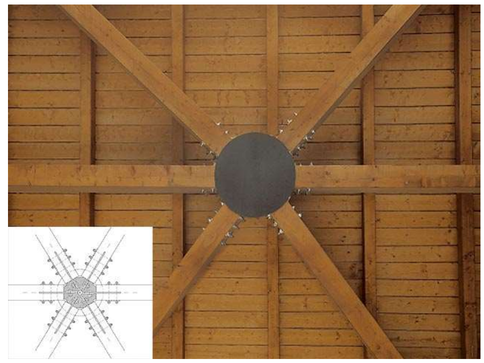
Lobby des Hotel Palafitte, CH-Monruz

Cantine di Mezzocorona - Italy

Dome structure







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The Metropol Parasol in Seville, Spain

Construction period: 2005-2011

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The Metropol Parasol in Seville, Spain

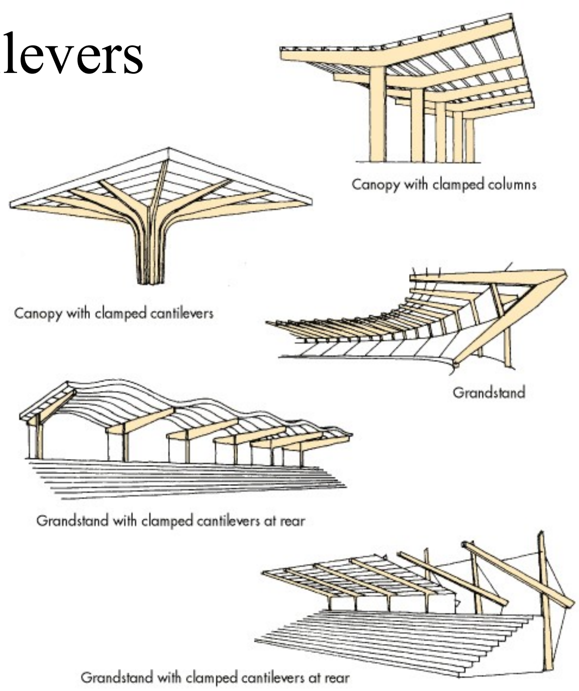
Individual elements:

- 3400 individual elements of glued Kerto-Q LVL
- Length max. = 16,5 m,
- thicknesses between 68 and 311 mm
- Largest (trunk) element 16,5 x 3,5 x 0,14 m
- 3000 load-bearing connection nodes

Total floor area: 12,670 square meters

The building: 150m long, 75m wide and 28.5m high.
Kerto-Q are arranged to an orthogonal grid of 1,50m x 1,50m
Kerto-Q is covered by 2-c-polyurethan as weather protection

Cantilevers



”Fägnad” – en spännande konstruktion vann 1:a pris, SEK 20 000 kr

Förslagsställare: Tomas Jonnergård och Åsa Landahl, Chalmers Tekniska Högskola, Göteborg

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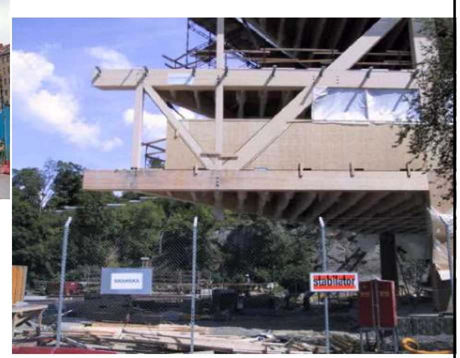
Universeum- Göteborg



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1 Augusti 2002

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Viking ship - Norway

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Trussed arches: L_{max} ~100m

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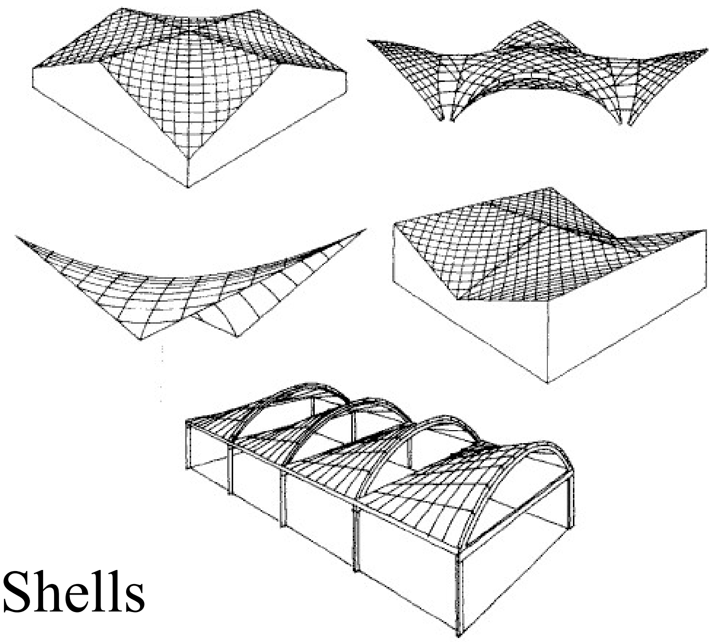

Shells

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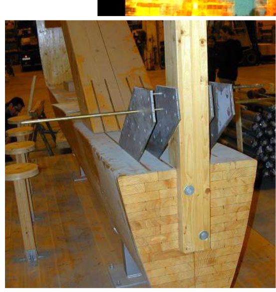
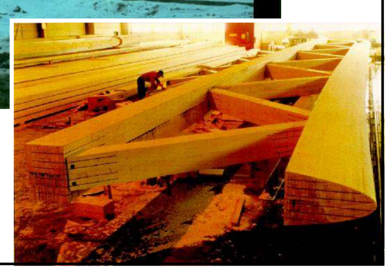
Gardemoen, Oslo airport





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New offices, Moelven Töreboda AB

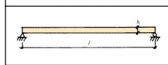
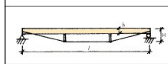
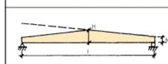
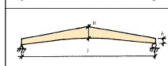
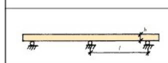
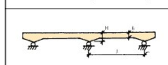
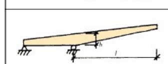
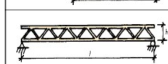
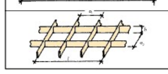
New offices, Moelven Töreboda AB

Structural systems using glulam.

Recommended roof slopes and spans.

Approximate sectional depths with normal loading.

http://www.svensktlimtra.se/en/limHTML/

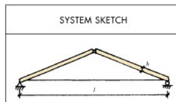
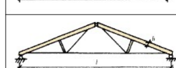
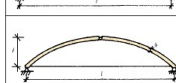
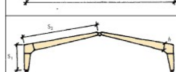
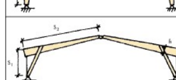
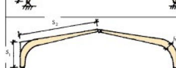
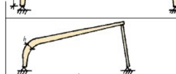
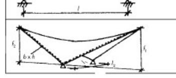
SYSTEM SKETCH	NAME	SUITABLE SLOPE	SUITABLE SPAN	DEPTH
	Straight beam on two supports	• 3•	< 30	$h \sim \frac{l}{17}$
	Straight braced beam on two supports	3-30•	< 50	$h \sim \frac{l}{40}$ $H \sim \frac{l}{12}$
	Symmetrical double pitched beam	3-10•	10-30	$h \sim \frac{l}{30}$ $H \sim \frac{l}{16}$
	Symmetrical double pitched beam with curved underside	3-15•	10-20	$h \sim \frac{l}{30}$ $H \sim \frac{l}{16}$
	Straight continous beam on several supports	• 3•	< 25	$h \sim \frac{l}{20}$
	Haunched continous beam on several supports	• 3•	< 25	$h \sim \frac{l}{24}$ $H \sim \frac{l}{16}$
	Cantilevered beam on two supports	< 10•	< 15	$h \sim \frac{l}{10}$
	Straight trussed beam on two supports	• 3•	30-85	$h \sim \frac{l}{10}$
	Grid	• 3•	12-25	$h \sim \frac{l}{20}$ ($a = 2,4 - 7,2$ m)

Structural systems using glulam.

Recommended roof slopes and spans.

Approximate sectional depths with normal loading.

http://www.svensktlimtra.se/en/limHTML/

SYSTEM SKETCH	NAME	SUITABLE SLOPE	SUITABLE SPAN	DEPTH
	Three-pin frame with or without a tie	• 14•	15 - 50	$h \sim \frac{l}{30}$
	Three-pin frame with tie and braced struts	• 14•	20 - 100	$h \sim \frac{l}{40}$
	Three-pin (two-pin) arch with or without a tie	$\frac{f}{l}$ • 0,14	20 - 100	$h \sim \frac{l}{50}$
	Three-pin portal frame with finger-jointed haunches	• 14•	15 - 25	$h \sim \frac{s_1+s_2}{13}$
	Knee braced portal frame	• 14•	10 - 35	$h \sim \frac{s_1+s_2}{15}$
	Three-pin portal frame with curved haunches	• 14•	15 - 50	$h \sim \frac{s_1+s_2}{15}$
	Propped half portal frame	• 20•	10 - 25	$h \sim \frac{l}{25}$
	Hyperbolic paraboloid shell (HP shell)	$\frac{f_1+f_2}{l_1+l_2}$ • 0,2	$l_1 \sim l_2$ 15 - 60	$h \sim b \sim \frac{l}{70}$ (kantbalkar)