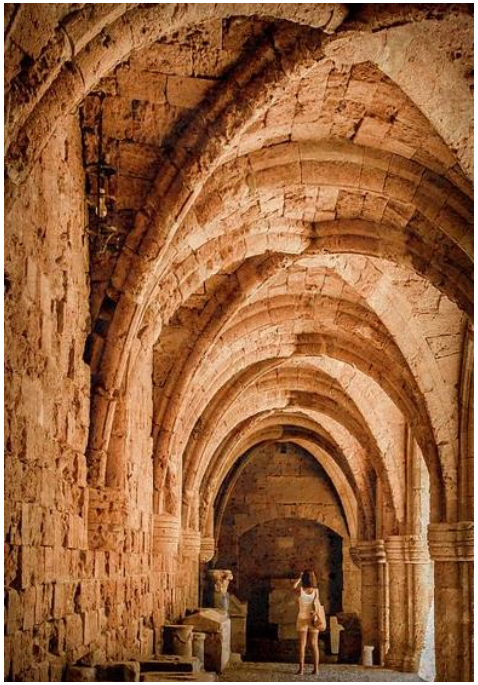


# Barrel Vaults and Cross Vaults

# Citation:

K. Bagi (2024): Mechanics of Masonry Structures. Course handouts, Department of Structural Mechanics, Budapest University of Technology and Economics



In case of any question or problem, do not hesitate to contact Prof. K. Bagi, kbagi.bme@gmail.com .

# THIS LECTURE

Barrel Vaults

- → Definition; Terminology
- → Origins
- → Cracking and failure modes; How to resist the lateral thrust
- → Constructional issues

Vaults in General: Catalan Vaulting

Skew Barrels

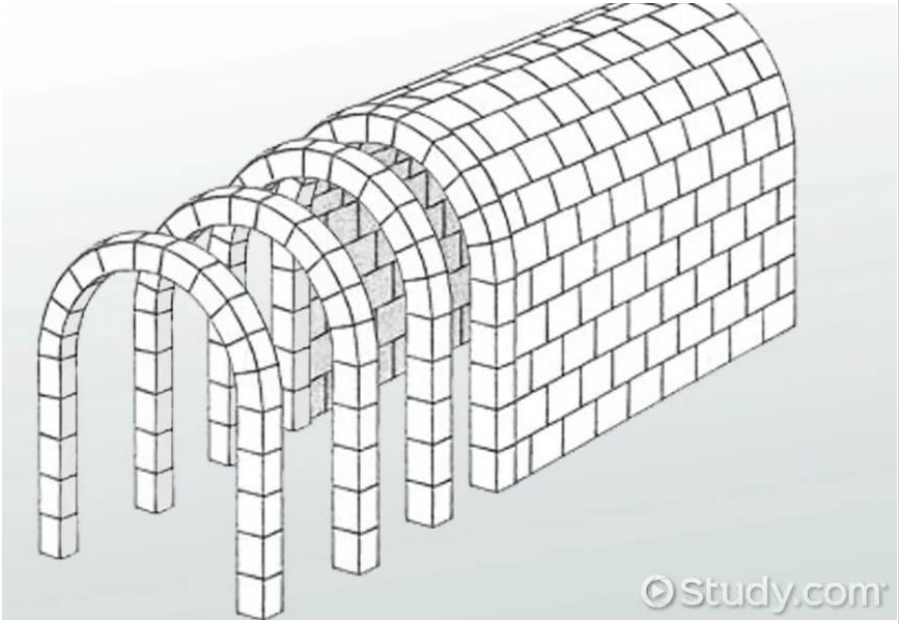
Cross Vaults

- → Definition; Origin and early examples
- → Main types; Terminology
- → Forces in cross vaults
- → Crack patterns; Strengthening

Underpitched vaults

Questions

# BARREL VAULTS




*study.com/academy/lesson/barrel-vault-definition-construction-architecture.html*

What is a barrel vault:

a half-open vault;

„translated arch”

parabolic points

1: crown (top block row, placed last)

2: the voussoirs (the building stones)

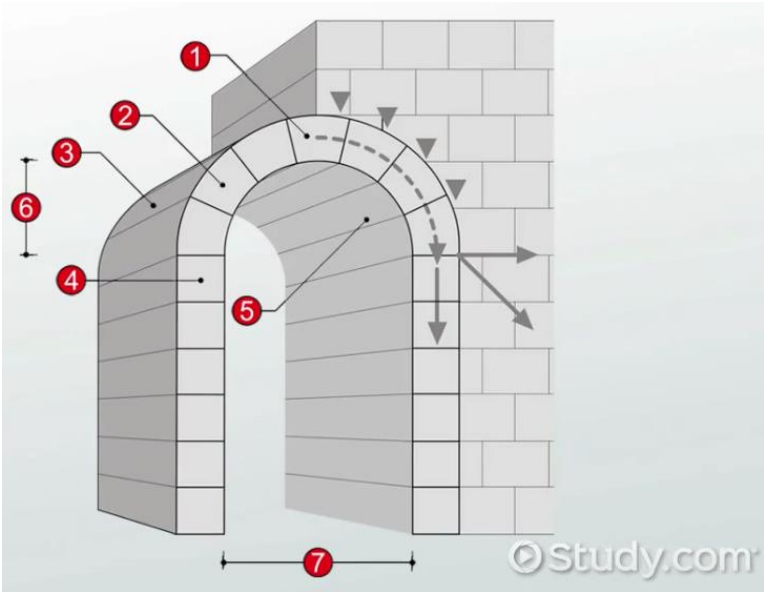
3: extrados (outer surface)

4: impost (provide transition)

5: intrados (inner surface)

6: rise

7: free span



# BARREL VAULTS

<u>Origins of barrel vaulting:</u>

In Mesopotamia and Egypt:

from 4th millennium BC
„pitched" brick vaulting

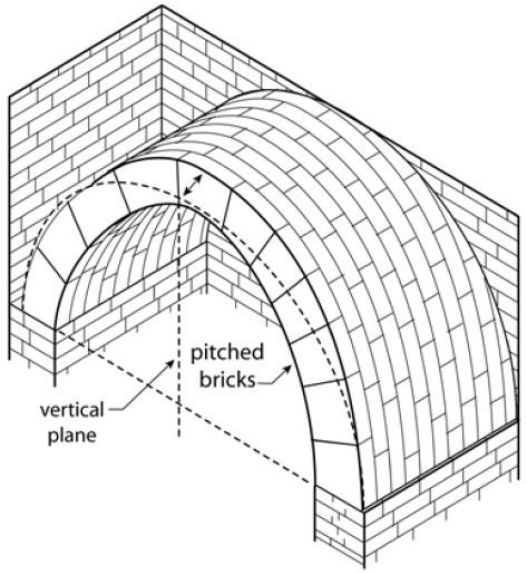
areas where wood was scarce [no centring]
gypsum mortar: → needs only 200 °C;
→ sets in minutes
mud brick (fired or sundried)

[Greeks hardly used]

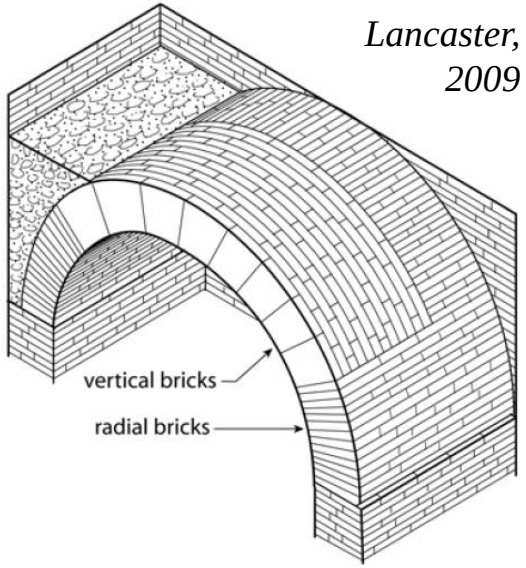
In the Roman empire:

vertical and radial bricks
early example: Argos, bath (1st century AD)

centring regularly applied
stone or brick; lime mortar (needs 900 °C)




*Lancaster, 2009*



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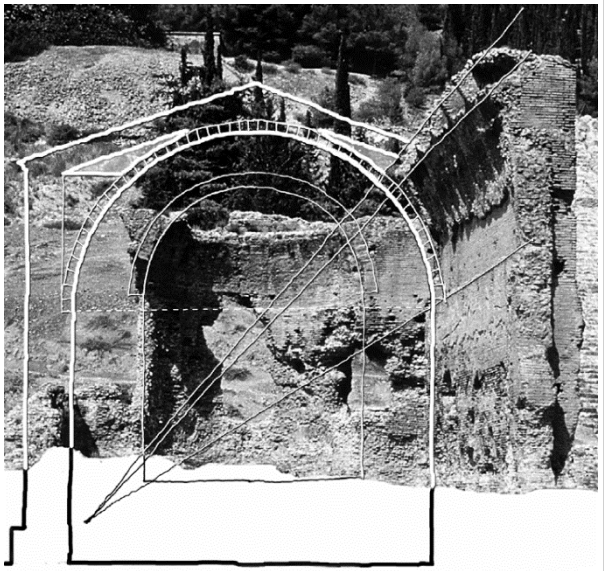


*Lancaster (2006)*

# BARREL VAULTS

Temple of Sulis Minerva, Bath, UK: ≈ Ist ct AD „Aquae Sulis", hot water spa

Celtic goddess of wisdom (≈≈ Minerva)

How it may have looked like:

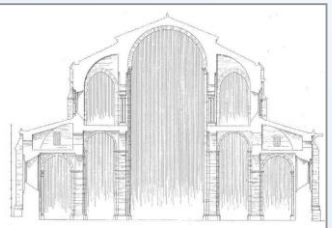
*wikivisually.com/wiki/Aquae_Sulis*

How it looks today:

later construction

*wikivisually.com/wiki/Aquae_Sulis*

# BARREL VAULTS



The Basilica of Saint Sernin, Toulouse, France: end of XIth century

[largest Romanesque church]

*https://www.bc.edu/bc_org/avp/cas/fnart/arch/st_sernin.html*

the main nave vault:

*https://www.flickr.com/photos/blieusong/7141038189*

„banded barrel vault”

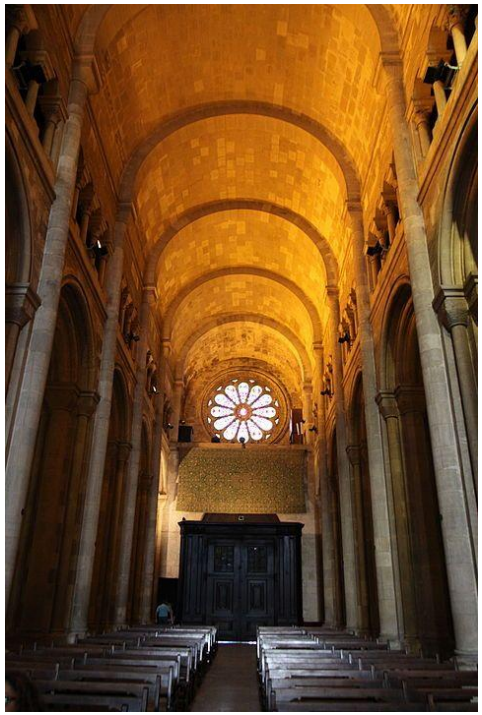
# BARREL VAULTS

Lisbon Cathedral, Portugal: the Romanesque nave from XIIth century

[ several earthquakes in the region ⇒

⇒ Gothic, Baroque, etc parts also ]

the nave vault:



*pinterest.ca/pin/166211042478736763/*

from outside:

*lisbon-tourism.com/en/lisbon-attractions/churches-in-lisbon/lisbon-cathedral.html*

# BARREL VAULTS

Ladykirk Church, Berwickshire, Scotland: XVIth century, Gothic structure

from outside:

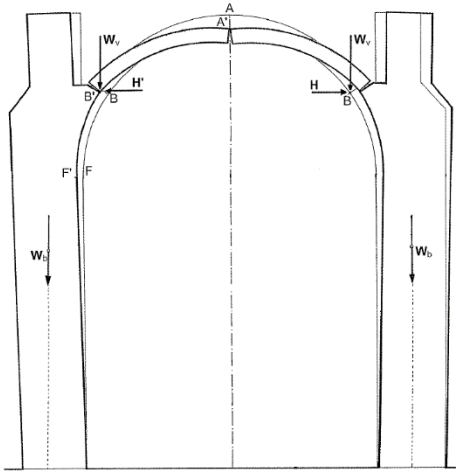
*imagedatabase.st-andrews.ac.uk/images*

the nave vault:

*arts.st-andrews.ac.uk/corpusofscottishchurches*

# BARREL VAULTS

*Huerta, 2010*

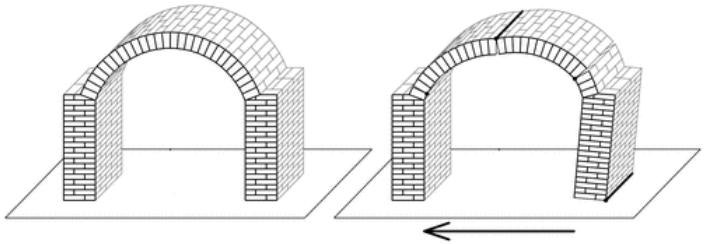


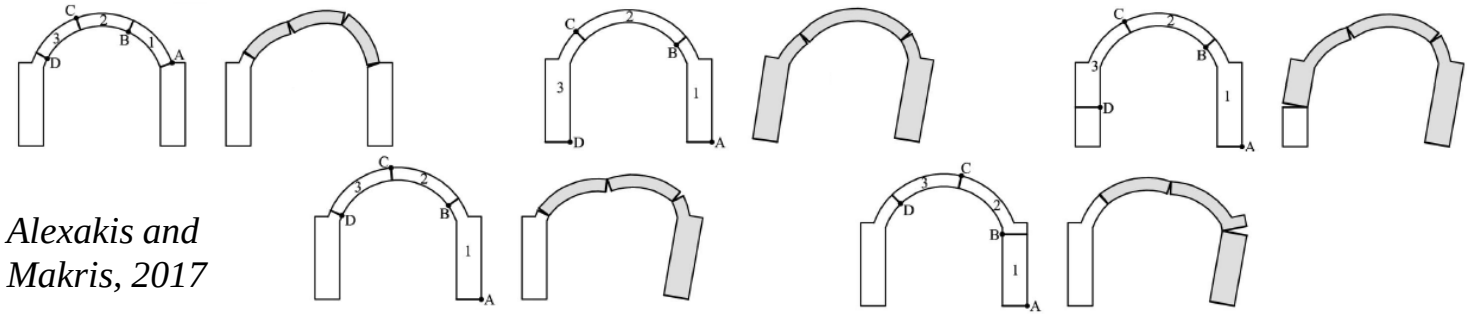
Cracking and failure modes

Typical load: selfweight & support displacements

Failure:
- (the barrel only, as an arch)
- together with the supporting structure

Remark:
Failure modes under
lateral ground accelerations:





*Alexakis and Makris, 2017*

# BARREL VAULTS

How to resist the lateral thrust?

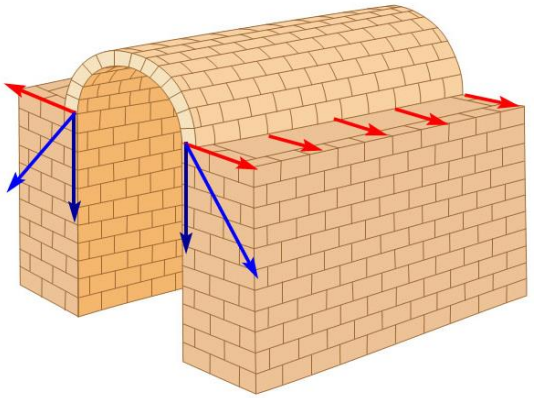
Underground or near-to-ground barrels:

→ earth pressure ✓

*Lancaster, 2009*

Freestanding barrel vaults on higher walls:

→ heavy, thick walls under the barrel:



*lanera.com/casteldelmonte/cvtech_172/page-172-02.html*

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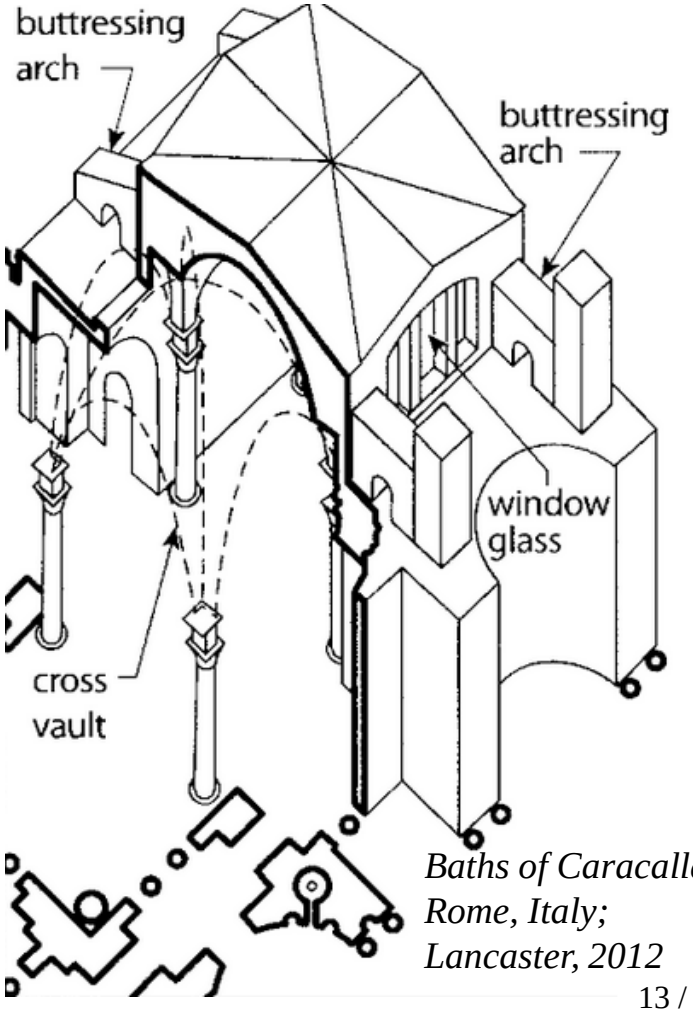


*Baths of Caracalla, Rome, Italy; Lancaster, 2012*

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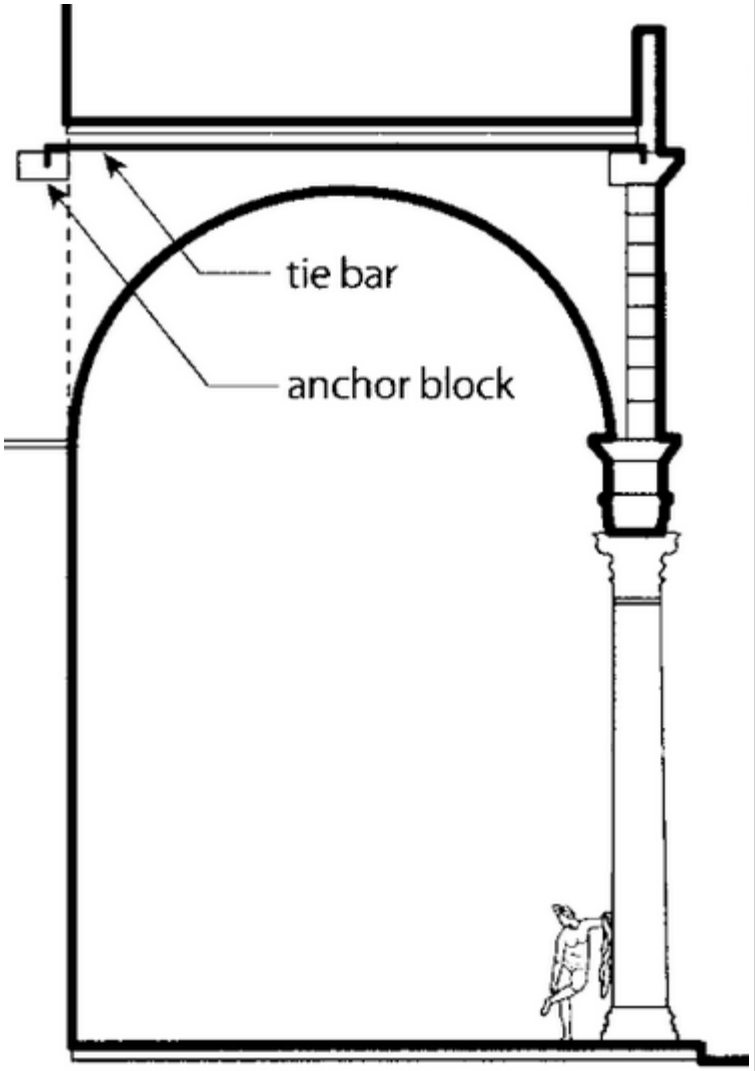
→ walls supported by buttresses

→ iron tie bars:

Roman invention,

from ≈ 2nd century AD




*Lancaster, 2012*

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→ walls supported by buttresses

→ iron tie bars

→ make the vault easier:

✓ use bricks (e.g. ≈1400 kg/m3) instead of stone (e.g. ≈2600 kg/m3)

✓ formulate coffers („indentations”):

*Ressler (2011), 11. The Glory of Rome*

# BARREL VAULTS

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→ neighbouring barrels: [ ≈ arcade ]

*https://www.architecturaldigest.com/story/colosseum-restoration-phase-one-complete*

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→ neighbouring barrels: [ ≈ arcade ]

→ crosswise barrels:

TOWARDS THE CROSS VAULT !

# BARREL VAULTS

How to resist the lateral thrust?

*Ressler (2011), 11. The Glory of Rome / Baths of Caracalla, early IIIrd century*

*Ressler (2011), 11. The Glory of Rome*

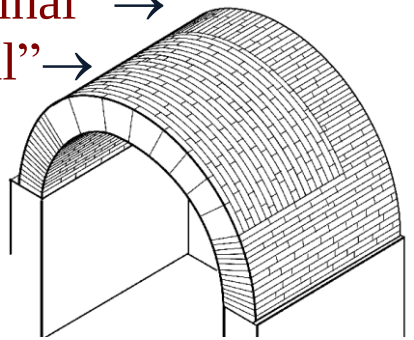
*http://acedulado.pw/marble-revetment-definition: Basilica of Maxentius, ≈310 AD*

→ crosswise barrels:

TOWARDS THE CROSS VAULT !

# BARREL VAULTS

~~radial:~~ „longitudinal” →
~~vertical:~~ „transversal”→



*Lancaster, 2015*

Constructional issues

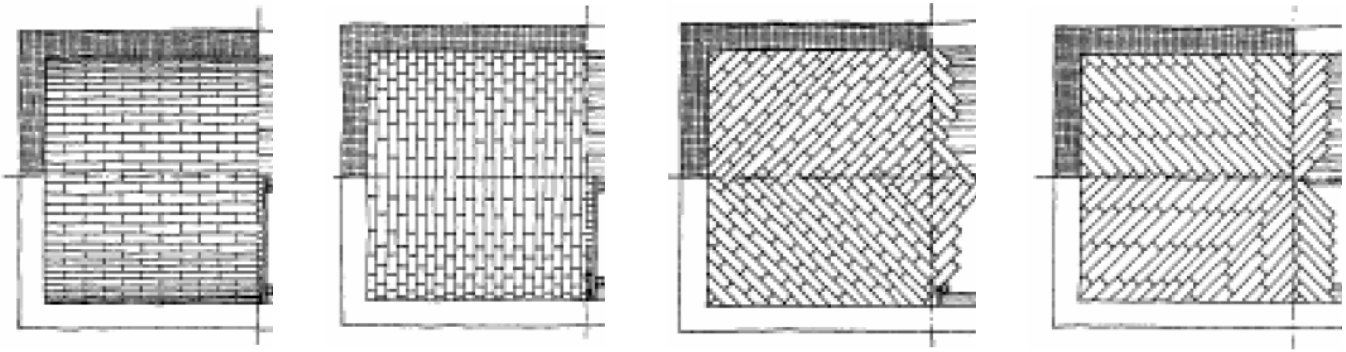
Terminology:

→ Course: a continuous row of masonry units

→ Heading joint: a contact between two masonry units in the same course

→ Coursing joint: a contact between two masonry units being located in neighbouring courses

Bond patterns for barrel vaults:



longitudinal vault | transversal vault | bone vault | inverted bone vault

*Levi, 1932*

# BARREL VAULTS

Constructional issues

Examples:

ceilings today:

e.g. school roof in Mali

*http://archinew.altervista.org/2014/02/12/vaulted-brick-primary-school-built-on-a-mali-plain-by-levs-architecten/*

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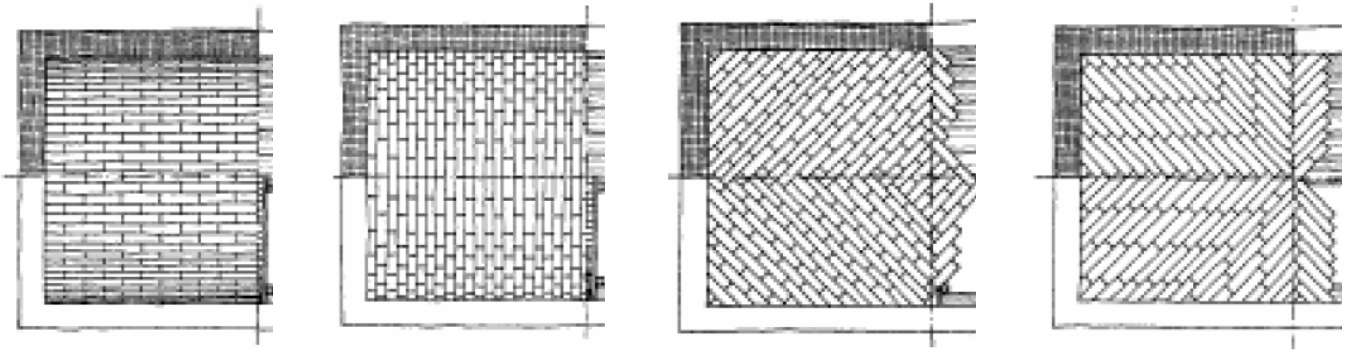

longitudinal vault

transversal vault

bone vault

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*http://www.naturalbuildingblog.com/brick-barrel-vaults/*

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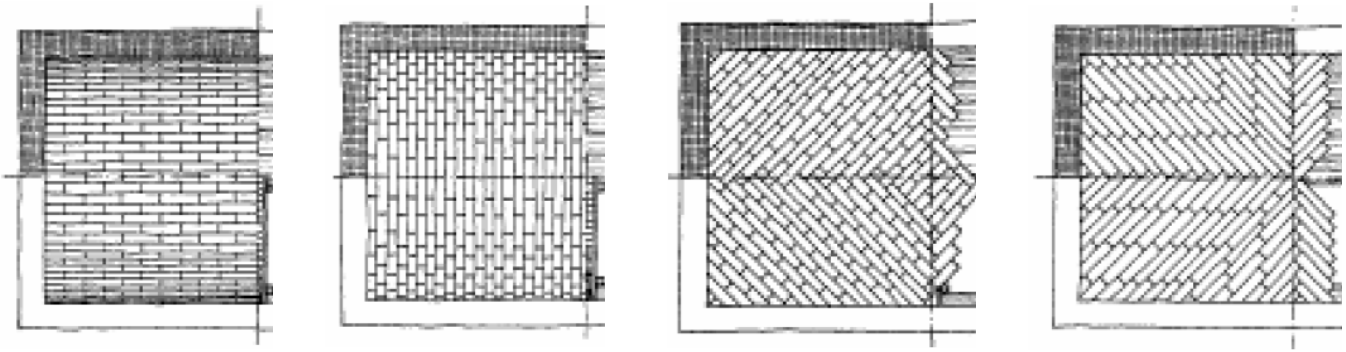

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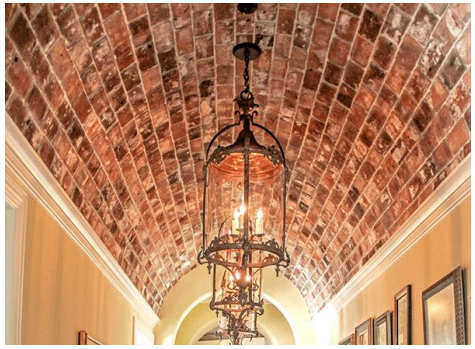

*https://www.archwaysandceilings.com/product/barrel-vaults/*

*www.estestinc.com/interior-design/residential/old-world/old-world-residence-6*

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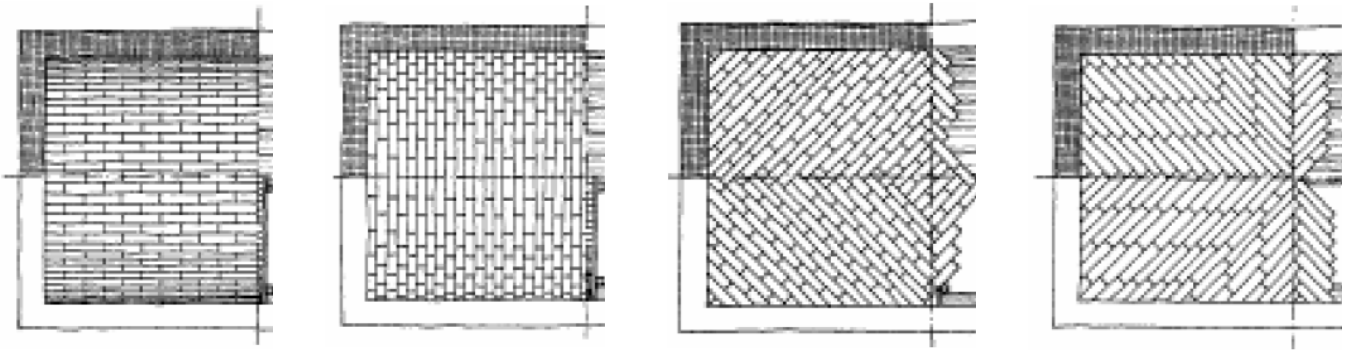


*Levi, 1932*

longitudinal vault

transversal vault

bone vault

inverted bone vault

# BARREL VAULTS

Constructional issues

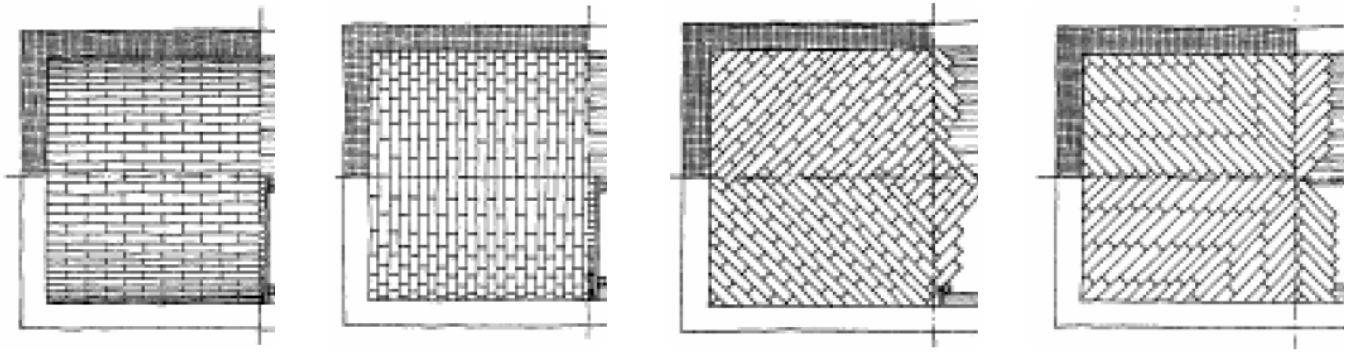
Examples:

ceilings today:

e.g. in Nubia, around 2008:

*https://www.youtube.com/watch?v=xsBfeL3vlGI*

Bond patterns for barrel vaults:



*Levi, 1932*

longitudinal vault

transversal vault

bone vault

inverted bone vault

# BARREL VAULTS

*https://www.ribaj.com/culture/barrel-vaults*

Constructional issues

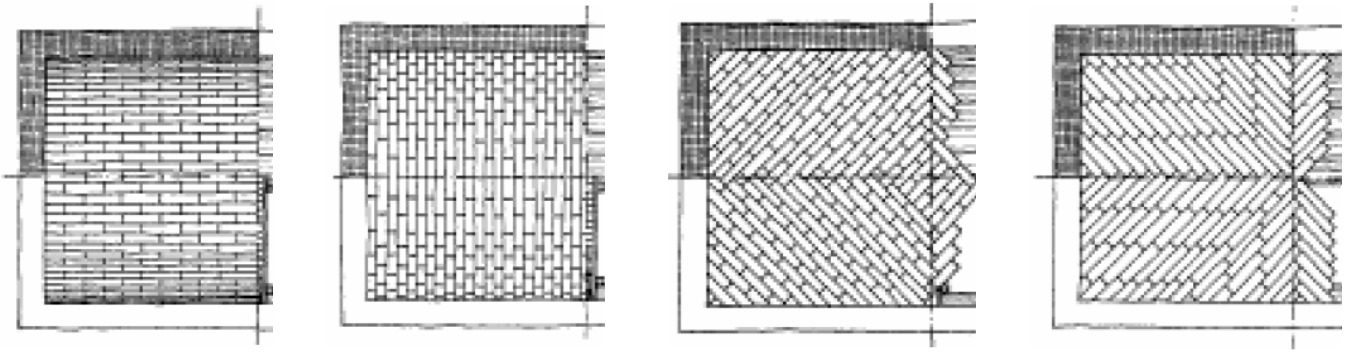
Examples:

New Gourna: a small experimental village

1946-52, Egypt, Luxor; architect: Hassan Fathy

UNESCO World Heritage

Bond patterns for barrel vaults:



longitudinal vault | transversal vault | bone vault | inverted bone vault

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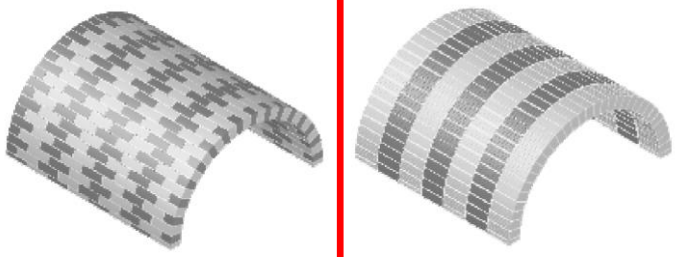
# BARREL VAULTS

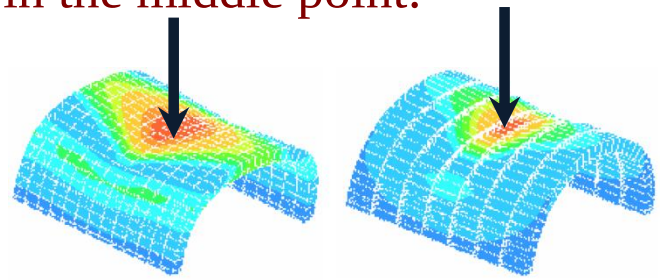
STRONGER

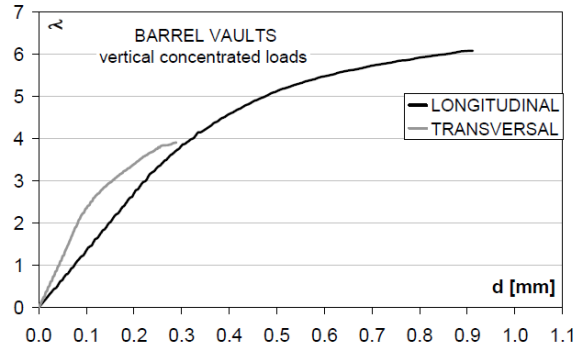



Constructional issues

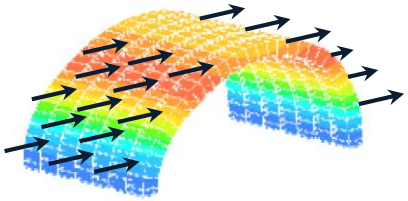
Romano & Grande (2008): FEM

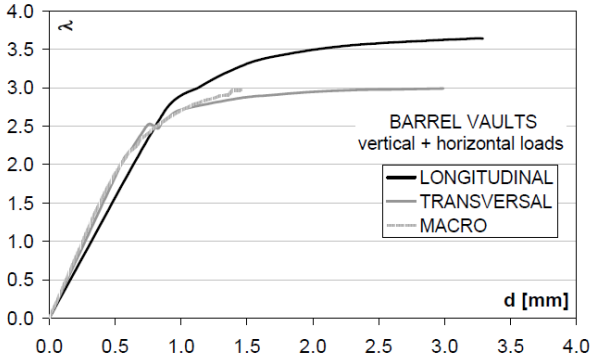
→ vertical concentrated load
in the middle point:






→ horizontal distributed load
[e.g. seismic acceleration]:





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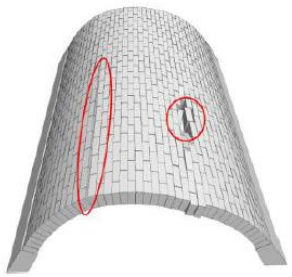
STRONGER



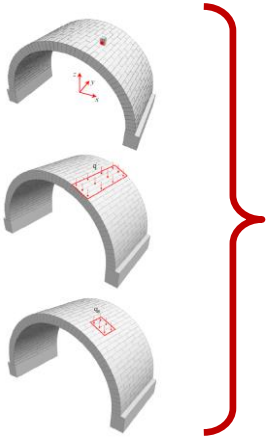
*longitudinal*

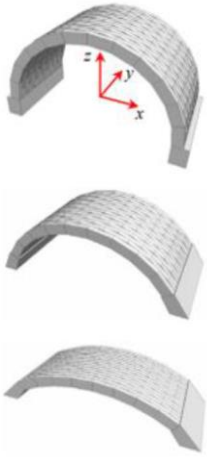
*transversal*

Constructional issues

Chen & Bagi (2021): DEM (3DEC)

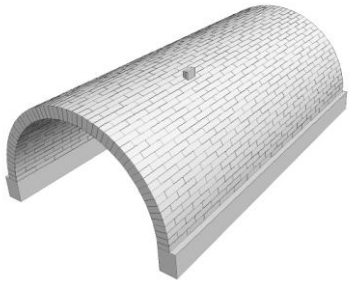
→ load bearing for vertical loads:





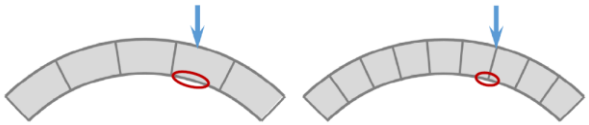
3 transversal  3 longitudinal

⇔



the same 6 geometries
for long barrels

→ size effect pointed out:

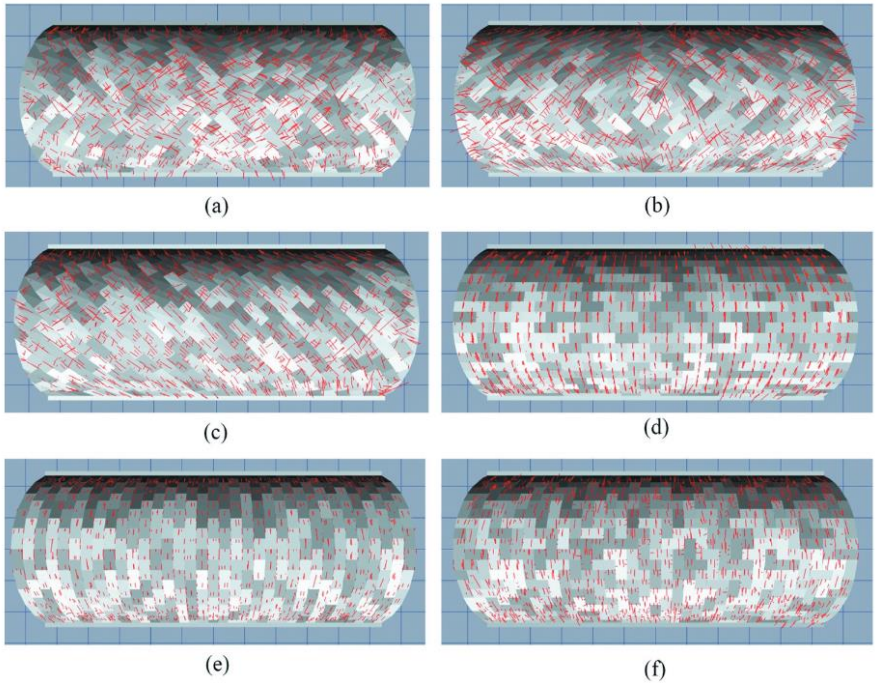


CLOSED-FORM SOLUTION:
← OPEN ISSUE

# BARREL VAULTS

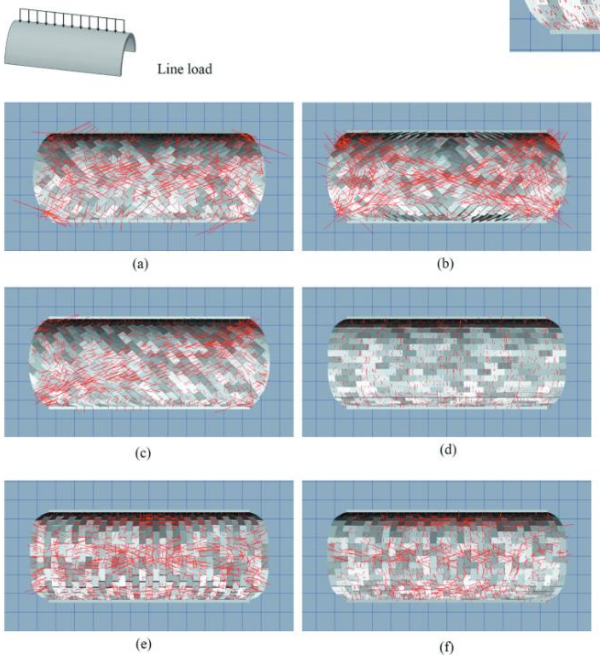
Constructional issues

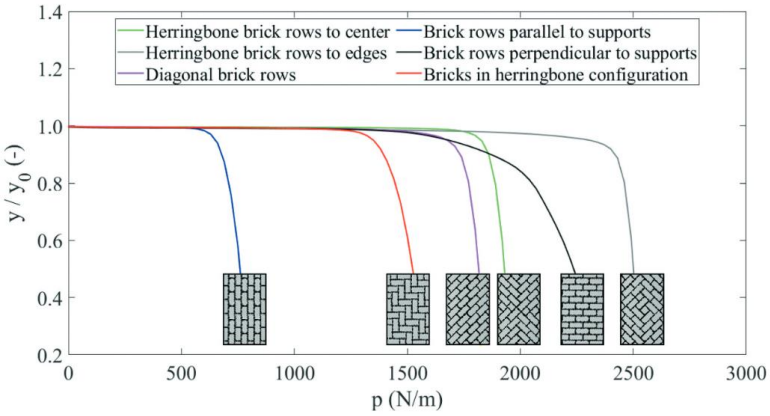
Boni et al (2021): DEM (CD)




→ selfweight:

→ line load:



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- → Origins
- → Cracking and failure modes; How to resist the lateral thrust
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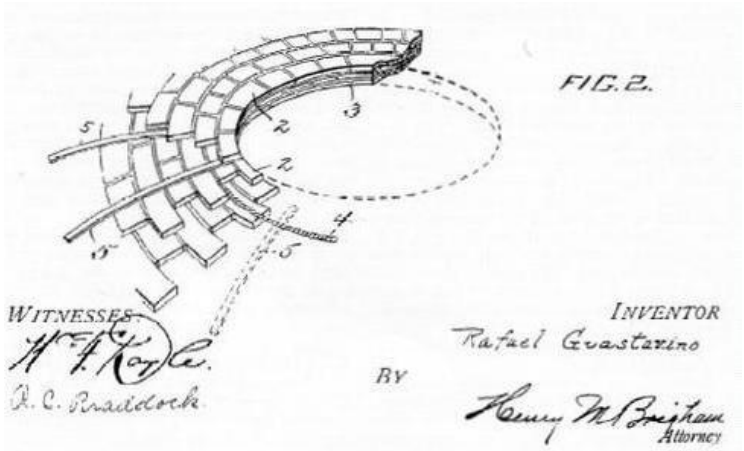
- → Main types; Terminology
- → Forces in cross vaults
- → Crack patterns; Strengthening

Underpitched vaults

Questions

# VAULTS IN GENERAL

*https://makezine.com/2018/10/20/weekend-watch-the-projects-and-adventures-as-amy-makes-stuff/*




Constructional issues

Tile vaulting („Guastavino vault”, „Catalan vault”):

thin tiles 3-4 layers; gypsum mortar

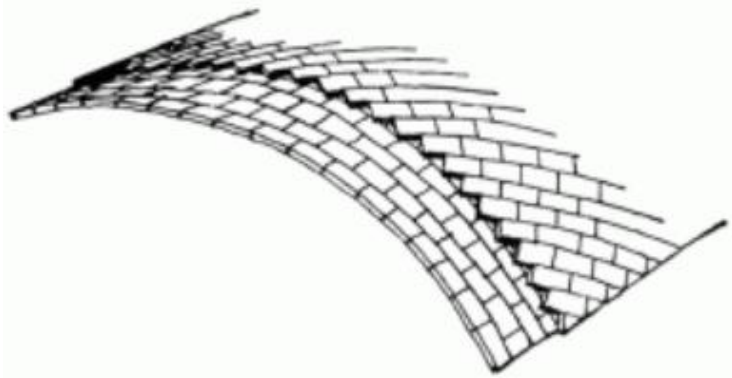
proceeding from bottom inwards ⇒

⇒ **centering not needed**! [fast setting]

thinner, lighter; fireproof

very fast construction

less horizontal thrust



*http://www.structuremag.org/?p=2046*

History:

Moorish origin, found from XIIth century

spread in the Mediterranian area

XVIII-XIXth century Catalan architecture

Rafael Guastavino, ≈ 1880, went to the US

US public buildings,

subway stations, staircases, …

# VAULTS IN GENERAL

Constructional issues

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„Catalan vault”):
thin tiles 3-4 layers; gypsum mortar
proceeding from bottom inwards ⇒
⇒ **centering not needed**! [fast setting]
thinner, lighter; fireproof
very fast construction
less horizontal thrust

→ MIT students:
(supervisor: prof. John Ochsendorf)
recently built: 1,5 days (!!!)
0,5 inch thick

*www.youtube.com/watch?v=VaEiUkTWG9Y*

# VAULTS IN GENERAL

*www.youtube.com/watch?v=VaEiUkTWG9Y*

Constructional issues

Tile vaulting („Guastavino vault”, „Catalan vault”):

→ Rafael Guastavino:

e.g. Boston Public Library:

e.g. NY Queensboro Food Emporium:

*https://untappedcities.com/2018/02/05/12- beautiful-locations-to-find-guastavino-tiles-in-nyc/*

e.g. City Hall Station, NY subway:

*https://www.architecturaldigest.com/gallery/guastavino-tile-arches/all*

# VAULTS IN GENERAL

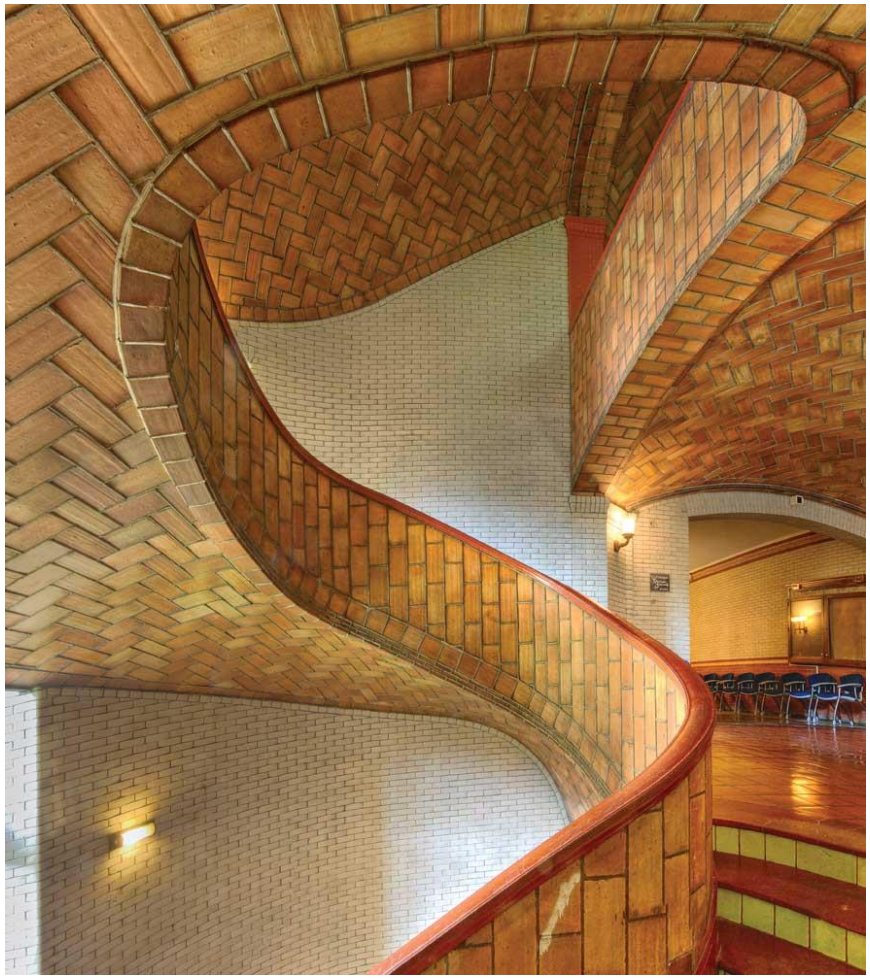
Constructional issues

Tile vaulting („Guastavino vault”, „Catalan vault”):

→ Rafael Guastavino:

e.g. Staircase in Baker Hall, at Carnegie-Mellon University:

*Fiveprime, https://hiveminer.com, Tags: building college architecture stairs oakland hall*



*https://2hpencil.com/tag/fibonacci-number/*

Suggested reading:
http://www.lowtechmagazine.com/2008/11/tiles-vaults.html

# THIS LECTURE

Barrel Vaults

- → Definition; Terminology
- → Origins
- → Cracking and failure modes; How to resist the lateral thrust
- → Constructional issues

Vaults in General: Catalan Vaulting

Skew Barrels

Cross Vaults

- → Definition; Origin and early examples
- → Main types; Terminology
- → Forces in cross vaults
- → Crack patterns; Strengthening

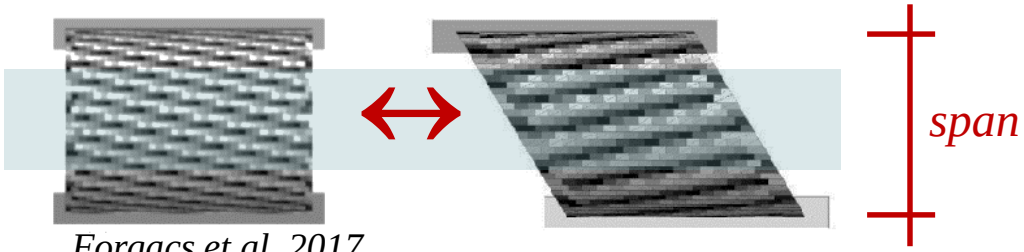
Underpitched vaults

Questions

# SKEW BARRELS

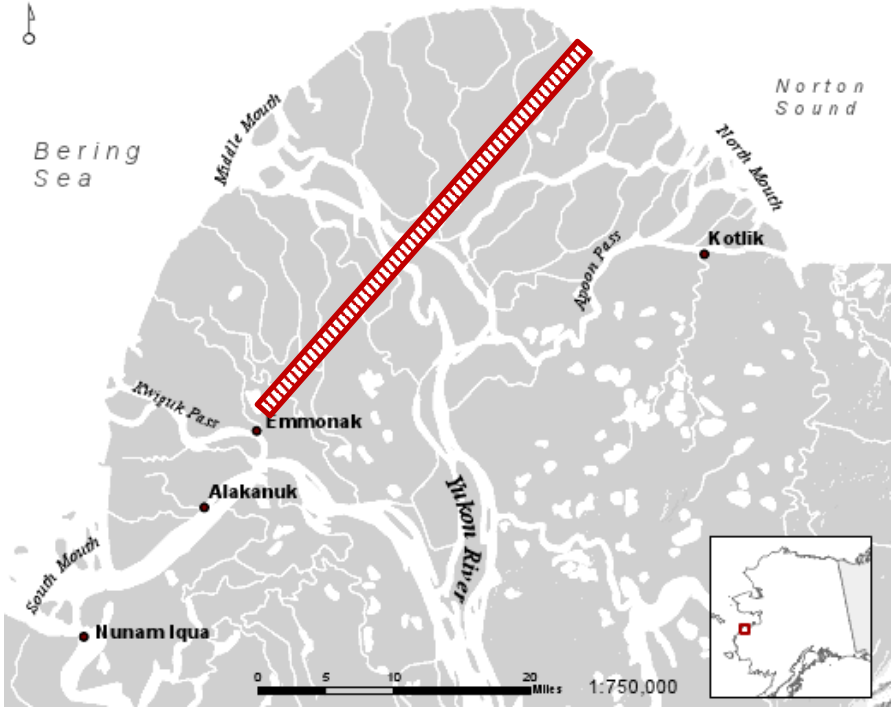
What is a skew barrel?

Top view:




*Forgacs et al, 2017*

Why not straight?

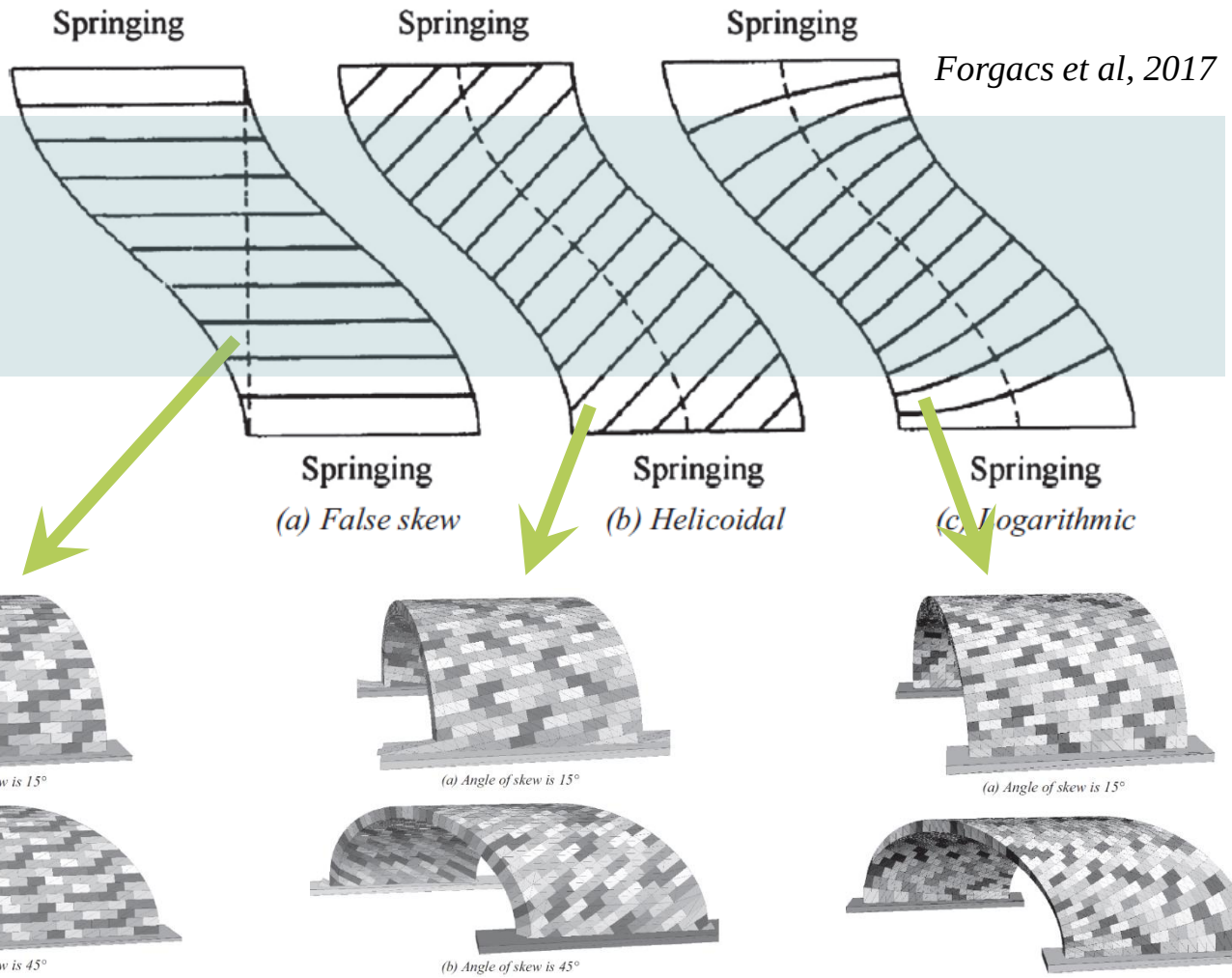



*eloka-arctic.org/communities/yupik/yukon-river.html*

# SKEW BARRELS

Construction geometries:

the developed surfaces:




*Forgacs et al, 2017*

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Construction geometries:

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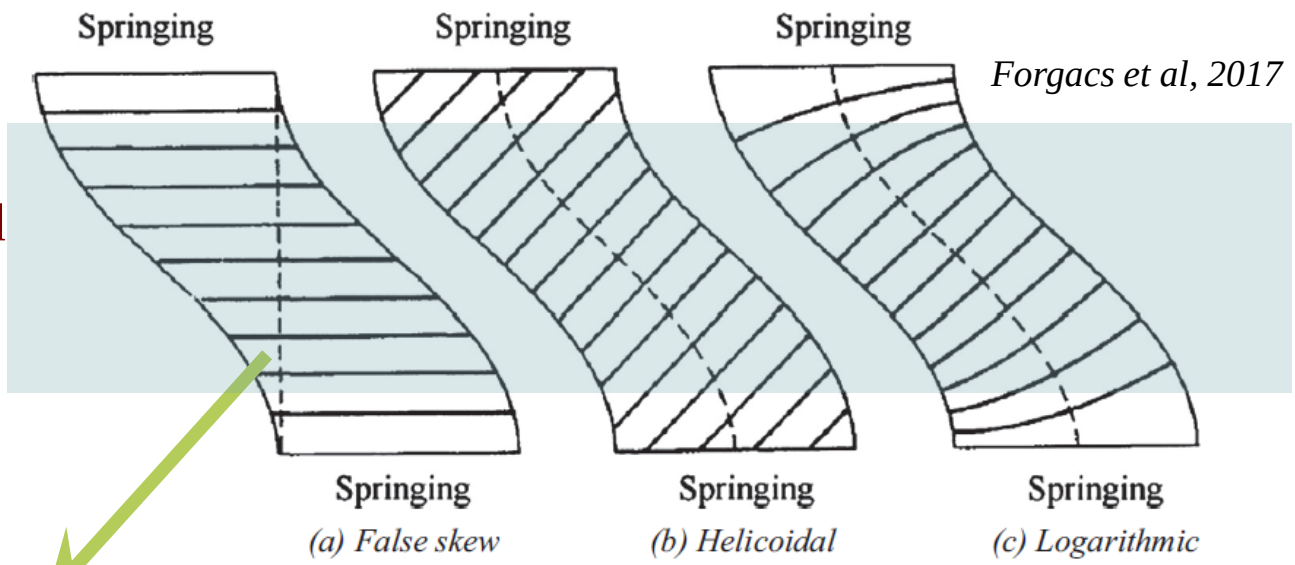
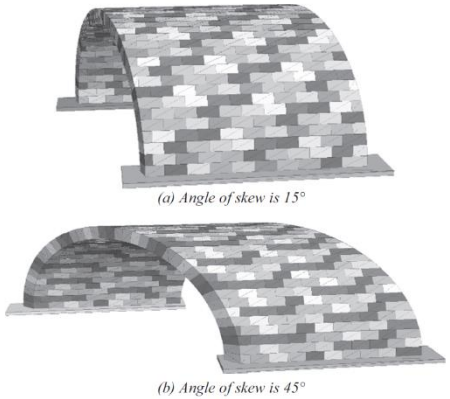



*Forgacs et al, 2017*



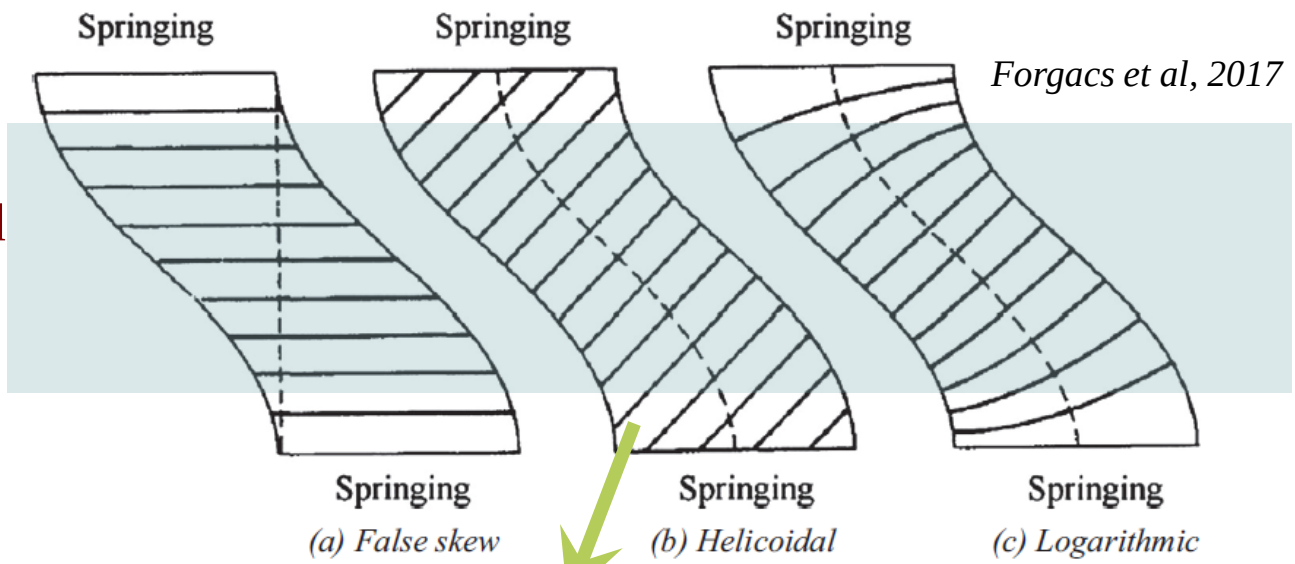

False skew constrution:

coursing joints parallel with the springings

# SKEW BARRELS

Construction geometries:

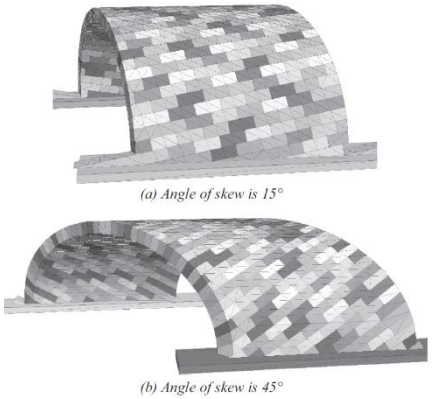
the developed surfaces:




*Forgacs et al, 2017*

Helicoidal construction:

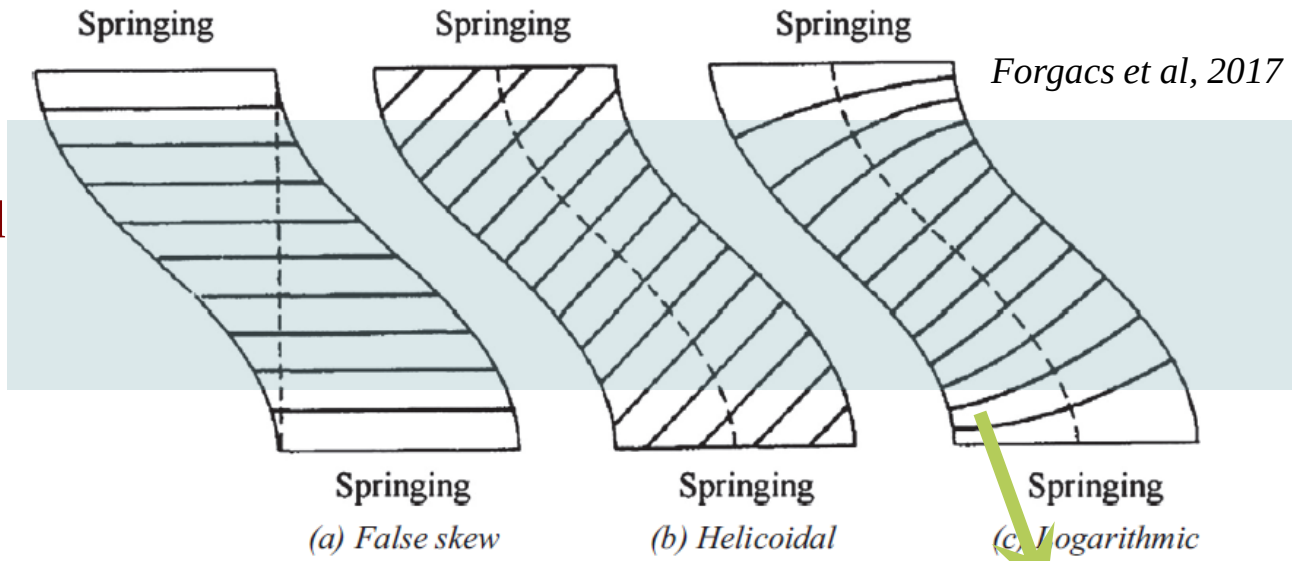
top coursing joints are ⊥ to the face; // to each other on the developed surface ⇒ same units



# SKEW BARRELS

Construction geometries:

the developed surfaces:

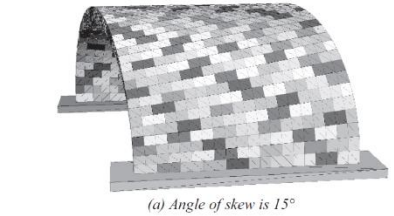



*Forgacs et al, 2017*

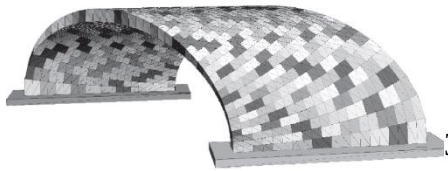
Logarithmic construction:

coursing joints are ⊥ to the arch face

⇒ units are different, unique shapes



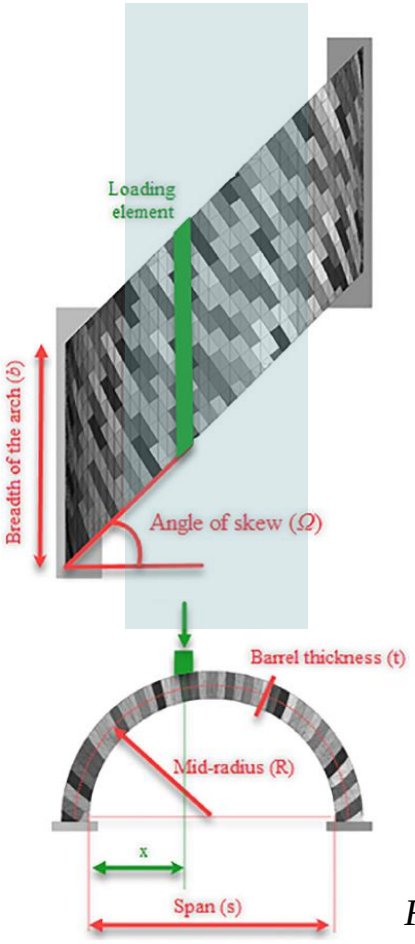
*(a) Angle of skew is 15°*

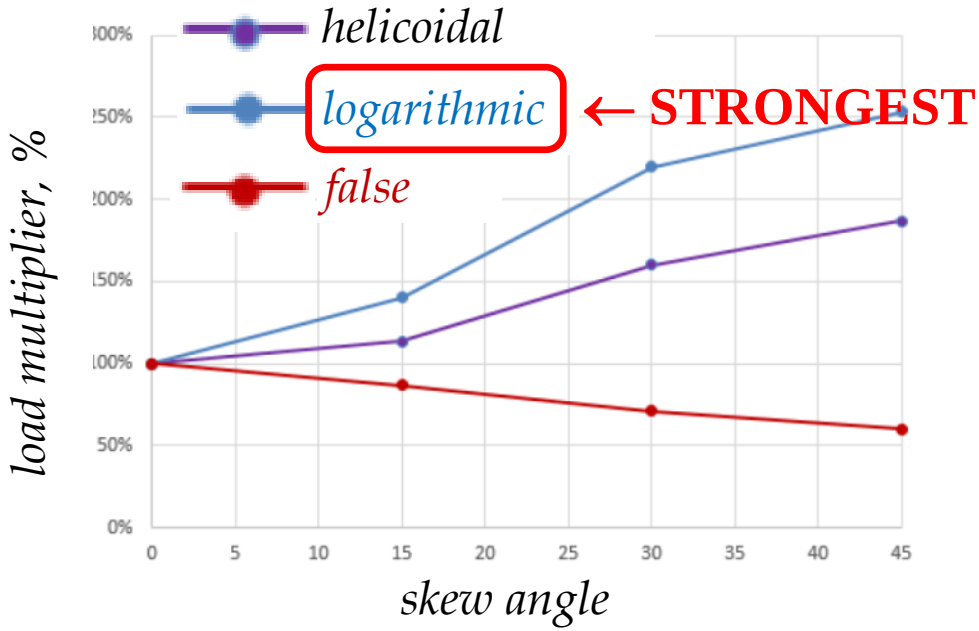


# SKEW BARRELS

Construction geometries:

Load bearing capacity:



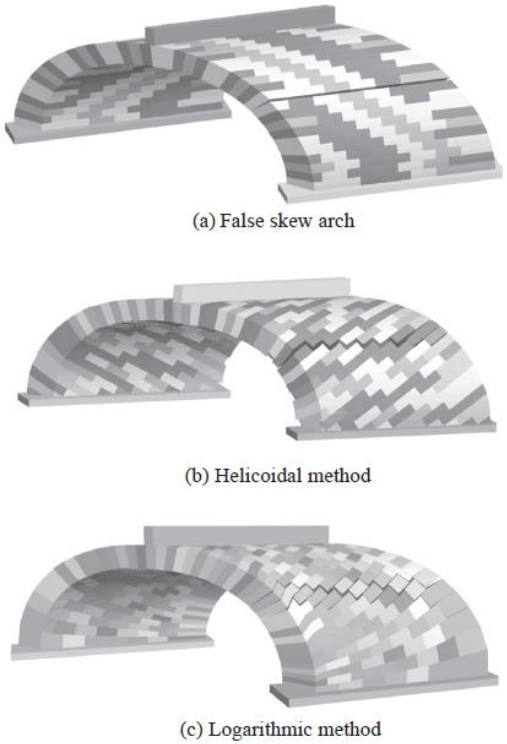




*Forgacs et al, 2018*

# SKEW BARRELS

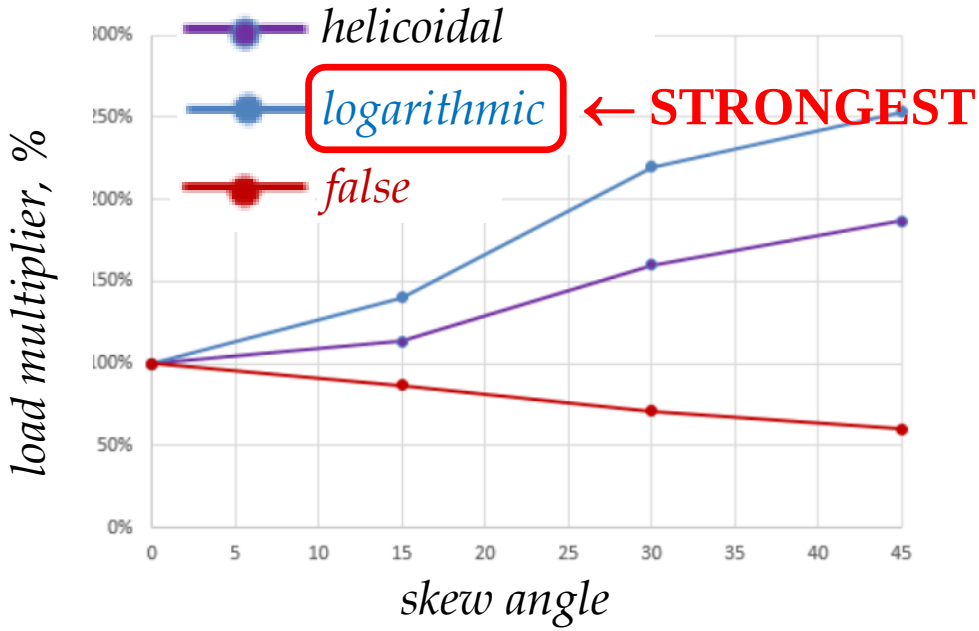
Construction geometries:

Failure mode:


(a) False skew arch

(b) Helicoidal method

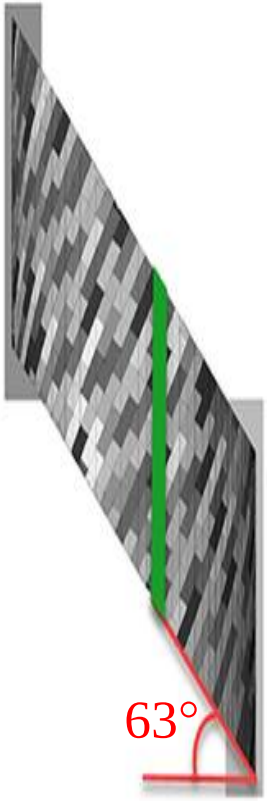
(c) Logarithmic method




Final conclusion: Skew barrels can be STRONGER than straight barrels!

# SKEW BARRELS

VERY skew bridge: Monkhide bridge, designed: Stephen Ballard, 1843;
over the canal Hereford to Gloucester, helicoidal, 63°




*Bill Harvey, http://billharvey.typepad.com*

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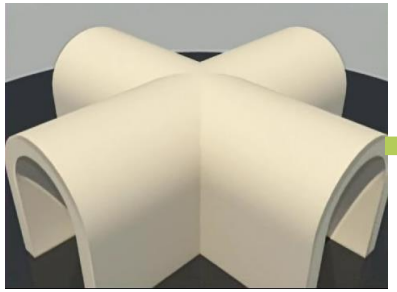
Questions

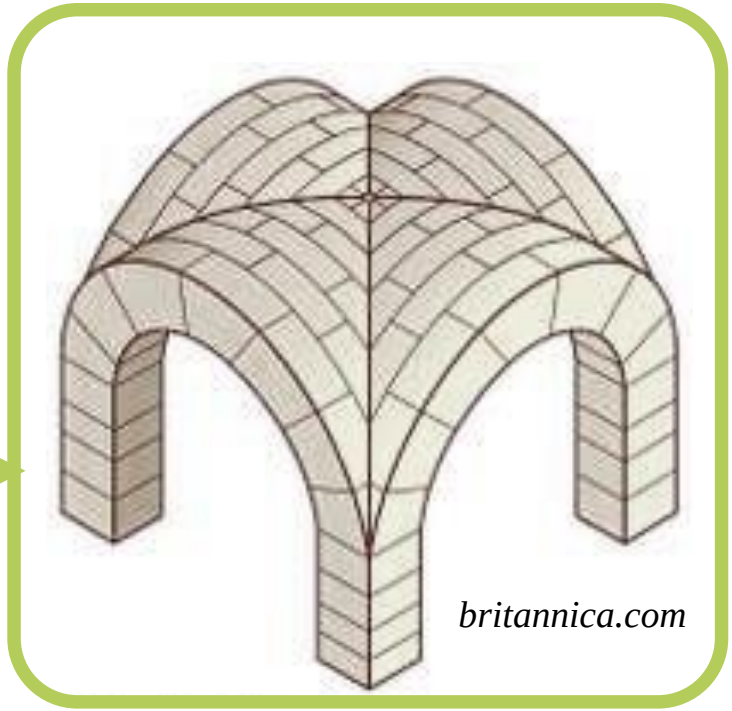
# CROSS VAULTS

What is a cross vault?

an open vault:

intersection of two barrel vaults

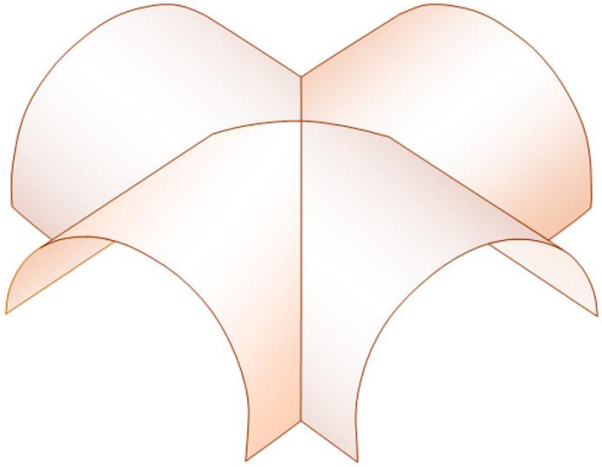





parabolic points + „creases” (groins)

# CROSS VAULTS

*http://www.lanera.com/casteldelmonte/cvtech_172/page-172-03.html*



Origin of cross vaulting:

→ earliest cross vault:

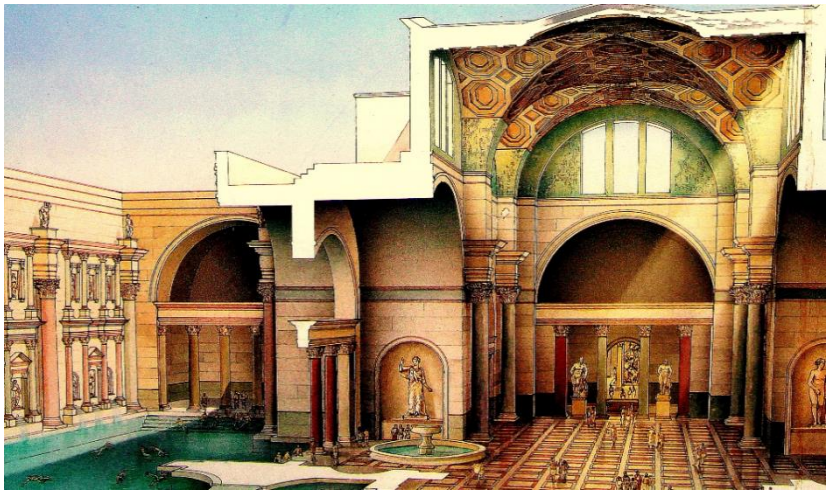
≈ 223 BC, in Delphi, Greece

→ Roman architecture: [ semicircular ]

public buildings: baths; churches

e.g. Baths of Caracalla: early IIIrd century AD [note: huge sizes]

*http://bathsofcaracallarome.blogspot.com/2014/08/how-baths-of-caracalla-were-built.html*



*https://www.photo.net/photo/17083092*

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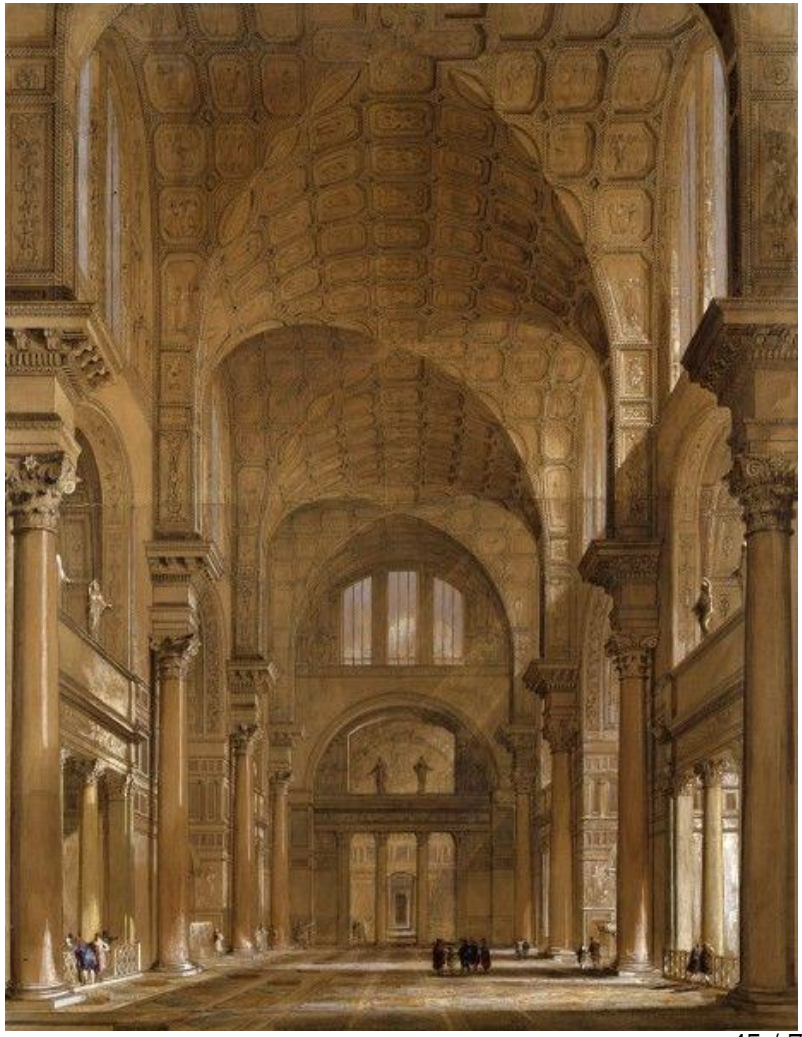

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*http://bathsofcaracallarome.blogspot.com/2014/08/how-baths-of-caracalla-were-built.html*

*https://en.wikipedia.org/wiki/Baths_of_Caracalla#Construction_%E2%80%93_216%E2%80%93235*

# CROSS VAULTS

Origin of cross vaulting:

→ European (Romanesque and) Gothic church architecture

Birth of Gothic architecture:

Basilica St Denis, France
(Abbot Suger, from ≈ 1135)

*https://www.bluffton.edu/homepages/facstaff/sullivanm/france/paris/stdenis/0128.jpg*

Fall of Gothic architecture:

Beauvais Cathedral, France
(1225…1573; two collapses)

*www.viafrance.com/en/beauvais/recommended-venues/cathedrale-saint-pierre-de-beauvais-p-55925*

# CROSS VAULTS

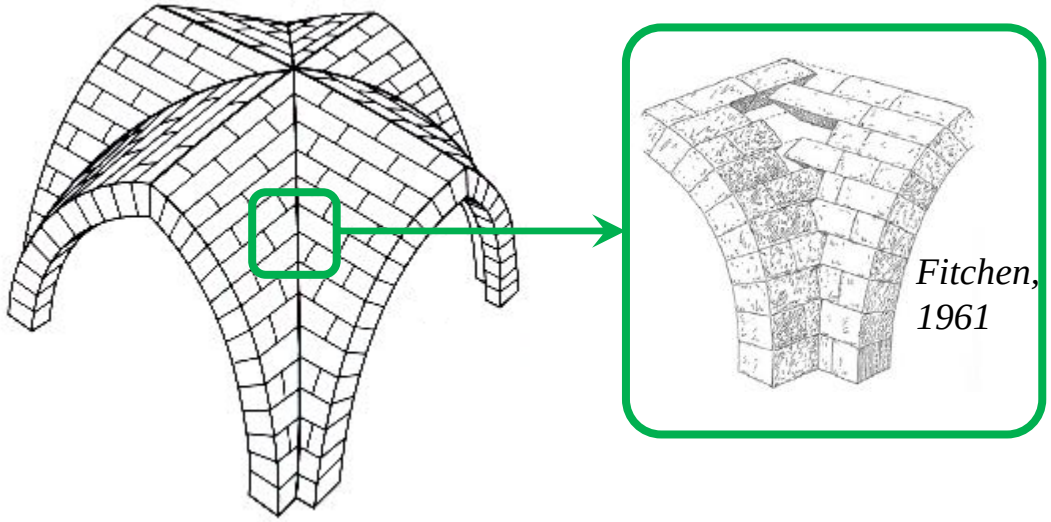
Main types of cross vaults:

→ unribbed („groin vault”):

construction:

centring is needed;

problem at groins




*slideplayer.com/slide/3986670/13*

→ ribbed („rib vault”):

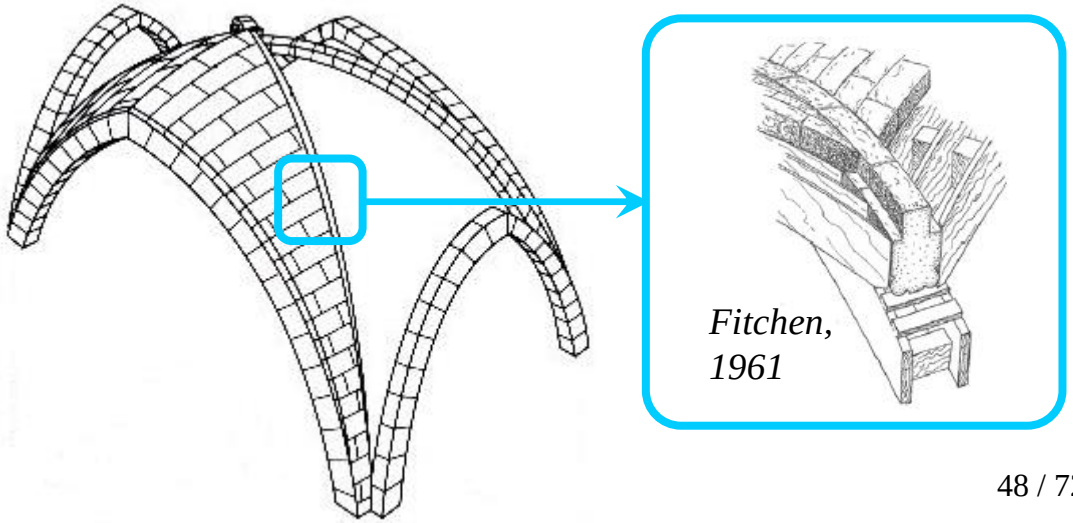
construction:

ribs on centring;

then simple centring

[ only planks ]

+ stress field smoothed

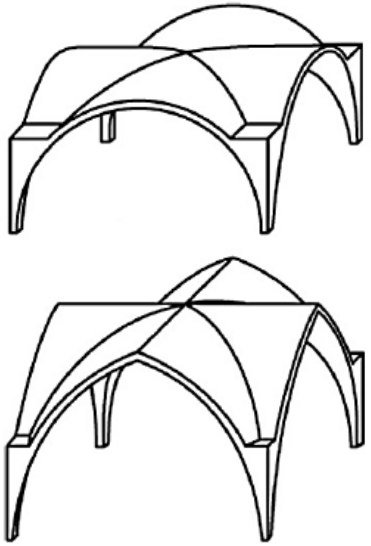


# CROSS VAULTS

Shape variations of cross vaults:

→ equal semicircular cylindrical barrels:

*Gaetani et al, 2015*



parabolic points

→ equal pointed cylindrical barrels:

→ higher at centre:

→ lower at centre:

elliptical points

MECHANICS:
← OPEN ISSUE

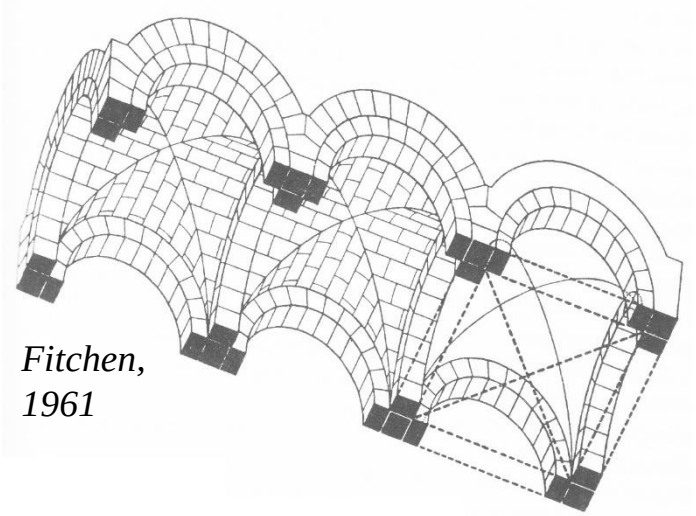
# CROSS VAULTS

Bond patterns:

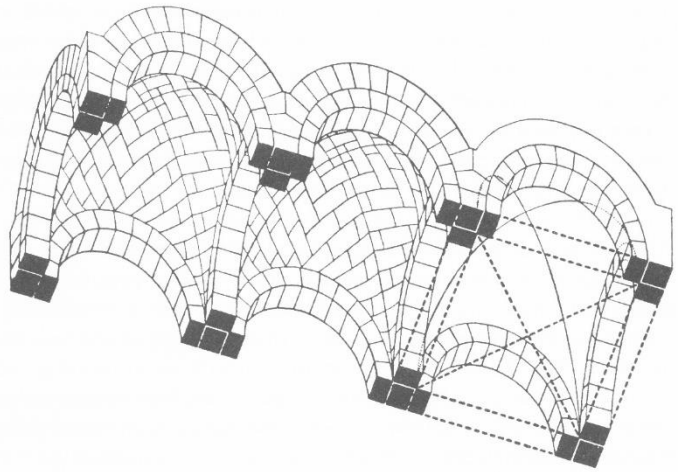
OPEN ISSUE: its mechanical effect?

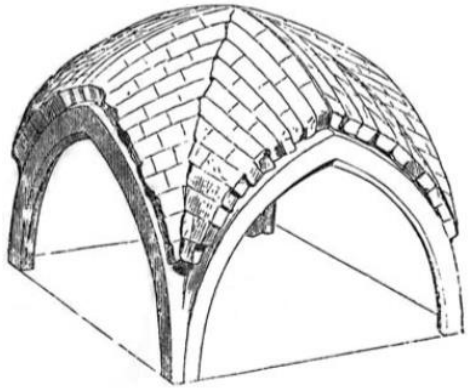
French coursing: [longitudinal]

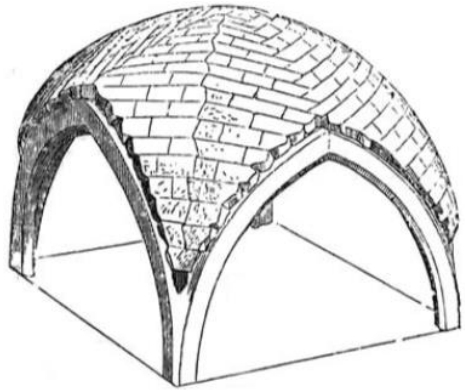
English coursing: [diagonal]



*Fitchen, 1961*



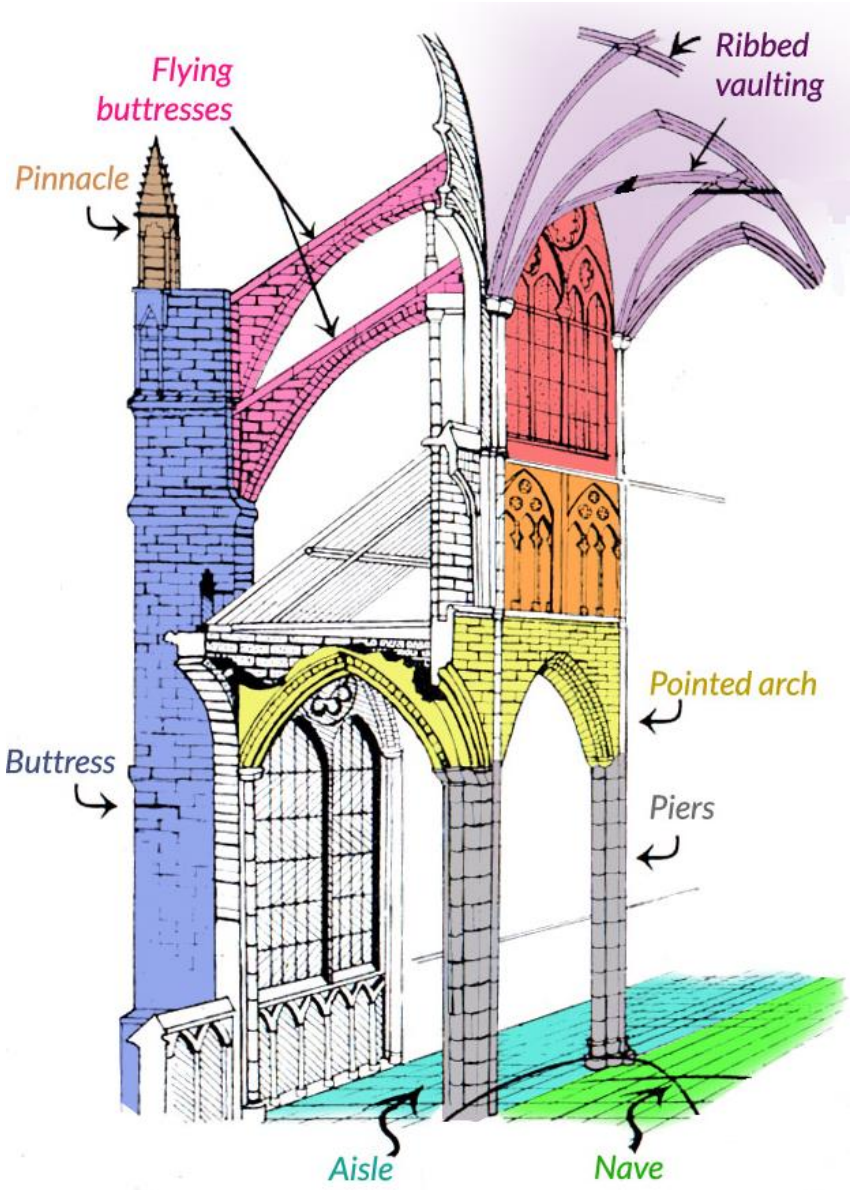




*Viollet-le-Duc, 1854–1868*

# CROSS VAULTS

Terminology:



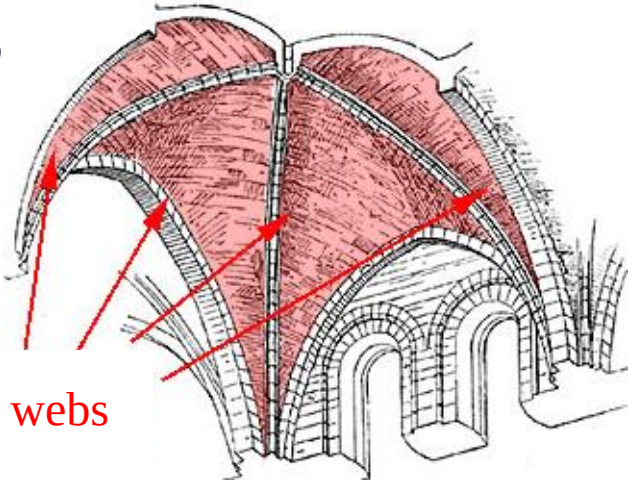

*http://www.culturaltravelguide.com/what-is-a-gothic-cathedral*

*pitt.edu/~medart/menuglossary/*

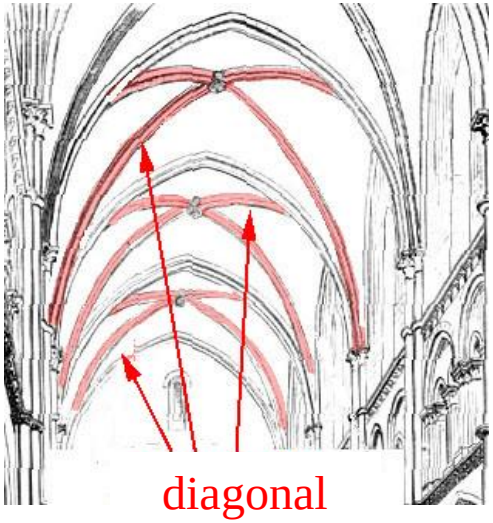
# CROSS VAULTS

Terminology:

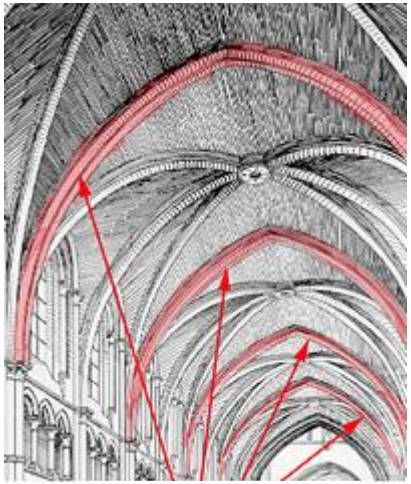
One bay:



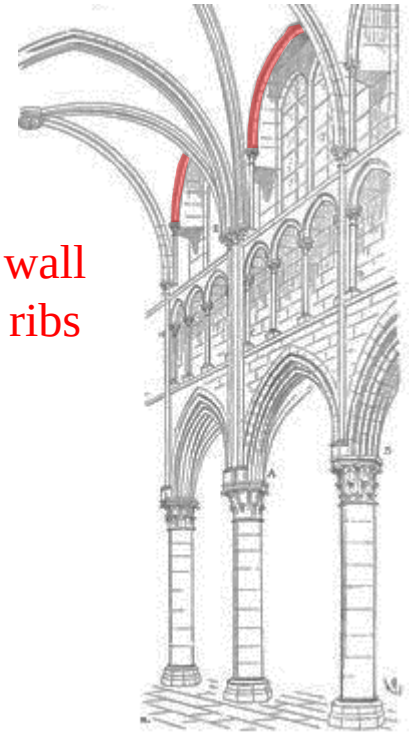
webs



diagonal ribs



transverse ribs



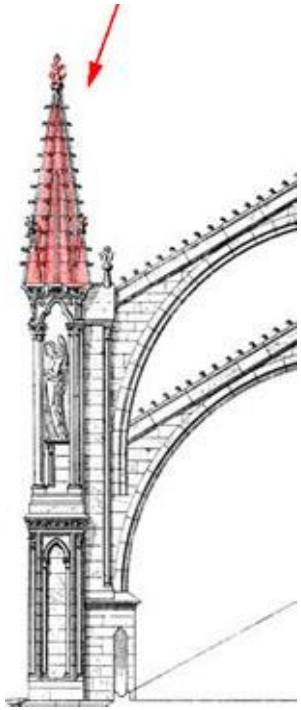
wall ribs

*pitt.edu/~medart/menuglossary/*

# CROSS VAULTS

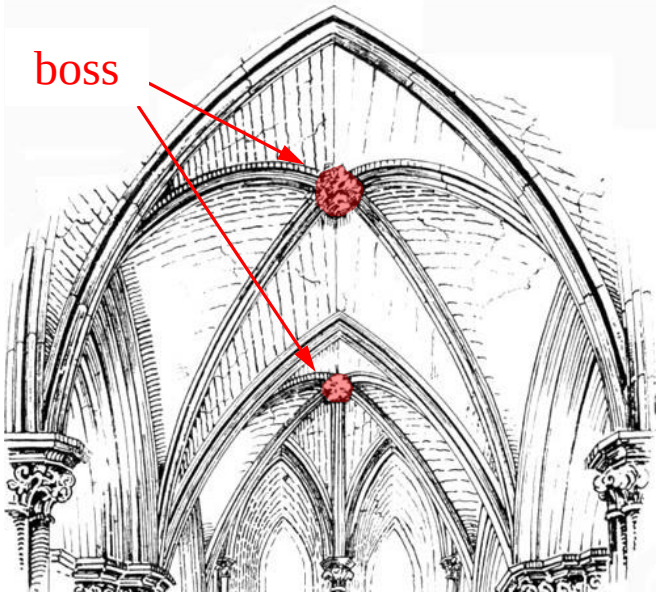
Terminology:

pinnacle



*http://www.victorianweb.org/art/architecture/gothic/vaulting.html*

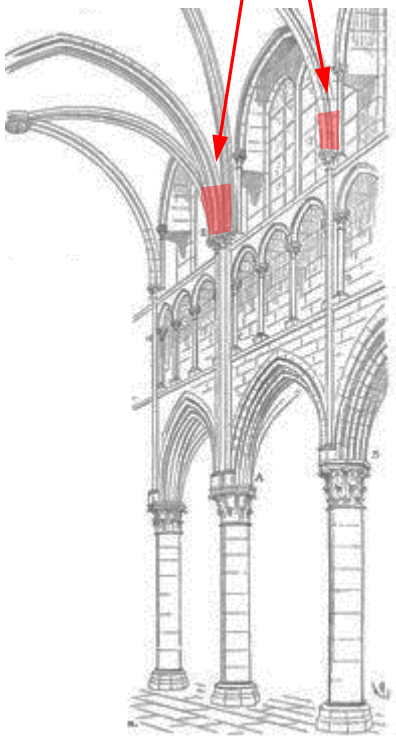
boss

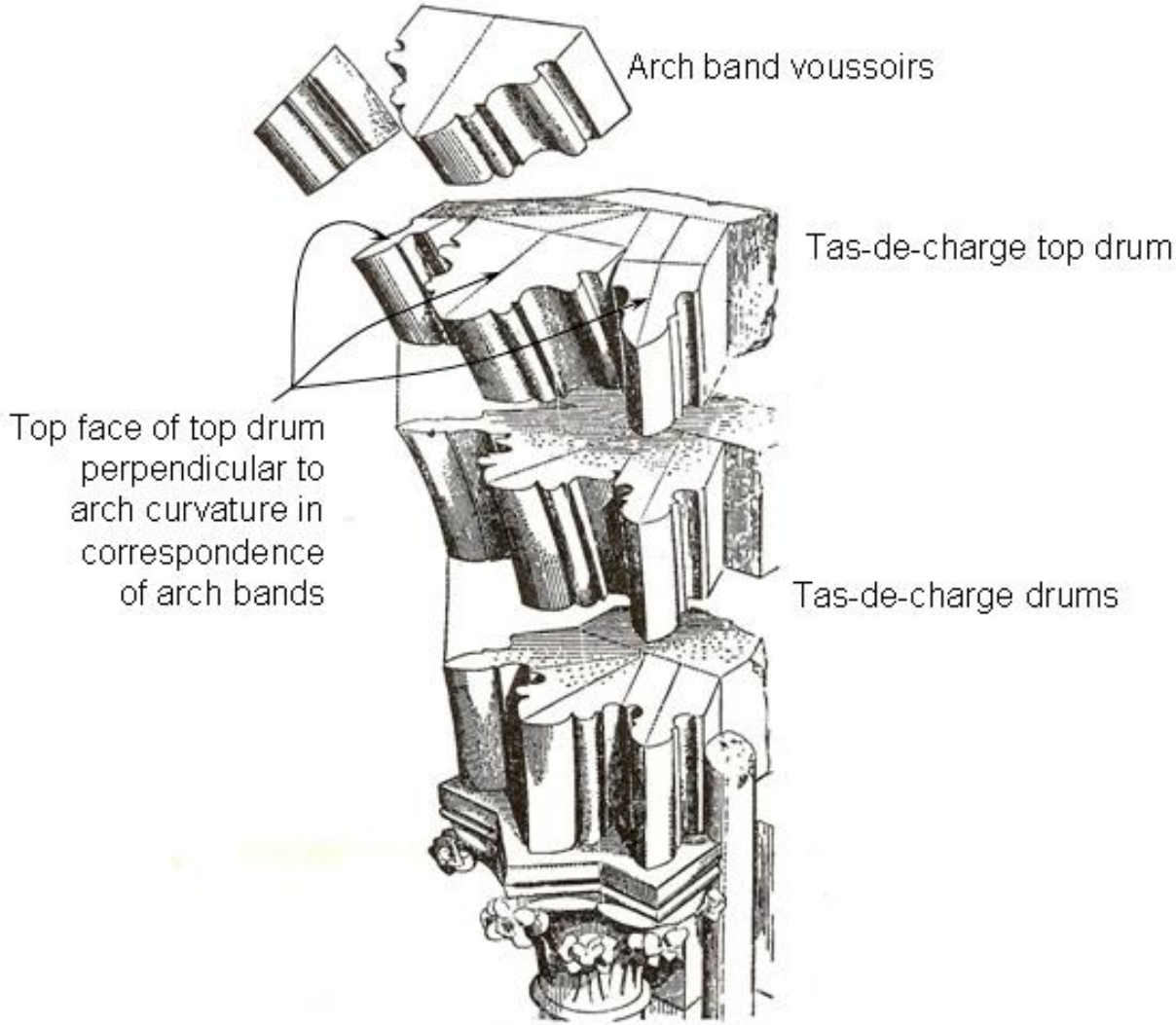


# CROSS VAULTS

Terminology:

tas-de-charge:






*lanera.com/casteldelmonte/cvtech_172/page-172-10.html*

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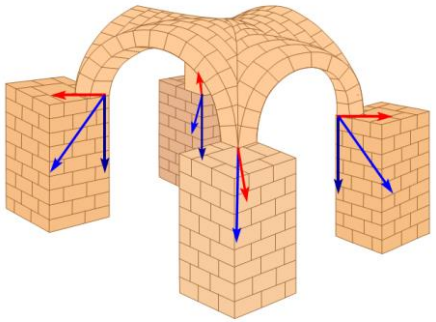
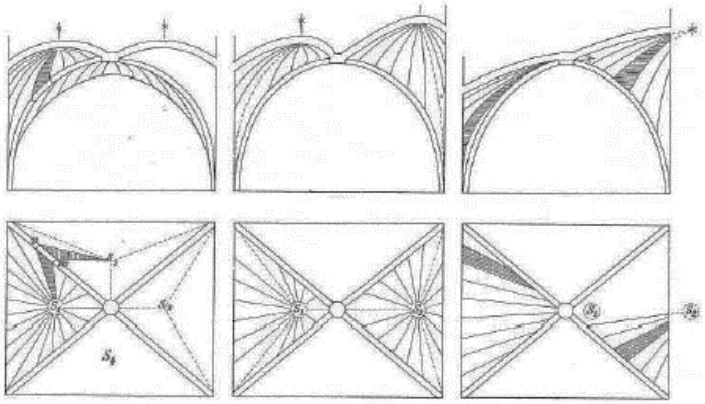
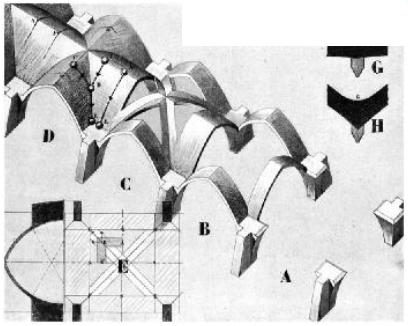


Internal forces in cross vaults:

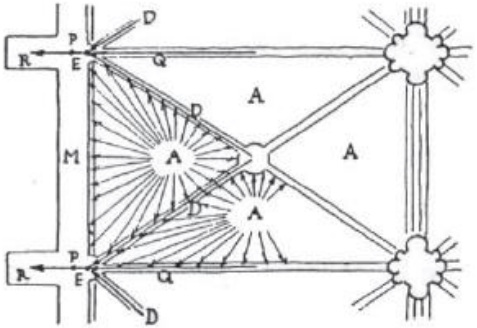
Theories:



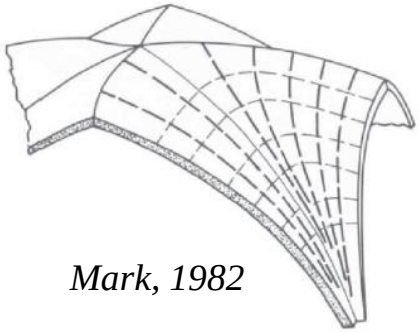
*Ungewitter, 1890*




*Abraham, 1934*




*Rave, 1939*



*Mark, 1982*

Role of ribs ???

decorative ↔ structural

(the shells carry the selfweight) (the ribs carry the shells)

# CROSS VAULTS

Internal forces in coss vaults: Lengyel&Bagi, 2015

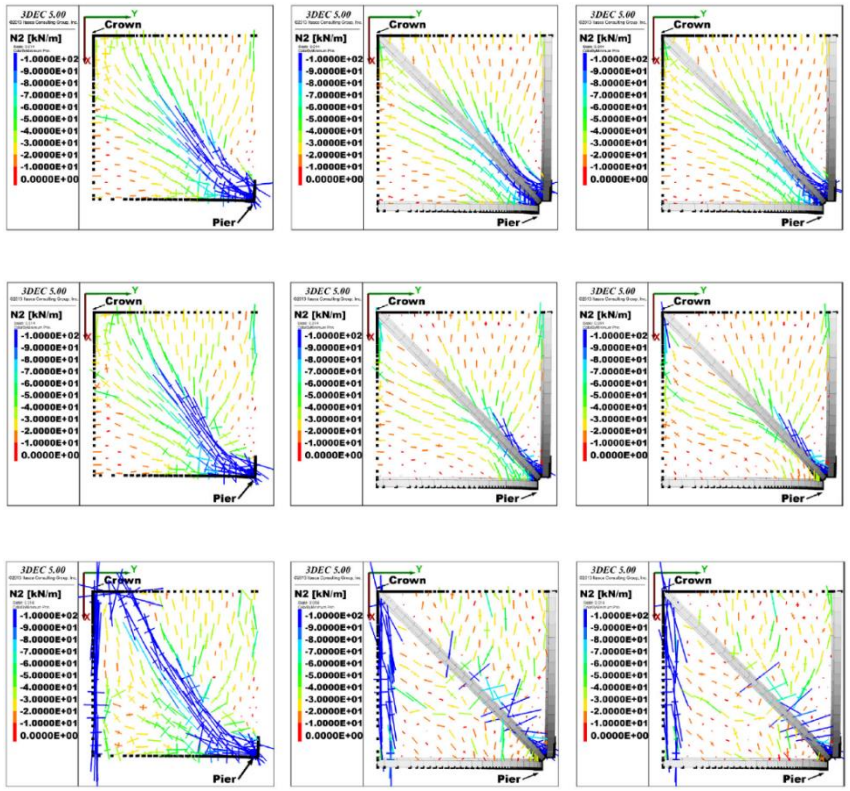
Outwards support displacement:

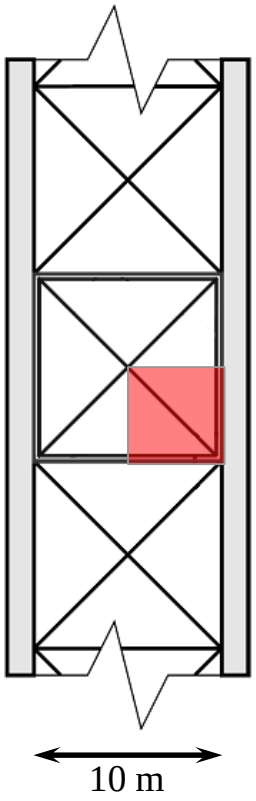
*NO RIB* *THIN RIB* *THICK RIB*

0 cm →

1 cm →

20 cm →



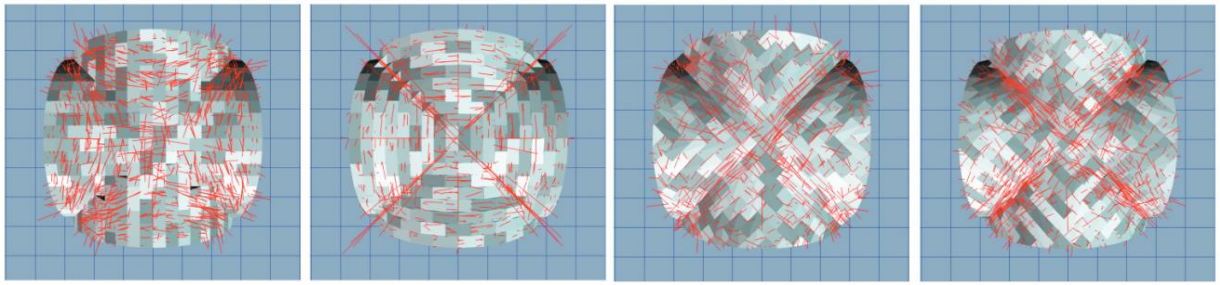

*Lengyel and Bagi, 2015: longitudinal patterns*

Suggested reading: Huerta (2009)

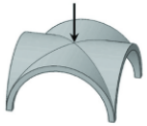
# CROSS VAULTS

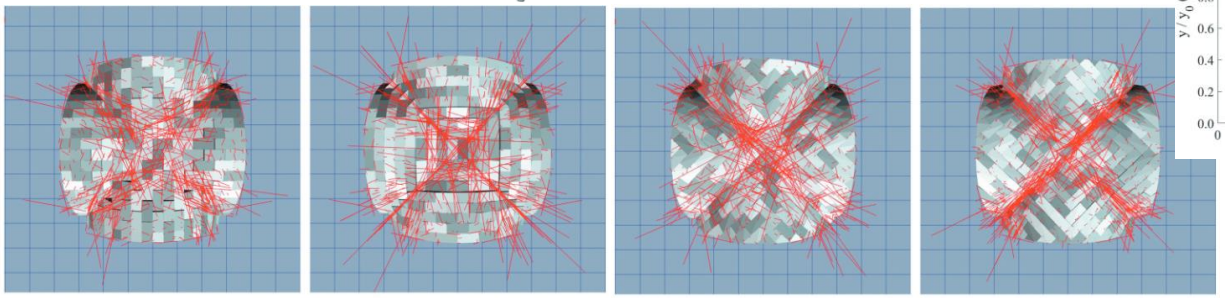
Internal forces in coss vaults: Boni et al, 2021

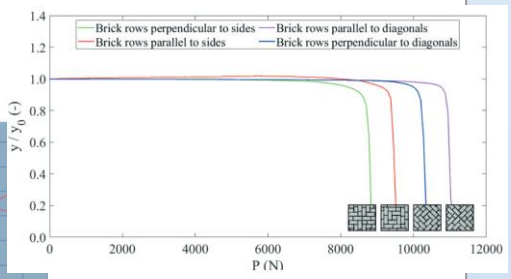
Selfweight only:



Concentrated force:







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Questions

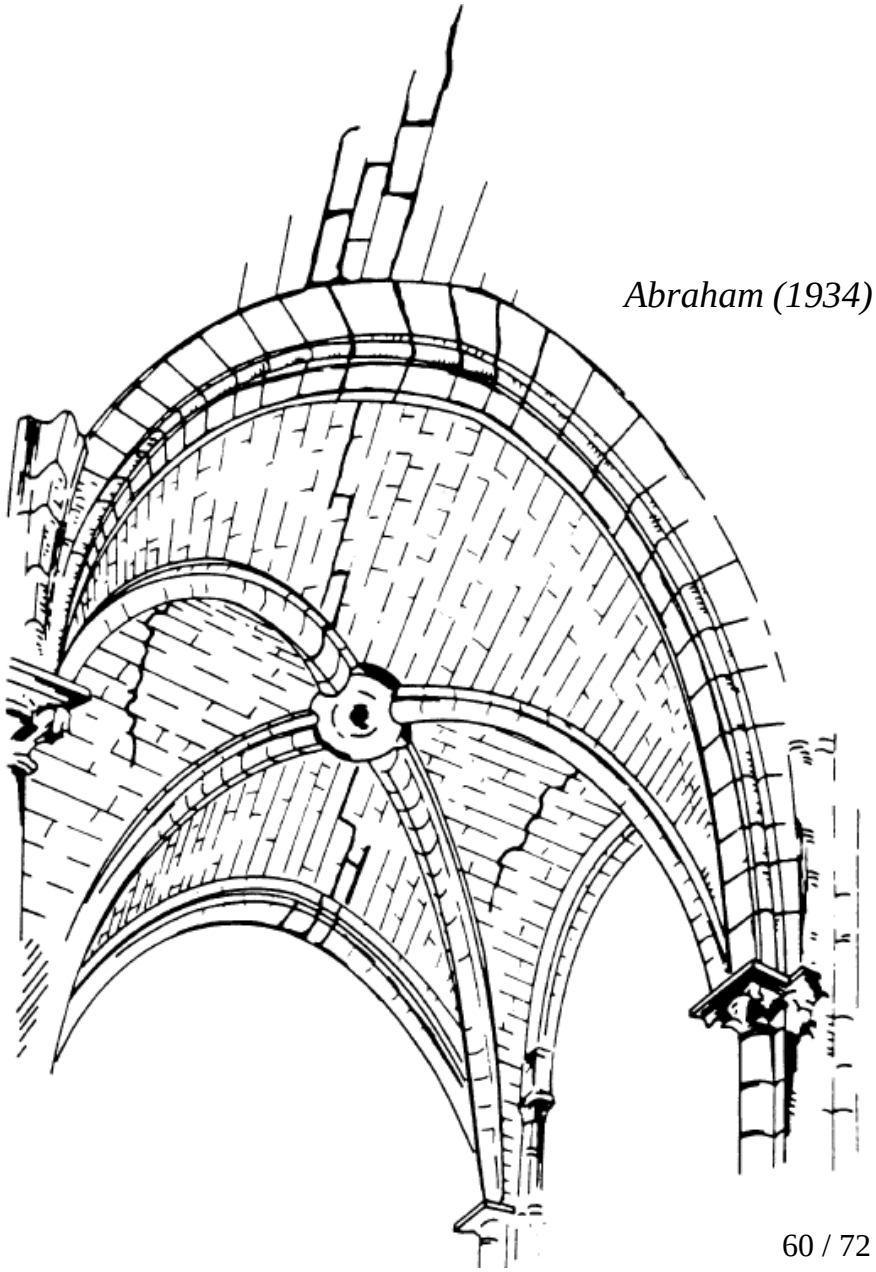
# CROSS VAULTS

Characteristic crack patterns:

(1) Longitudinal hinging cracks near the crown

(2) Sabouret's cracks

(3) Complete separation from the lateral walls



*Abraham (1934)*

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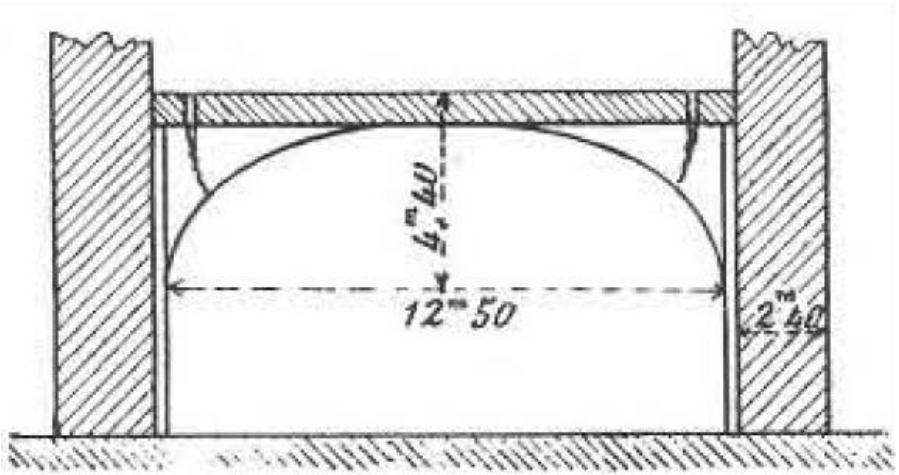
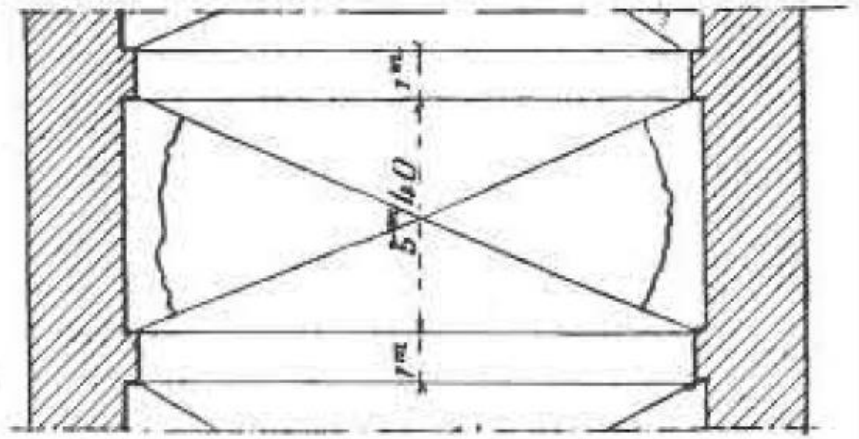
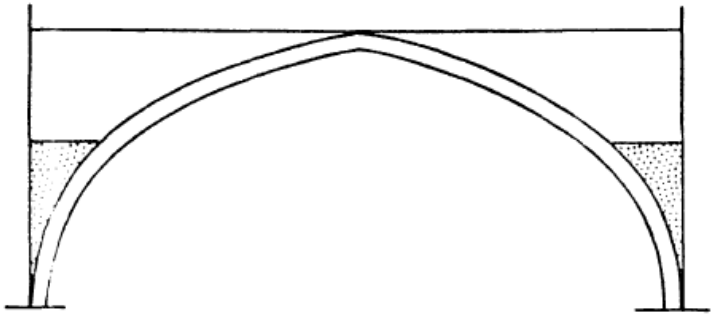


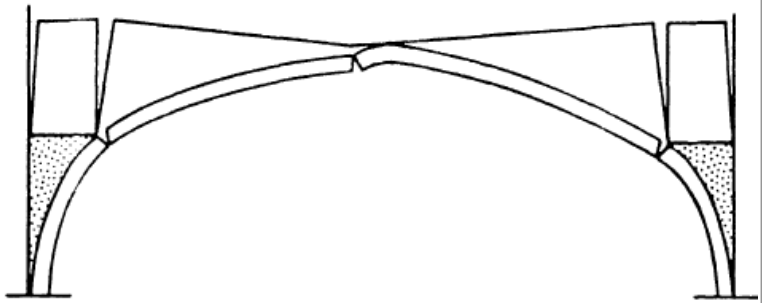



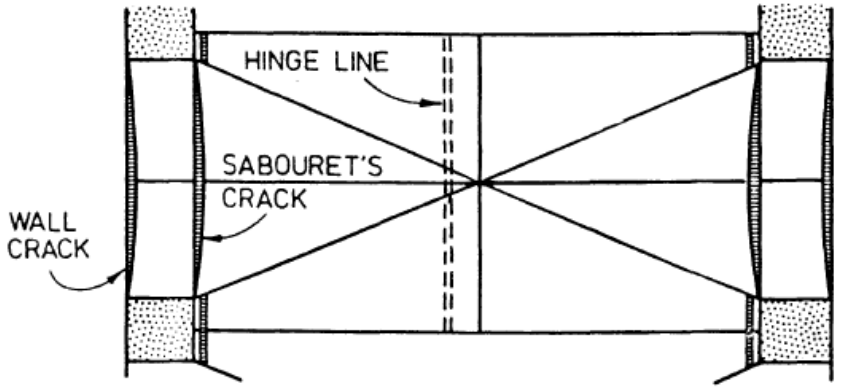

*Sabouret (1928)*

# CROSS VAULTS

*Heyman (1983)*








Characteristic crack patterns:

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(3) Complete separation from the lateral walls

*McInerney and DeJong (2015)*

# CROSS VAULTS

Strengthening:

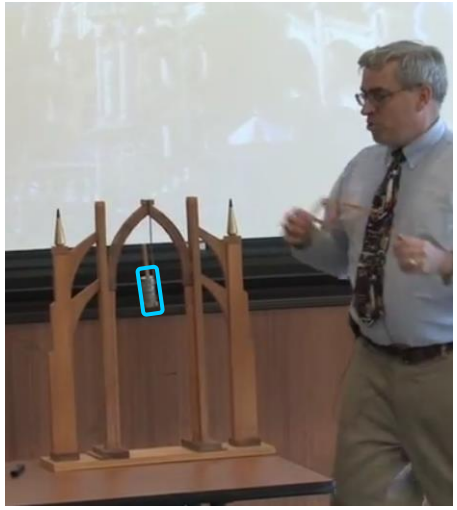
REMEMBER:

→ buttresses:

now place at the transverse arches

→ flying buttresses:

now place at the transverse arches



*Ressler (2016)*

# CROSS VAULTS

Strengthening:

→ buttresses:

*Battle Abbey, Sussex, UK, alamy.com/stock-photo/wall-buttresses.html*

*Gloucester Cathedral, UK, alamy.com/stock-photo/stone-masonry-church-stonework-buttresses.html*

→ flying buttresses:

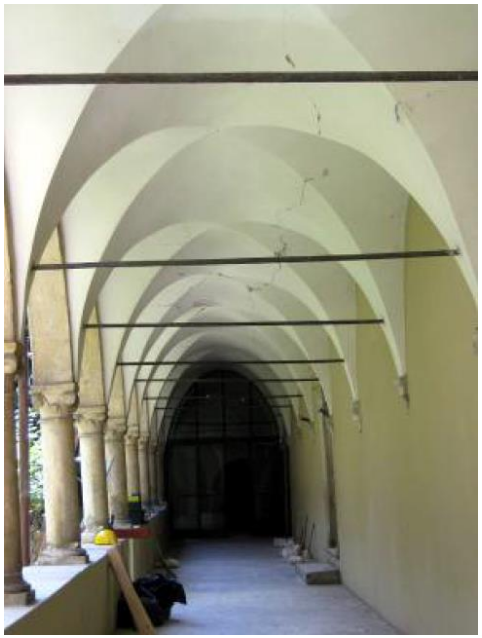
*Basilica St. Magdalene, Vezelay, France thoughtco.com/what-is-a-flying-buttress-4049089*

*juniorsbook.com/tell-me-why-numerous-questions-and-answers/what-is-a-flying-buttress/*

# CROSS VAULTS

Strengthening:

→ tension rods:



*Cloister of Beata Antonia in L'Aquila, UNIPD (2010)*

→ FRP strips:

grid arrangement

annular arrangement

*Foraboschi (2004)*

**OPEN ISSUE!**

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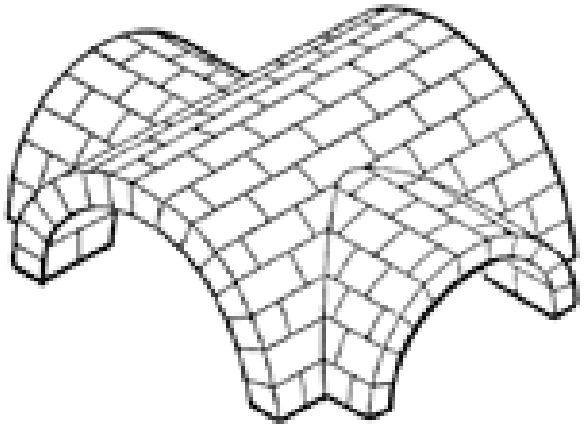
# UNDERPITCHED VAULTS

Definition: „Welsh vault” ;

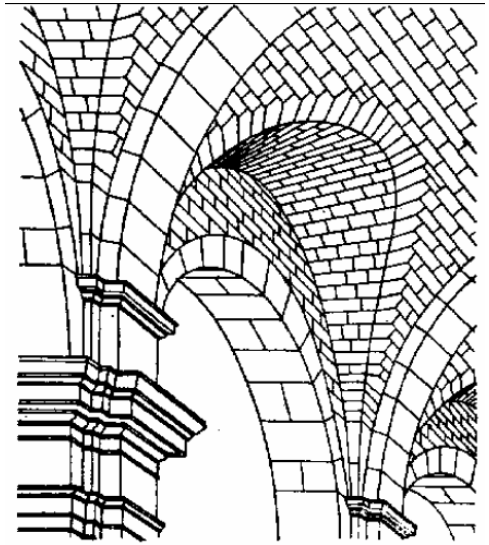
→ A construction formed by the penetration of two barrel vaults of unequal size, springing from the same level

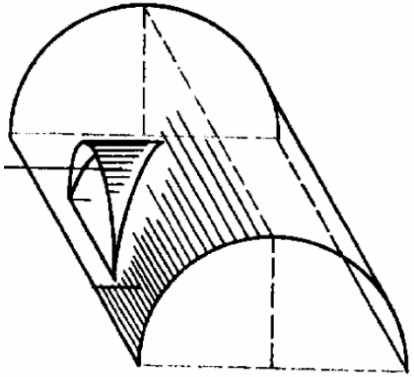
→ A barrel vault intersected by lower vaults

first appeared: Roman Empire; spread: XVI.-XVIII. century Europe



*encyclopedia2.thefreedictionary.com*





*Floor structures. Building Construction I., http://15123.fa.cvut.cz/*

hardly any analysis of the mechanics! → OPEN ISSUE

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spread: XVI.-XVIII. century Europe

*Cathedral of the Immaculate (Bosa, Italy) wikimapia.org/ 31232881/Interior-of-the-Cathedral-of-the-Immaculate*

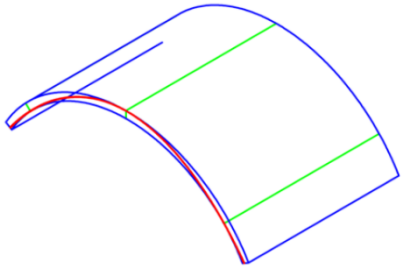
*Church of St. Agnes, Lublin, Poland lublinarchitecture.pollub.pl/?p=514*

hardly any analysis exist on the mechanics! → OPEN ISSUE

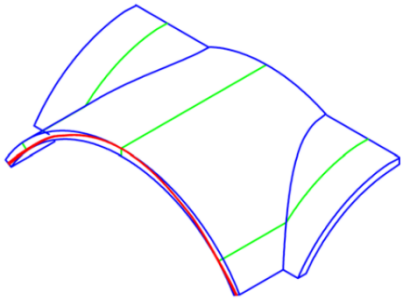
# UNDERPITCHED VAULTS

Crack patterns:

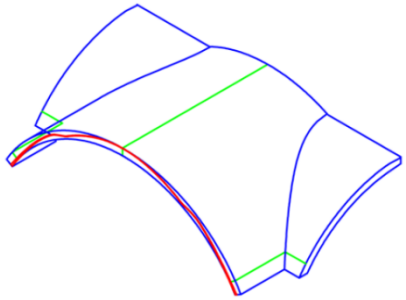
Holzer, 2013: (FEM & LSA)



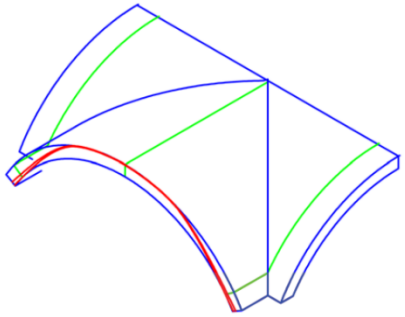
barrel vault



underpitched vault: pattern assuming that the lunettes can crack vertically (≈ Sabouret)



underpitched vault: pattern assuming that the lunettes stick to the main barrel, rotating with it, and separate from their bottom part



cross vault

# SUGGESTED VIDEOS

https://study.com/academy/lesson/barrel-vault-definition-construction-architecture.html (elementary)

https://study.com/academy/lesson/the-development-of-vaulting-in-architecture.html (elementary)

https://www.youtube.com/watch?v=VaEiUkTWG9Y (introduction to Guastavino vaulting, John Ochsendorf, 1:30:05)

https://www.youtube.com/watch?v=r-tG68WvNDM&t=185s („Form and Forces", John Ochsendorf, 1:17:17)

https://www.youtube.com/watch?v=DI-leSI68dM (Jacques Heyman: The membrane analysis of thin masonry shells, 50:46)

https://www.youtube.com/watch?v=dhB0VhuKCUs (How flying buttress works)

https://www.khanacademy.org/humanities/medieval-world/gothic1 (Birth of the Gothic: Abbot Suger & ambulatory of St Denis, elementary)

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# QUESTIONS

1. Explain and illustrate the meaning of the following terms: ***barrel*** vault; ***crown***; ***free span***; ***rise***; ***pitched*** brick vaulting; ***course***; ***heading joint***; ***coursing joint***; ***skew*** barrel; ***cross*** vault / ***groin*** vault / ***ribbed*** cross vault; ***webs*** of a cross vault; ***transverse*** / ***diagonal*** / ***wall*** ribs; ***boss***; ***tas-de-charge***; ***underpitched*** (Welsh) vault; ***lunette***.

2. Introduce the ***typical crack pattern*** of a barrel vault standing on walls. What methods do you know to resist the ***lateral thrust*** ?

3. What is "tile vaulting" / "***Catalan vaulting***"?

4. What are the three main ***construction geometries for skew barrels***? Introduce them on small freehand drawings. How are they related to each other regarding ***load bearing capacity***?

5. Introduce the main types and shape variations of cross vaults. Introduce the ***French*** and the ***English*** bond pattern of cross vaults.

6. Introduce the ***typical crack patterns*** of cross vaults (three types). What methods do you know to protect a cross vault against cracking?