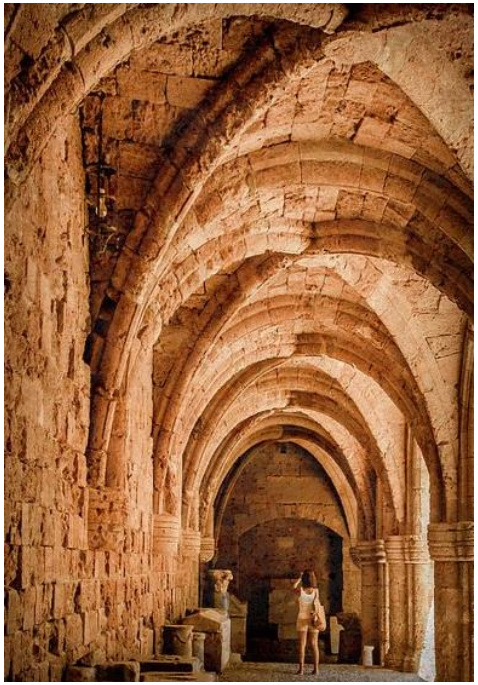


Barrel Vaults and Cross Vaults

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

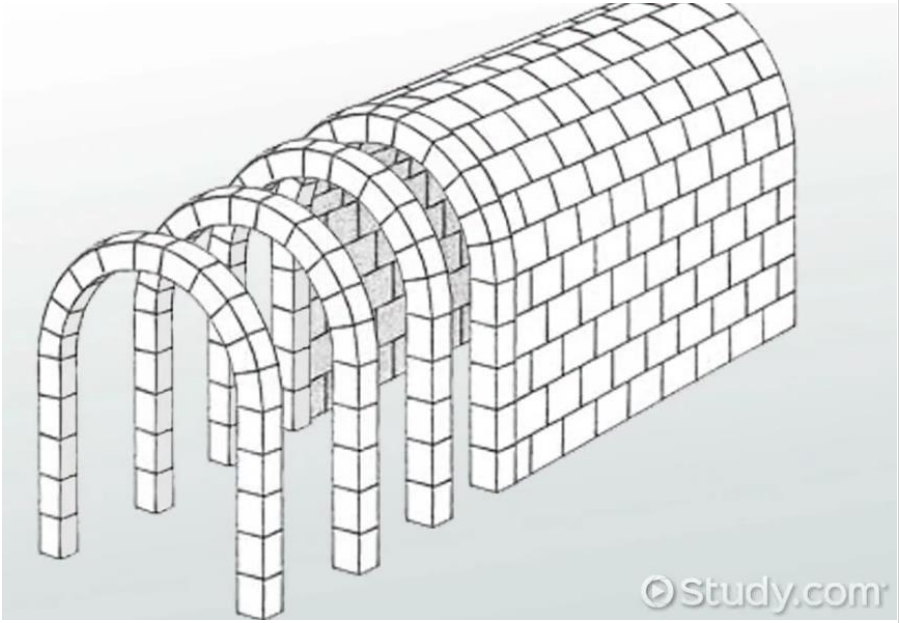
Cross Vaults

- → 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)

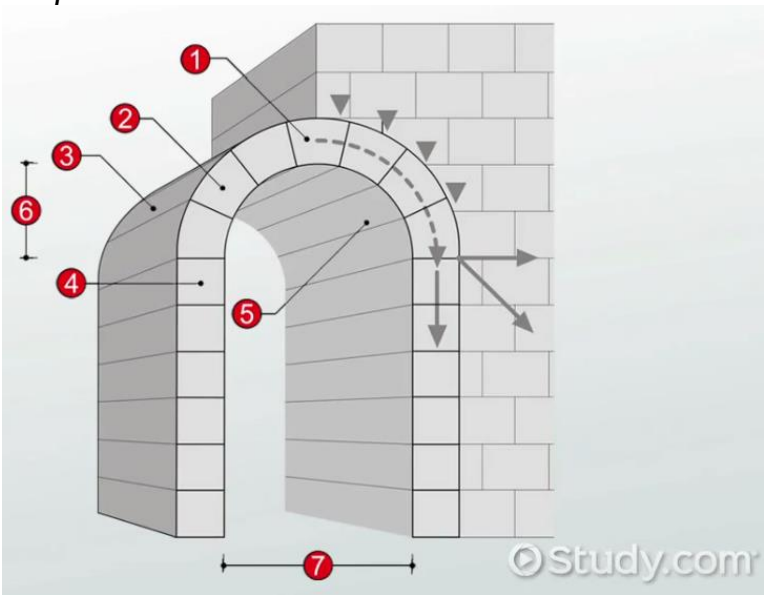
3: extrados (outer surface)

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

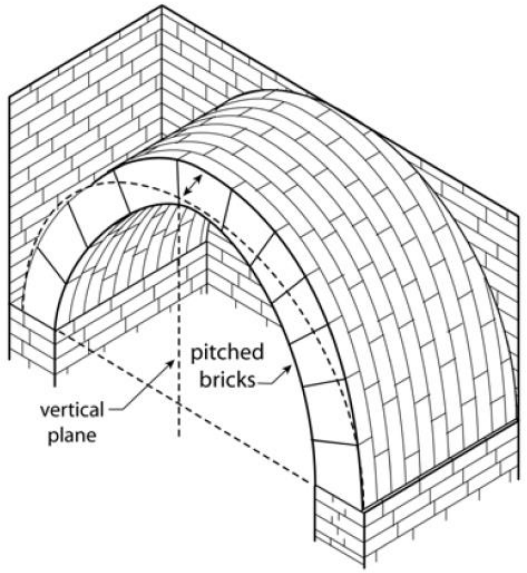
areas where wood was scarce [no centring]
gypsum mortar: → needs only 200 °C;
→ sets in minutes
mud brick (fired or sundried)

[Greeks hardly used]

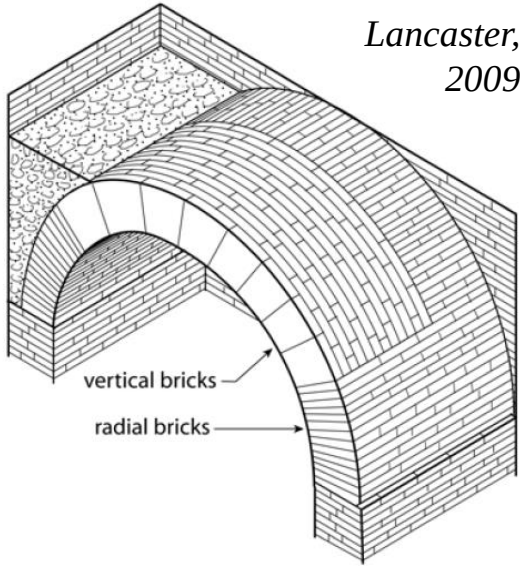
In the Roman empire:

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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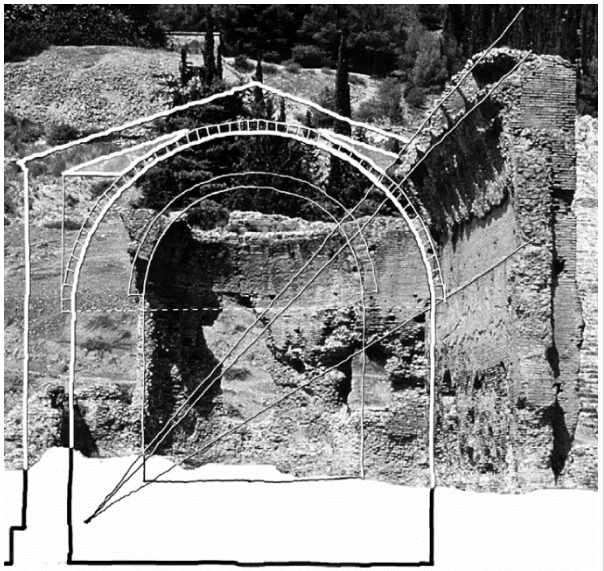


Lancaster (2006)

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:

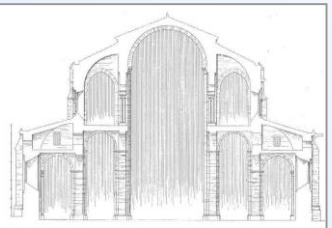
wikivisually.com/wiki/Aquae_Sulis

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”

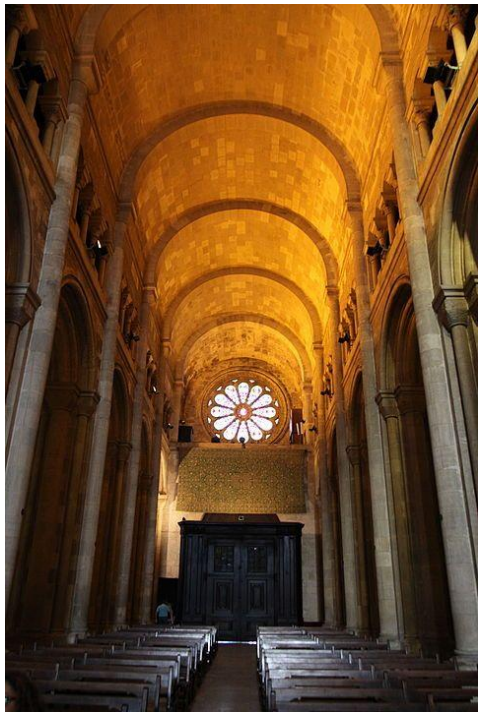
BARREL VAULTS

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:

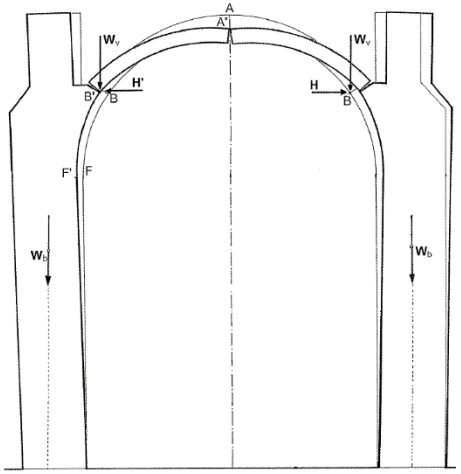
imagedatabase.st-andrews.ac.uk/images

the nave vault:

arts.st-andrews.ac.uk/corpusofscottishchurches

BARREL VAULTS

Huerta, 2010

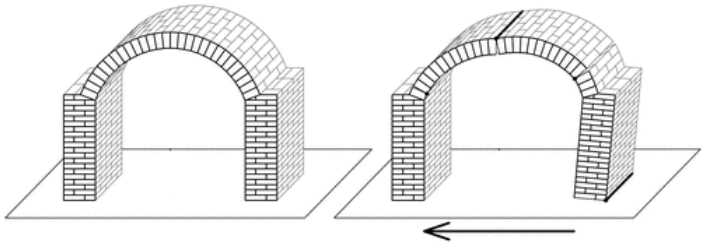


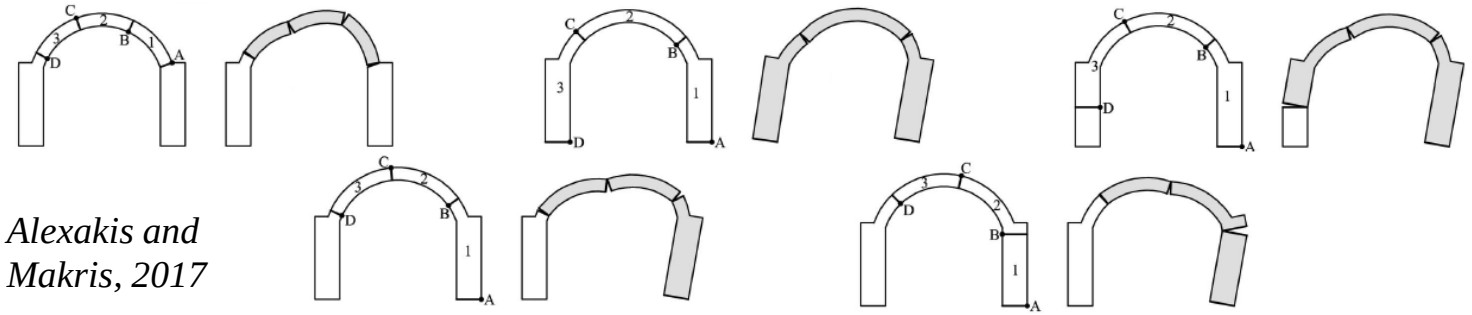
Cracking and failure modes

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?

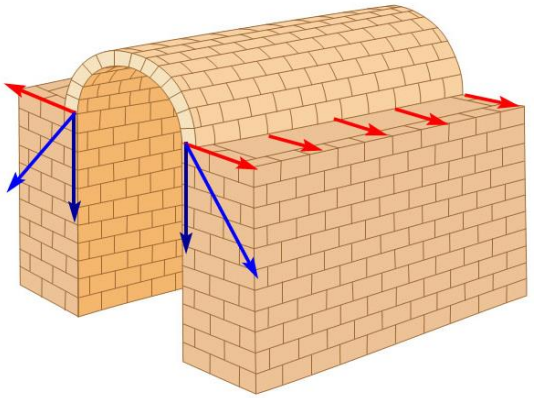
Underground or near-to-ground barrels:

→ 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

BARREL VAULTS

How to resist the lateral thrust?

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Freestanding barrel vaults on higher walls:

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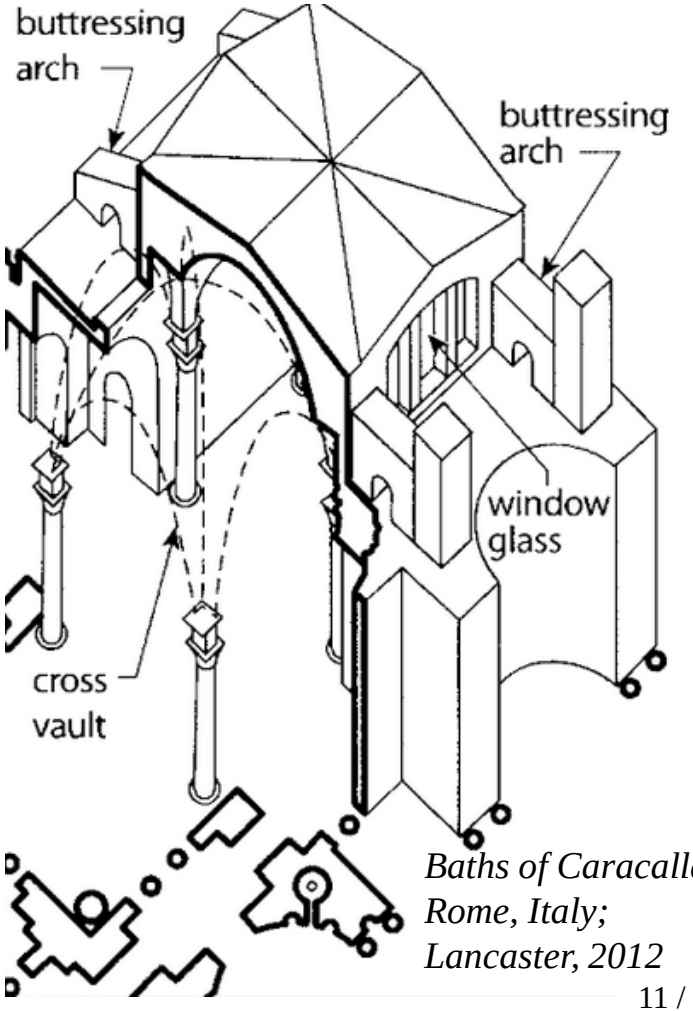
→ walls supported by buttresses:



Baths of Caracalla, Rome, Italy; Lancaster, 2012

BARREL VAULTS

How to resist the lateral thrust?

Underground or near-to-ground barrels:

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Freestanding barrel vaults on higher walls:

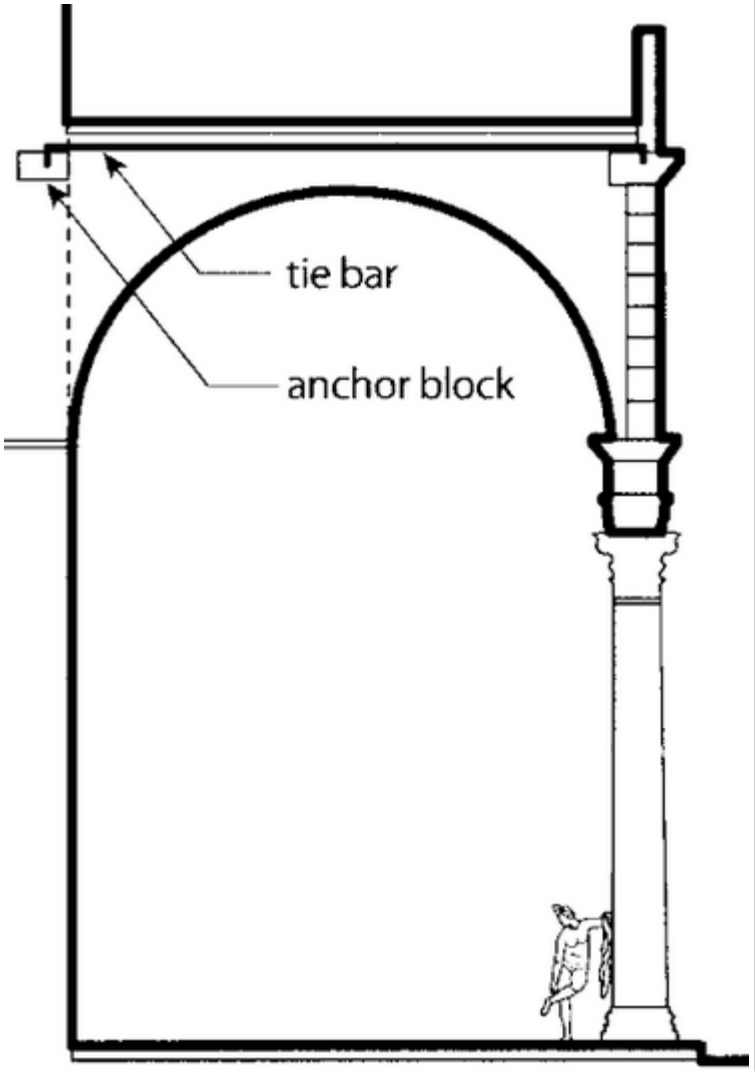
→ heavy, thick walls under the barrel

→ walls supported by buttresses

→ iron tie bars:

Roman invention,

from ≈ 2nd century AD



Lancaster, 2012

BARREL VAULTS

How to resist the lateral thrust?

Underground or near-to-ground barrels:

→ earth pressure ✓

Freestanding barrel vaults on higher walls:

→ heavy, thick walls under the barrel

→ 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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→ heavy, thick walls under the barrel

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→ make the vault easier

→ neighbouring barrels: [≈ arcade]

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

BARREL VAULTS

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→ make the vault easier

→ 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

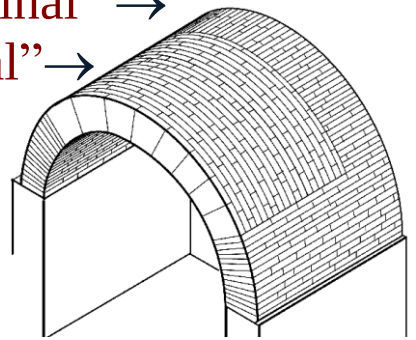
http://acedulado.pw/marble-revetment-definition: Basilica of Maxentius, ≈310 AD

→ crosswise barrels:

TOWARDS THE CROSS VAULT !

BARREL VAULTS

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



Lancaster, 2015

Constructional issues

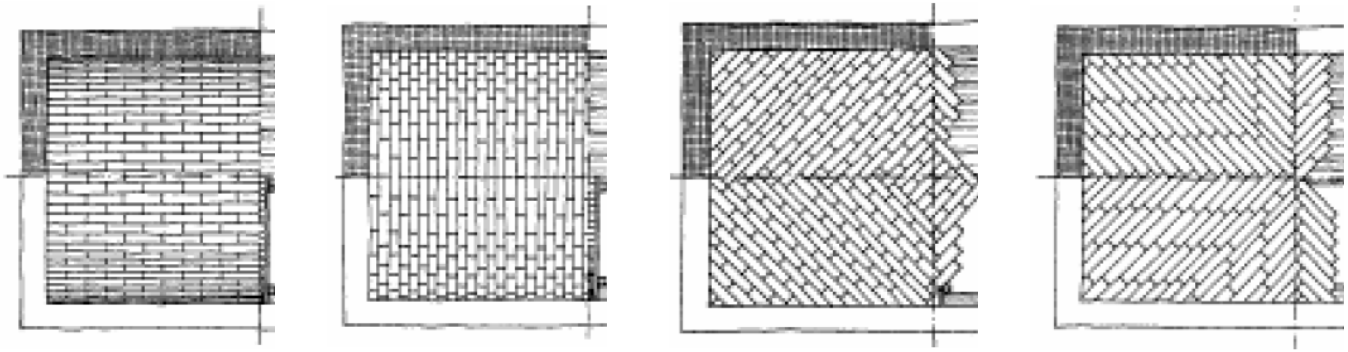
Terminology:

→ 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:

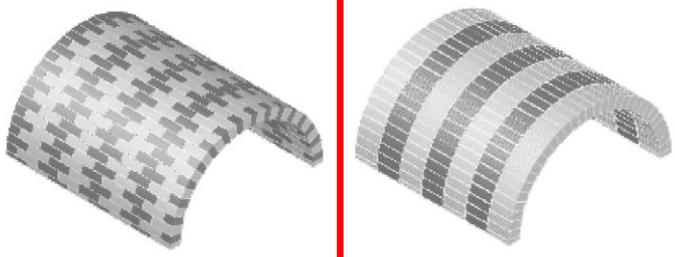


longitudinal vault | transversal vault | bone vault | inverted bone vault

Levi, 1932

BARREL VAULTS

STRONGER

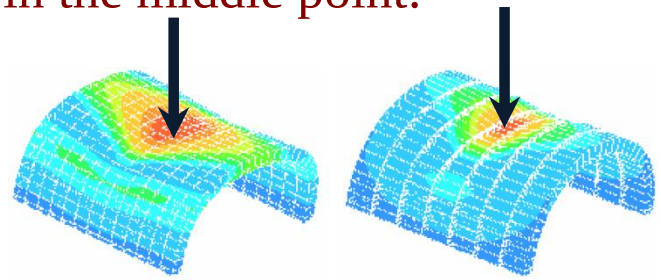


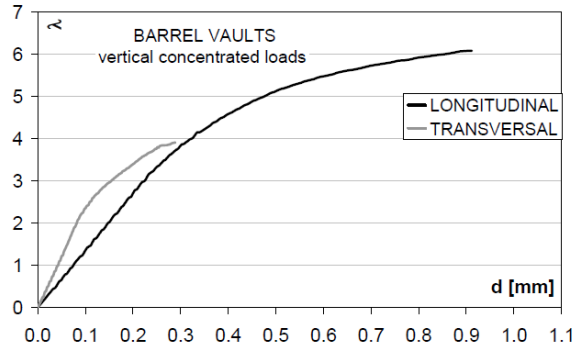
longitudinal *transversal*

Constructional issues

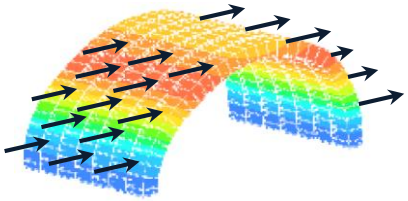
Romano & Grande (2008):

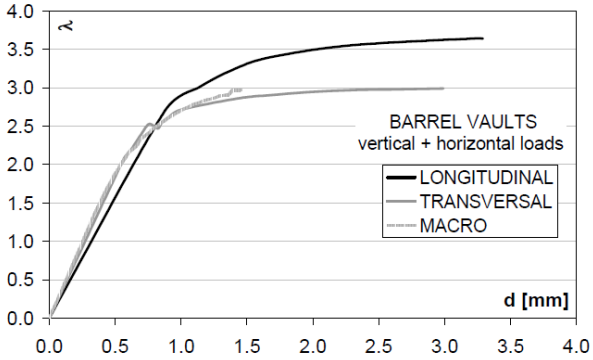
→ vertical concentrated load in the middle point:





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





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Barrel Vaults

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Vaults in General: Catalan Vaulting

Skew Barrels

Cross Vaults

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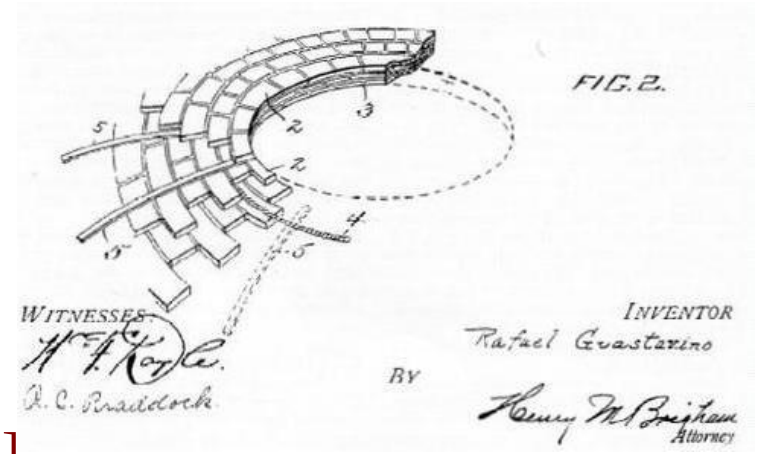
- → Forces in cross vaults
- → Crack patterns; Strengthening

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

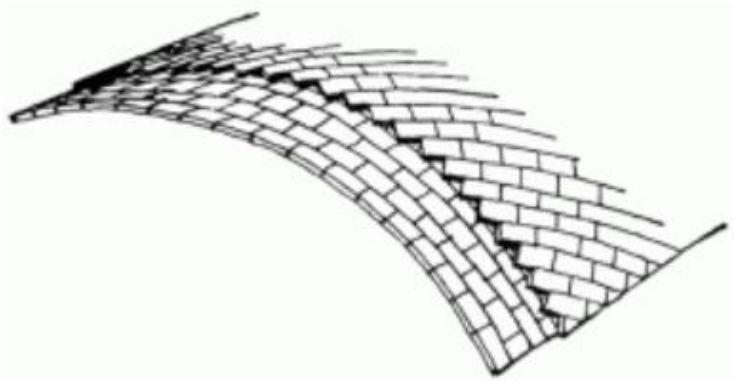
proceeding from bottom inwards ⇒

⇒ 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

Tile vaulting („Guastavino vault”,
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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

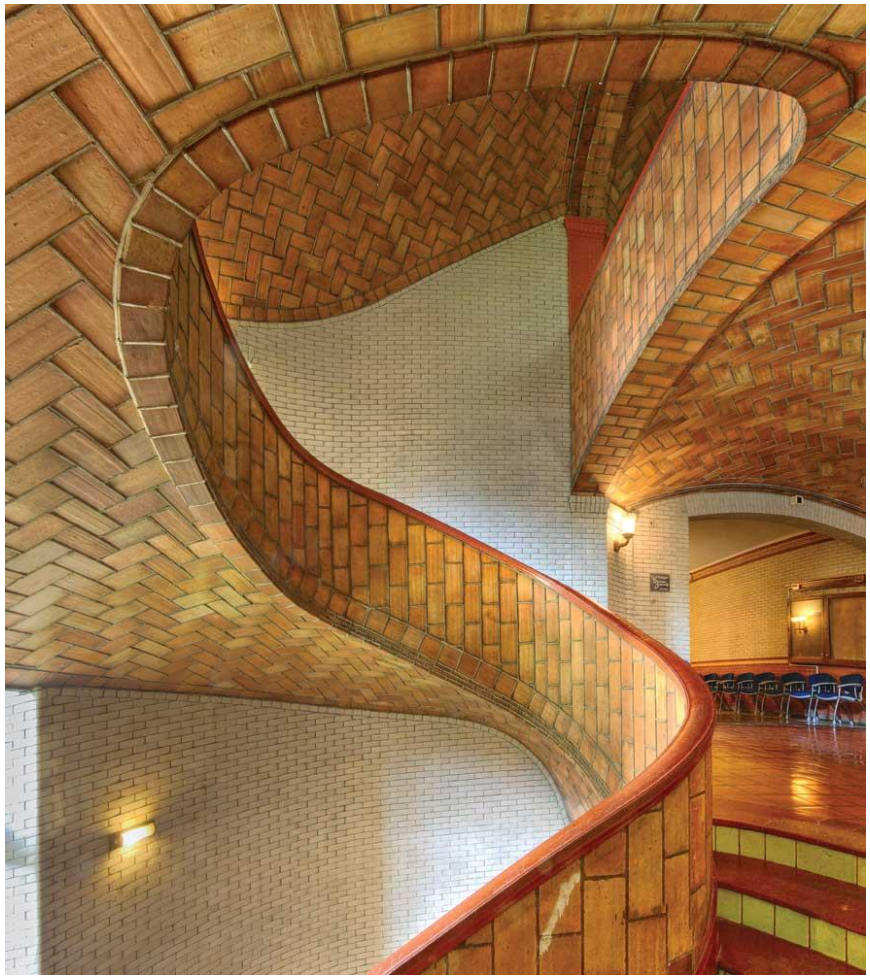
Constructional issues

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

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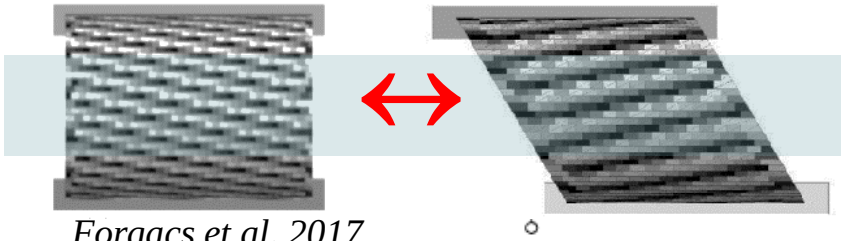
Questions

SKEW BARRELS

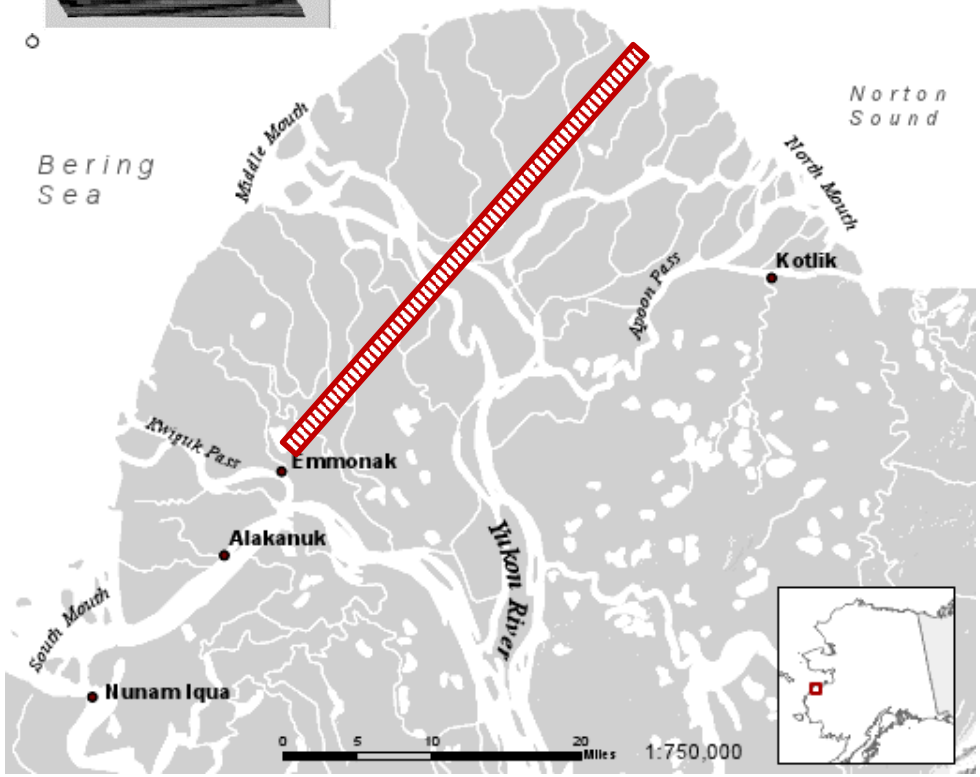
What is a skew barrel?

Top view:



Forgacs et al, 2017

Why not straight?

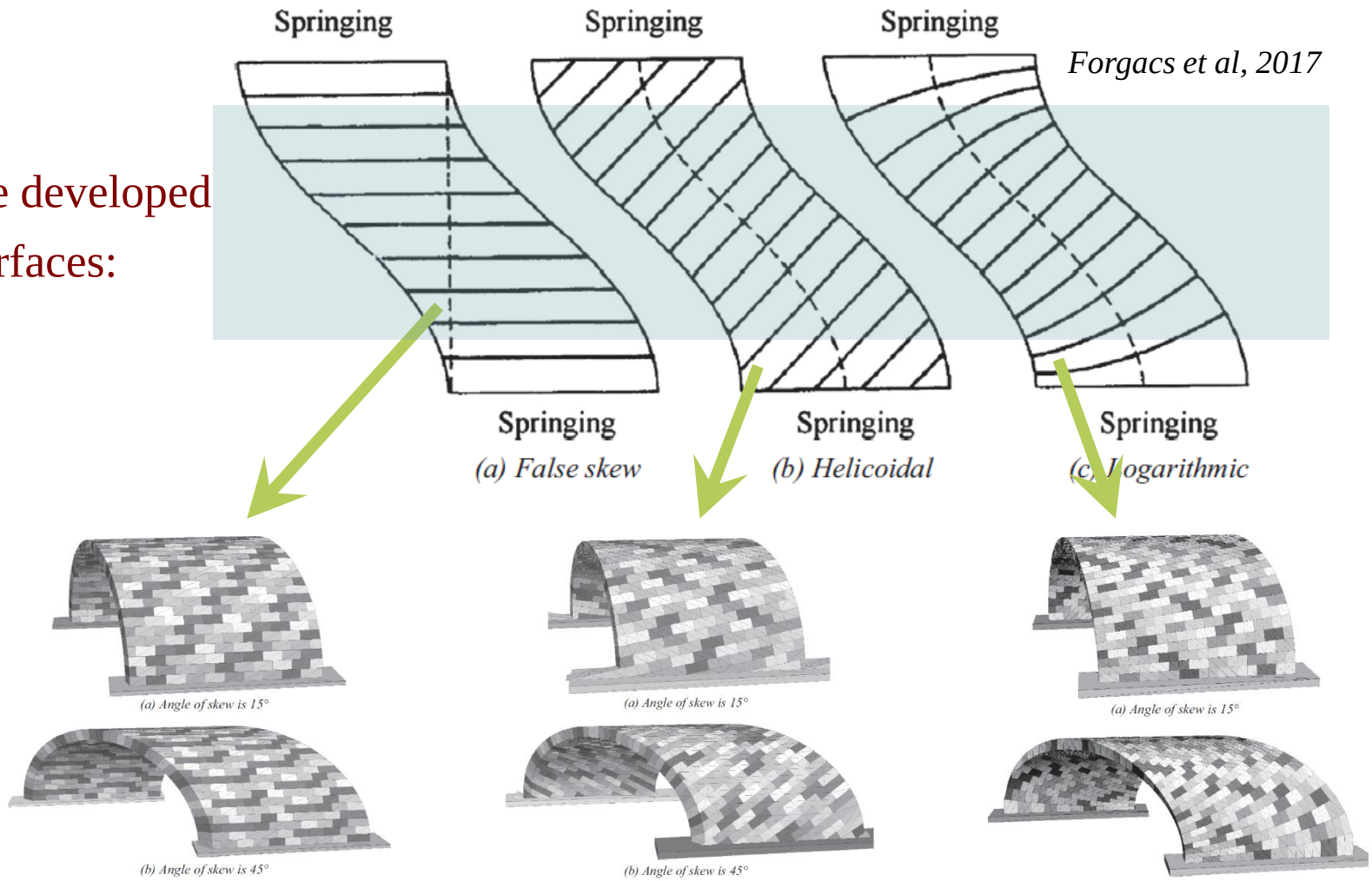


eloka-arctic.org/communities/yupik/yukon-river.html

SKEW BARRELS

Construction geometries:

the developed surfaces:



Forgacs et al, 2017

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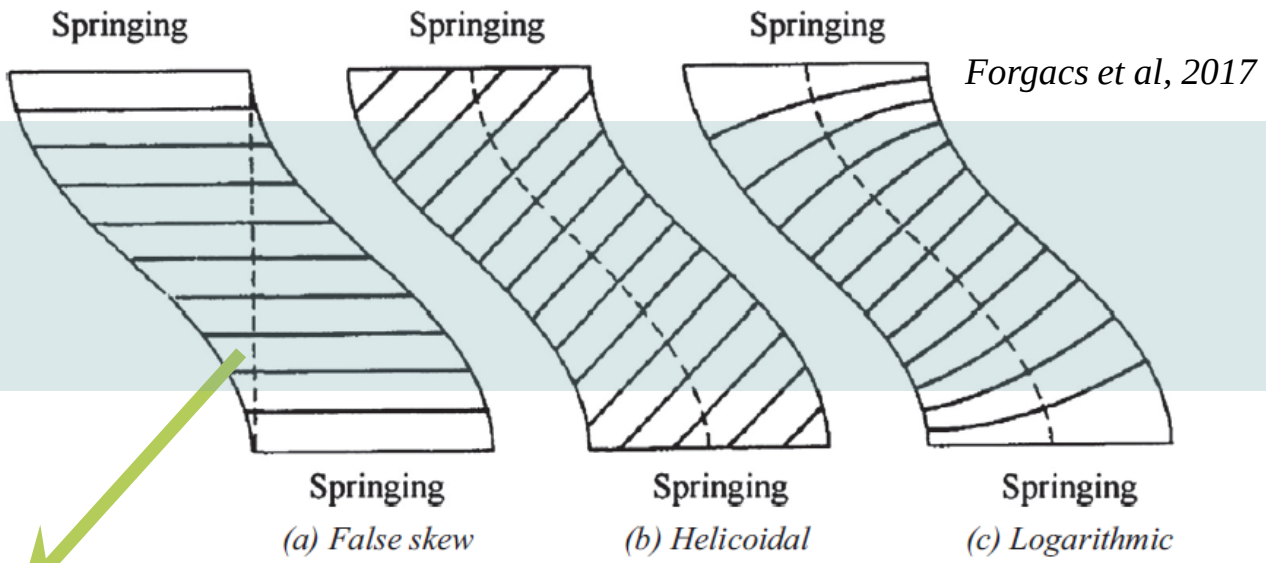
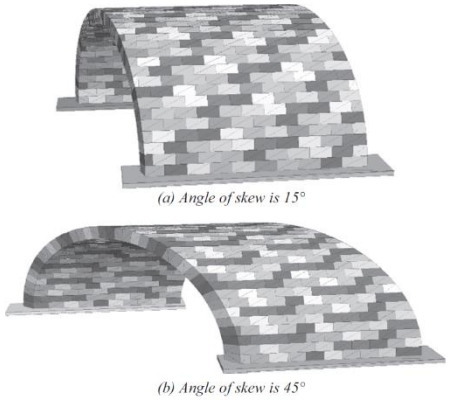


Forgacs et al, 2017



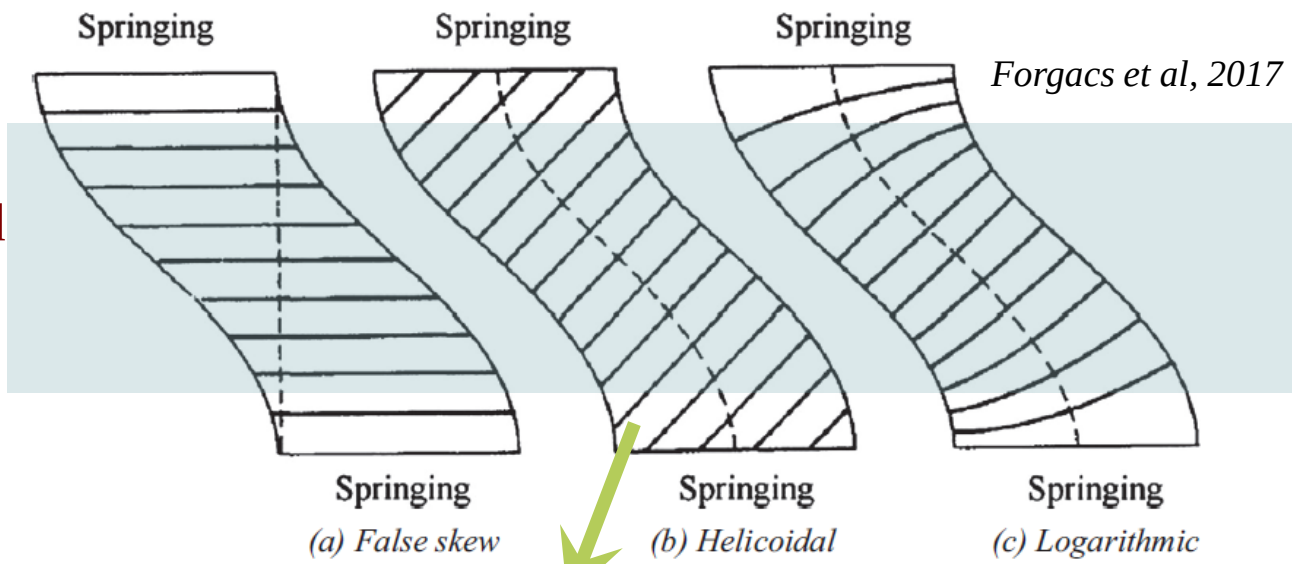
False skew constrution:

coursing joints parallel with the springings

SKEW BARRELS

Construction geometries:

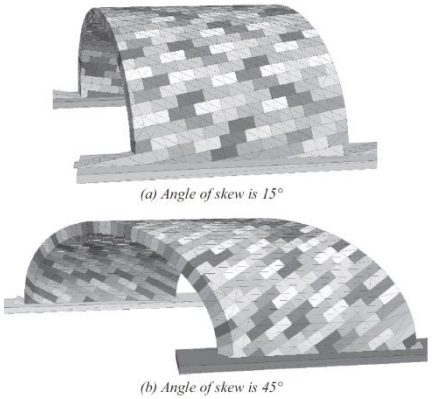
the developed surfaces:



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:

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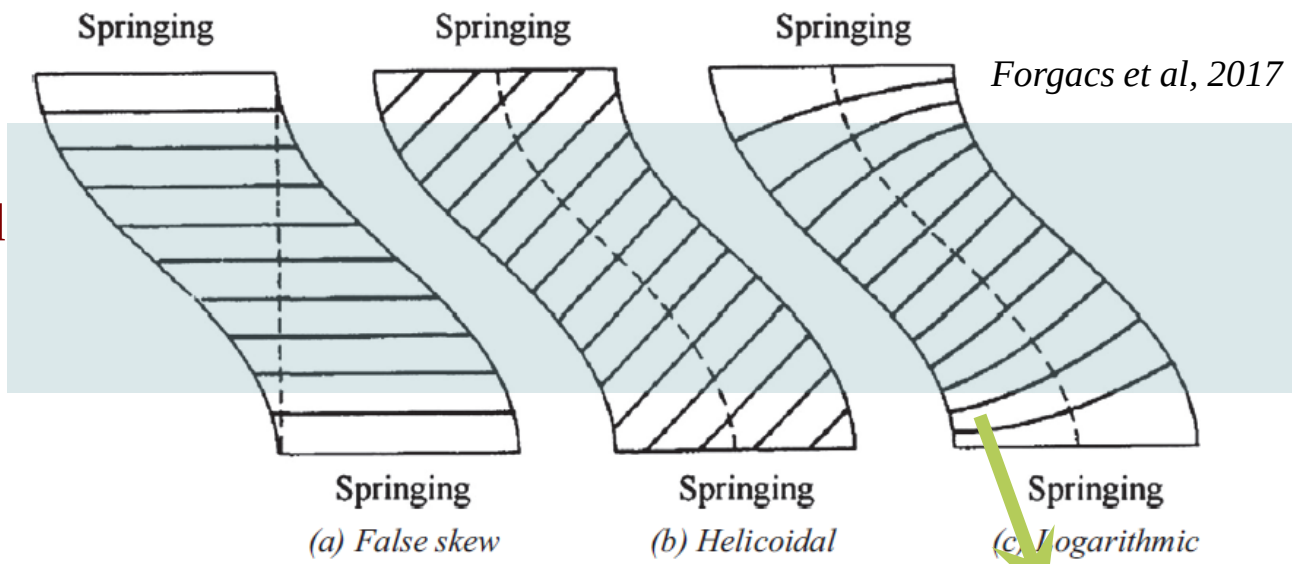
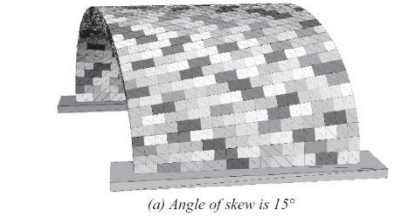


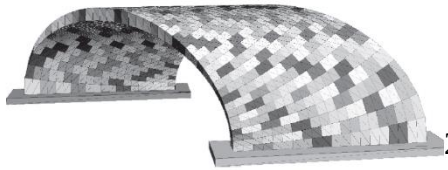
Forgacs et al, 2017

Logarithmic construction:

coursing joints are ⊥ to the arch face

⇒ units are different, unique shapes

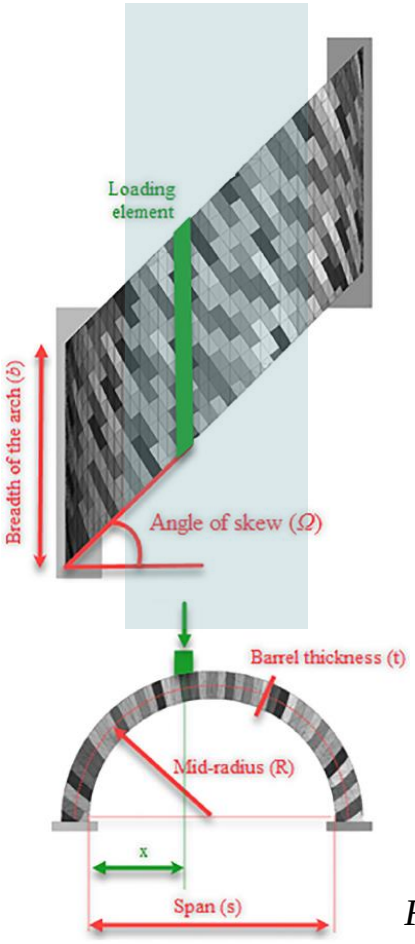


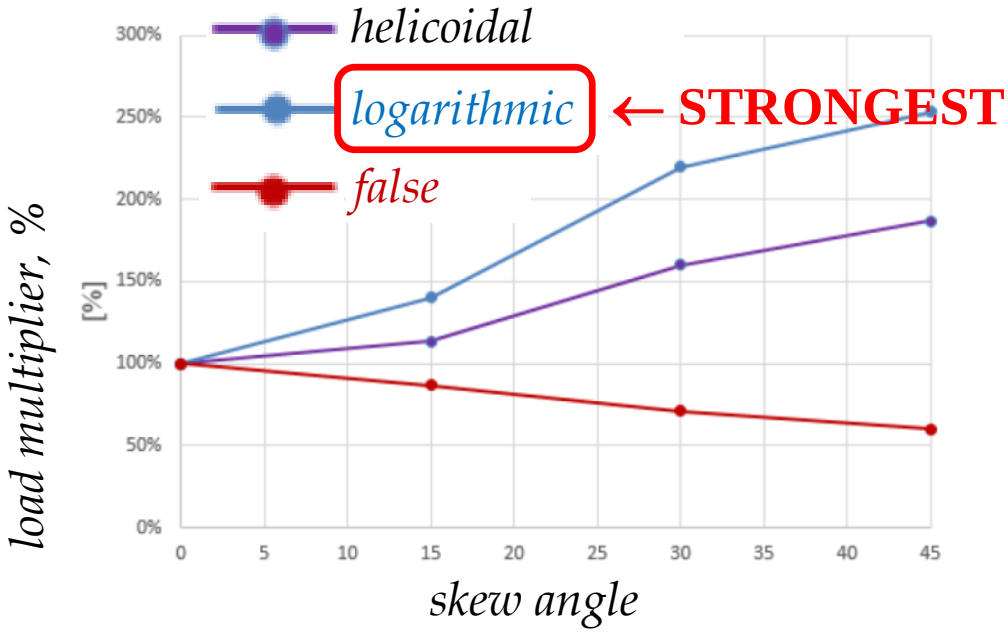


SKEW BARRELS

Construction geometries:

Load bearing capacity:



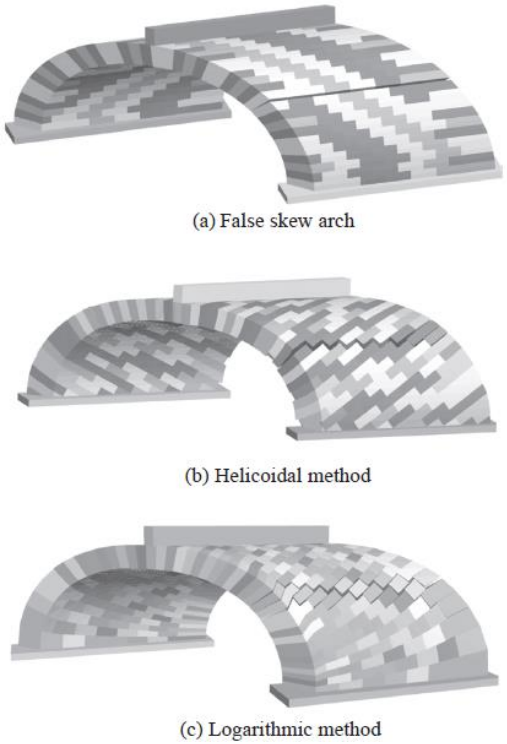


Forgacs et al, 2018

SKEW BARRELS

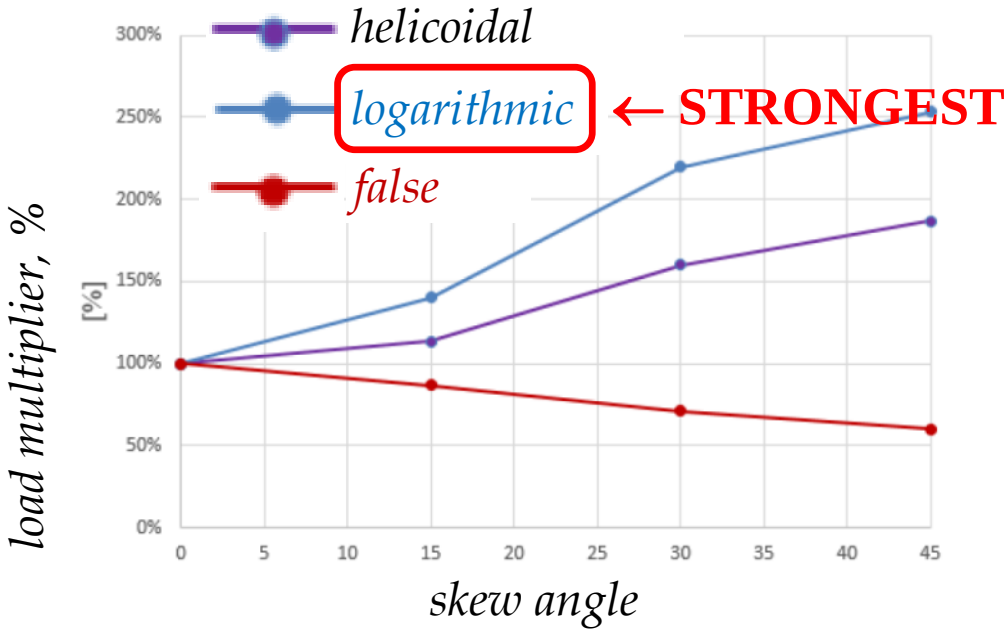
Construction geometries:

Failure mode:


(a) False skew arch

(b) Helicoidal method

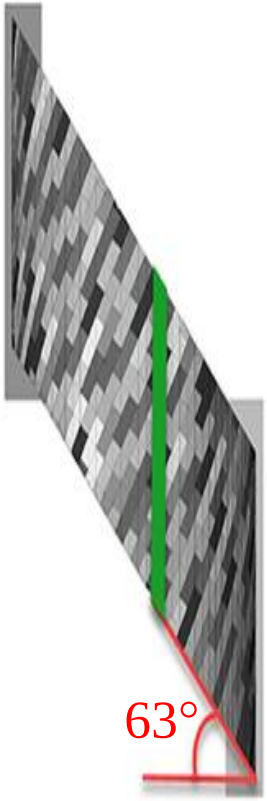
(c) Logarithmic method



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

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

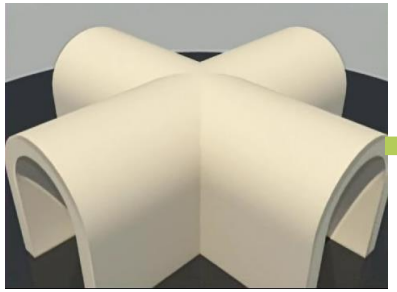
Questions

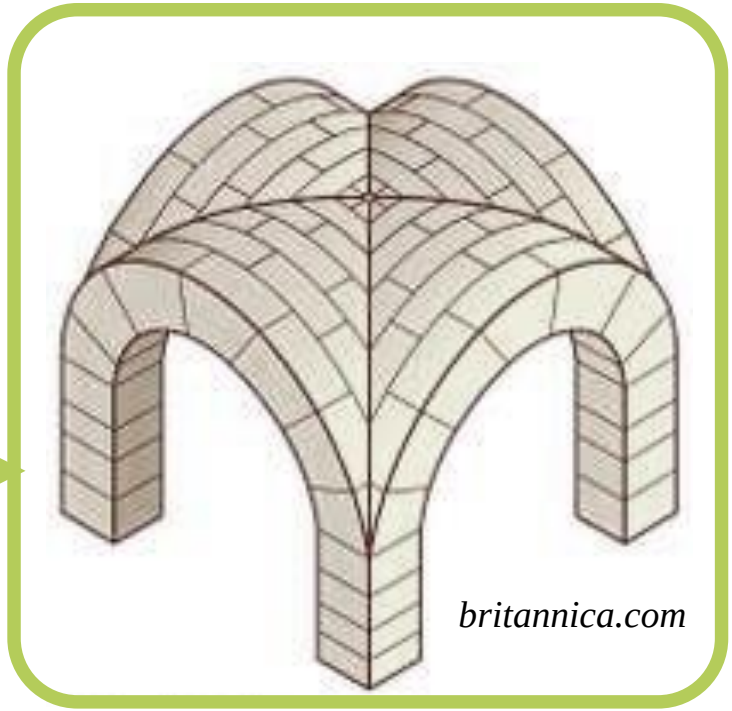
CROSS VAULTS

What is a cross vault?

an open vault:

intersection of two barrel vaults

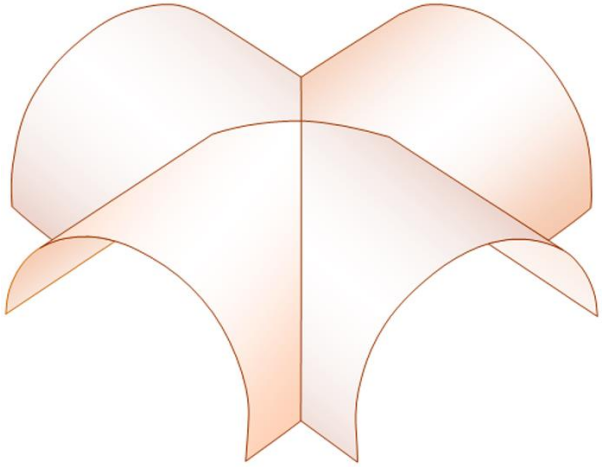




parabolic points + „creases” (groins)

CROSS VAULTS

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



Origin of cross vaulting:

→ earliest cross vault:

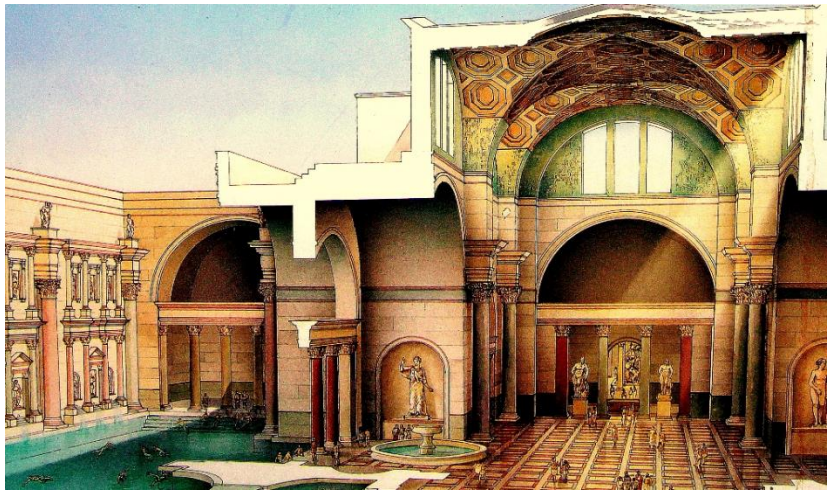
≈ 223 BC, in Delphi, Greece

→ 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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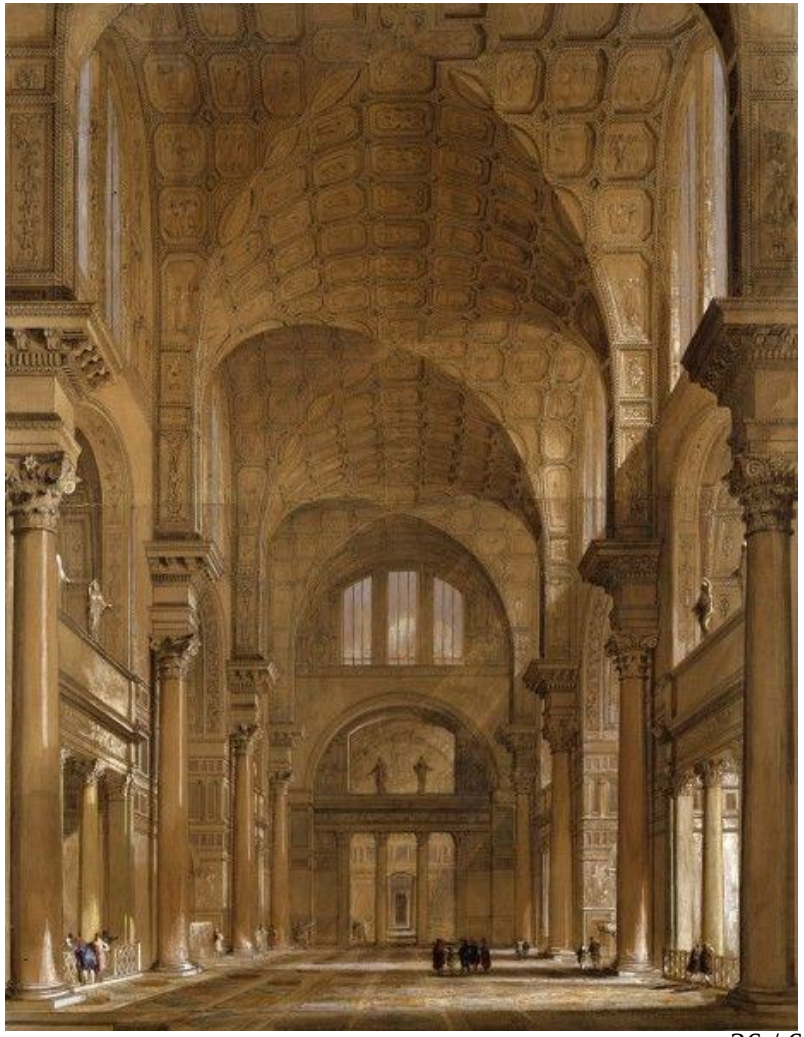

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https://en.wikipedia.org/wiki/Baths_of_Caracalla#Construction_%E2%80%93_216%E2%80%93235

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

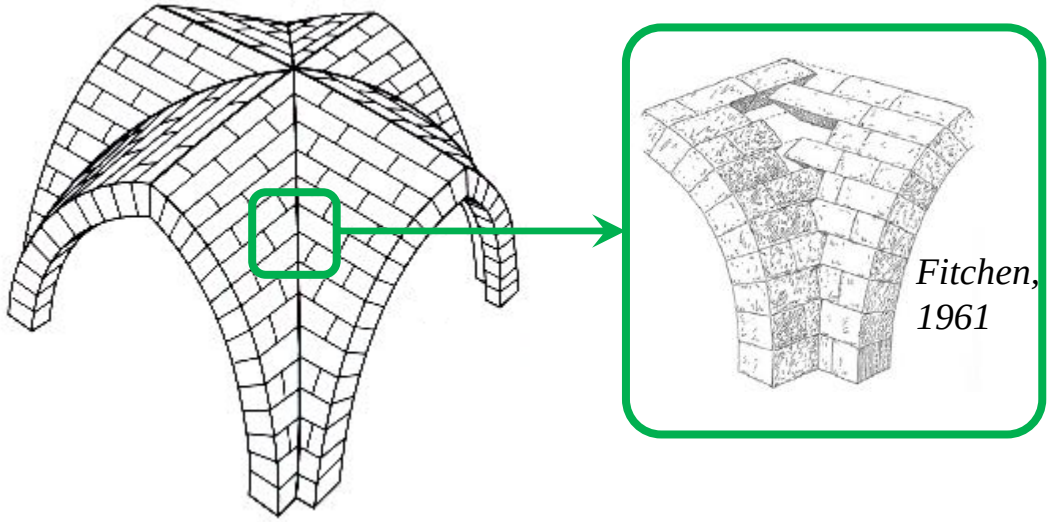
Main types of cross vaults:

→ unribbed („groin vault”):

construction:

centring is needed;

problem at groins



slideplayer.com/slide/3986670/13

→ ribbed („rib vault”):

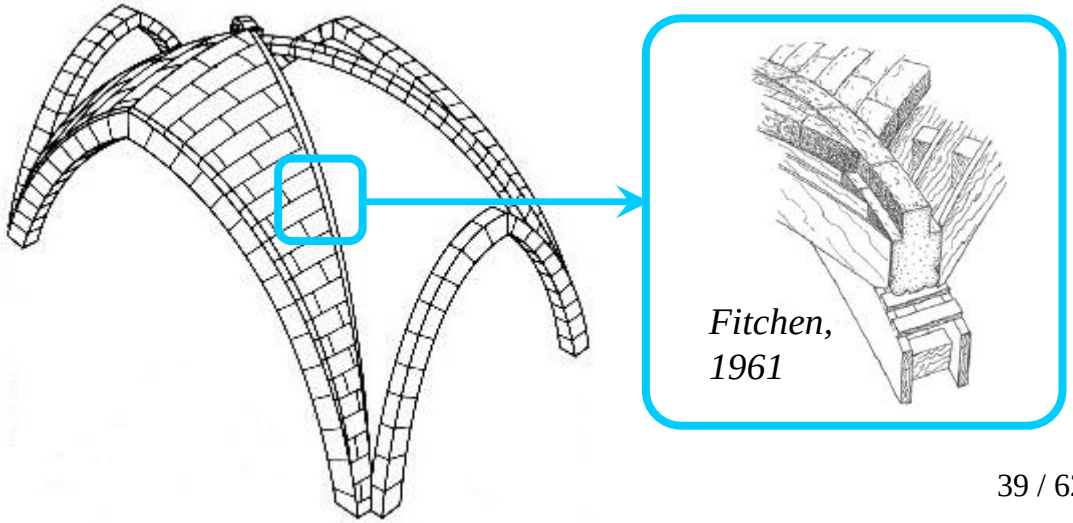
construction:

ribs on centring;

then simple centring

[only planks]

+ stress field smoothed



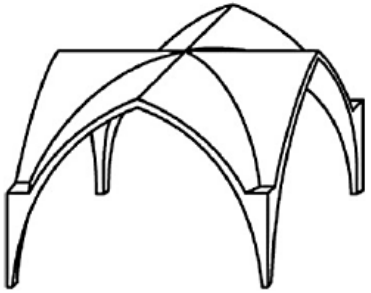
CROSS VAULTS

Shape variations of cross vaults:

Gaetani et al, 2015

→ equal semicircular cylindrical barrels:

→ equal pointed cylindrical barrels:



parabolic points

→ higher at centre:

→ lower at centre:

elliptical points

MECHANICS:
← OPEN ISSUE

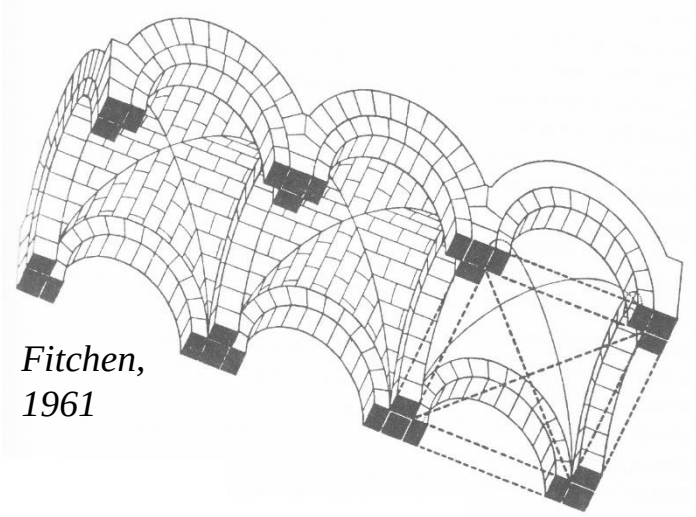
CROSS VAULTS

Bond patterns:

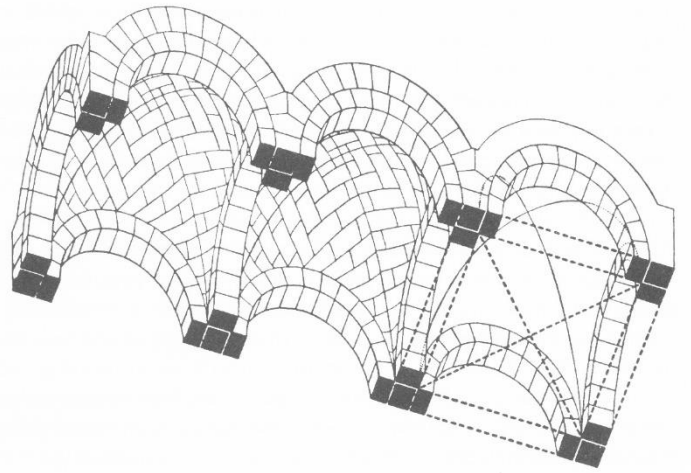
OPEN ISSUE: its mechanical effect?

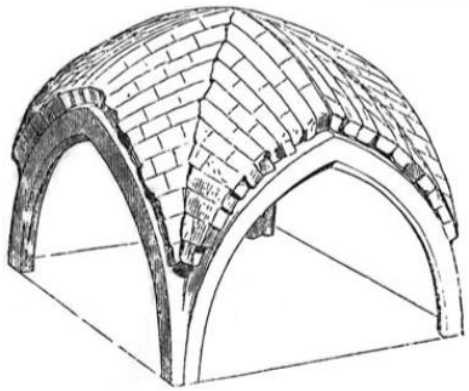
French coursing: [longitudinal]

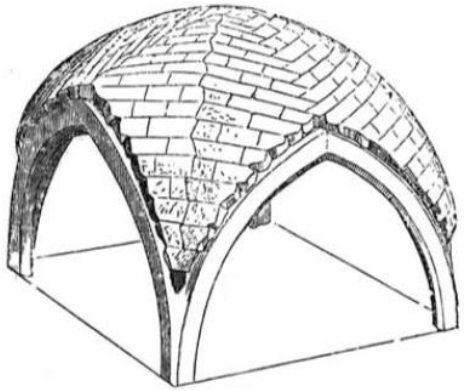
English coursing: [diagonal]



Fitchen, 1961



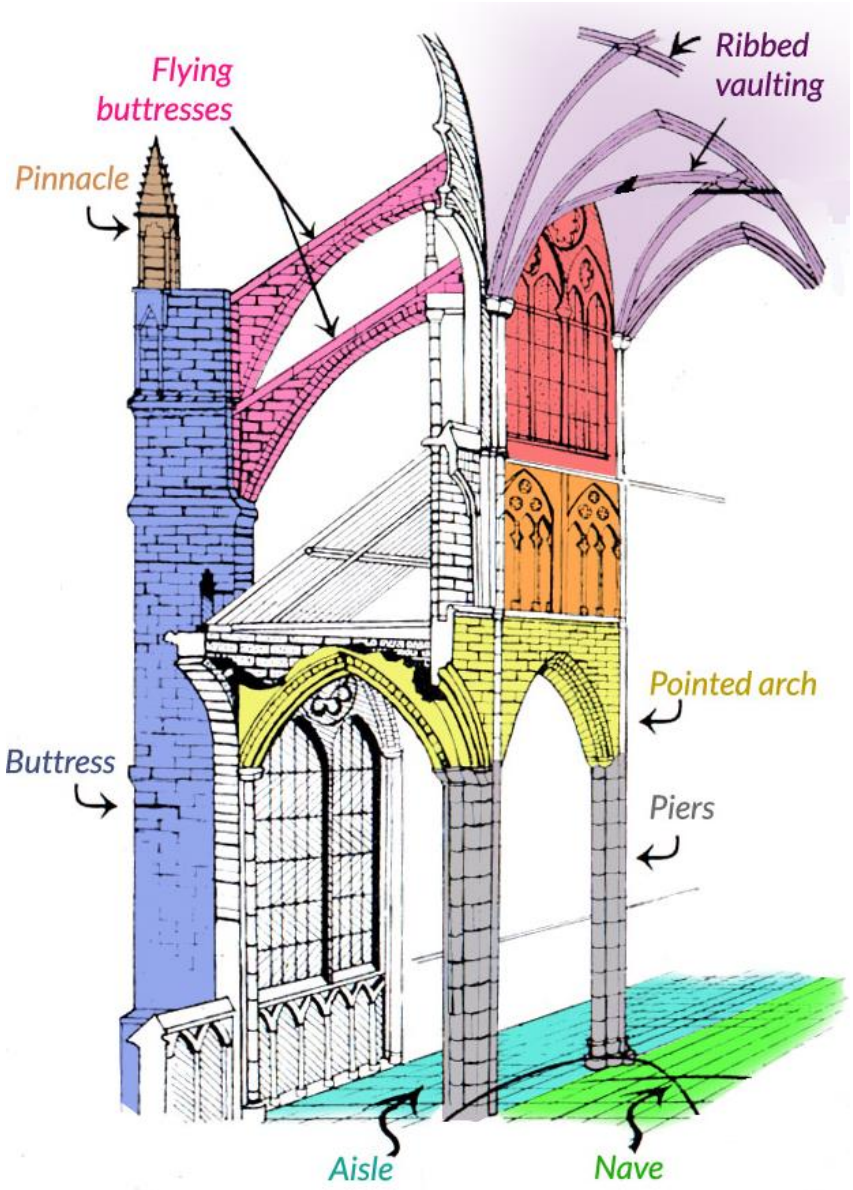




Viollet-le-Duc, 1854–1868

CROSS VAULTS

Terminology:



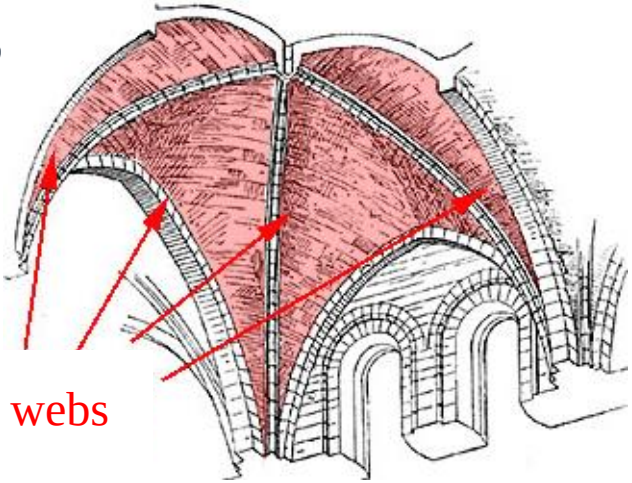
http://www.culturaltravelguide.com/what-is-a-gothic-cathedral

pitt.edu/~medart/menuglossary/

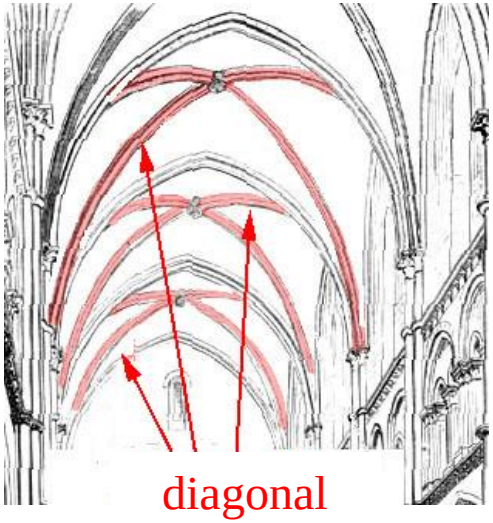
CROSS VAULTS

Terminology:

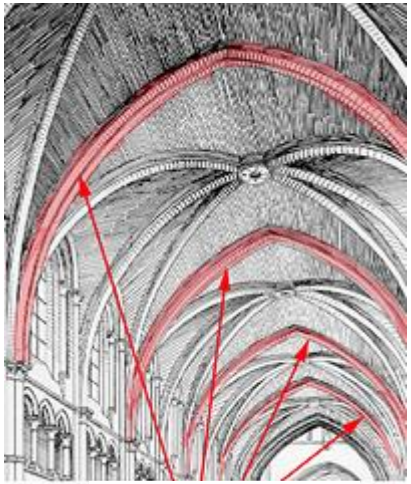
One bay:



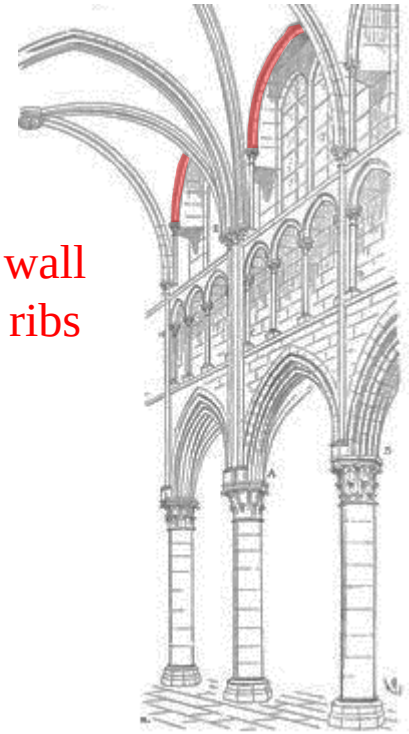
webs



diagonal ribs



transverse ribs



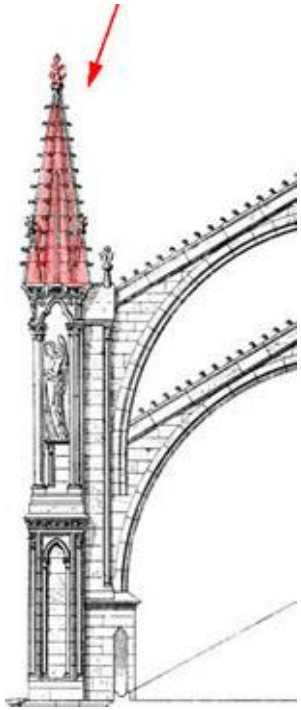
wall ribs

pitt.edu/~medart/menuglossary/

CROSS VAULTS

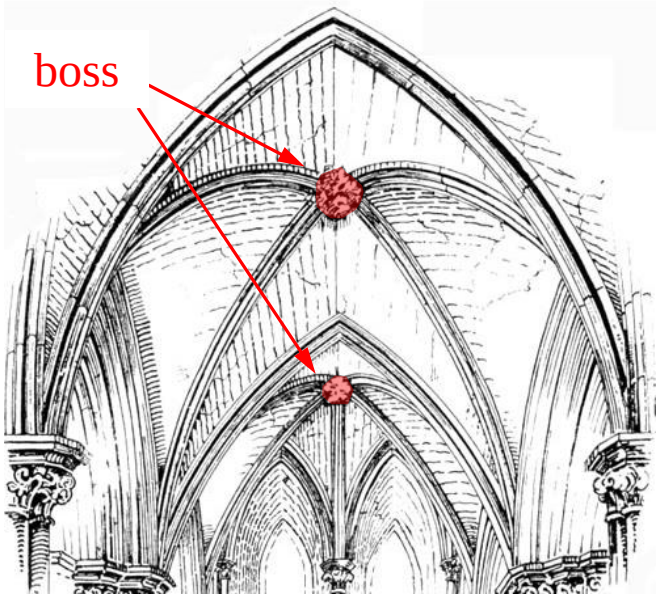
Terminology:

pinnacle



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

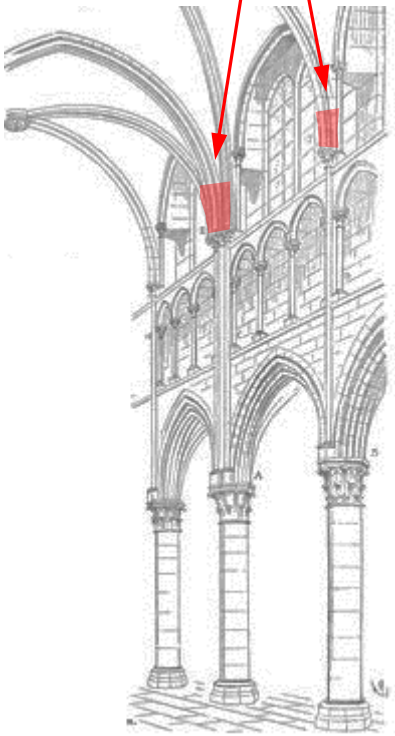
boss

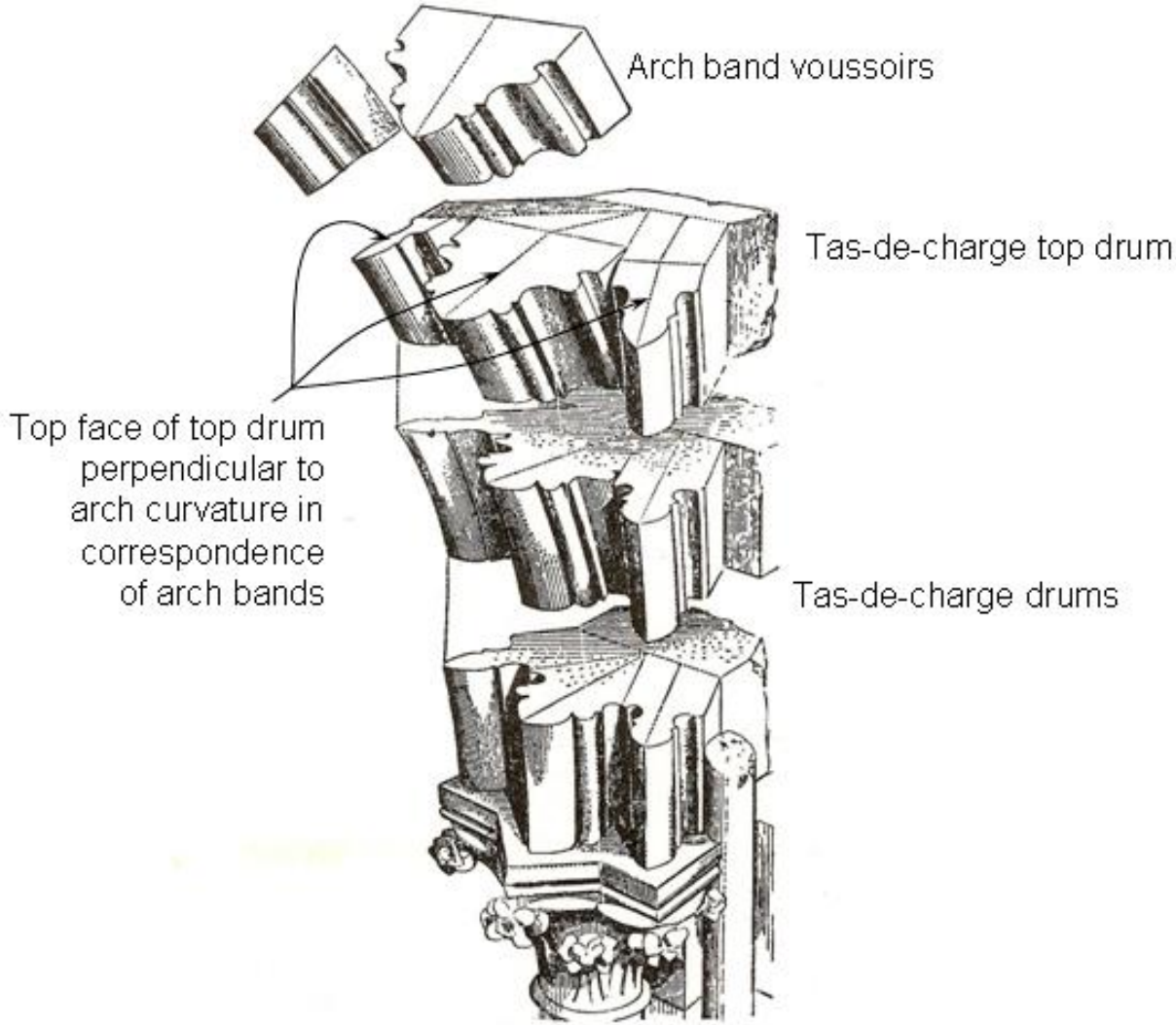


CROSS VAULTS

Terminology:

tas-de-charge:





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

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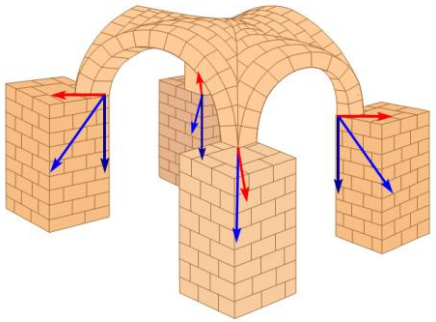
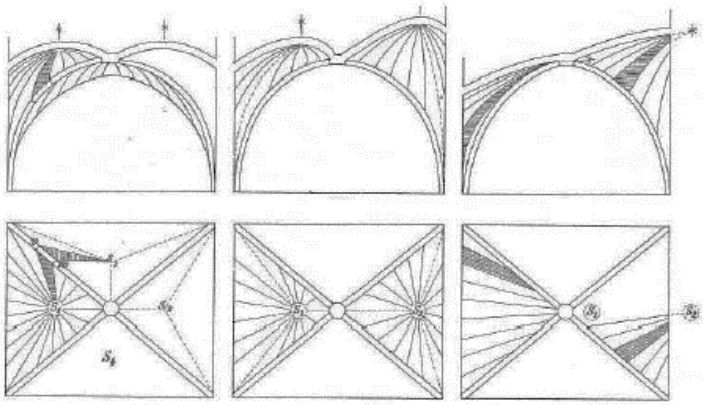
CROSS VAULTS

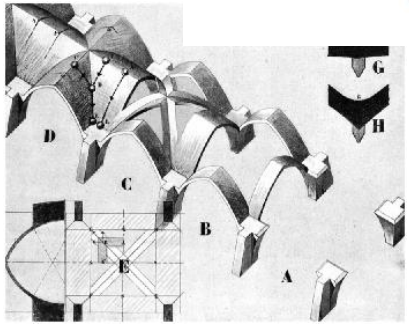


Internal forces in cross vaults:

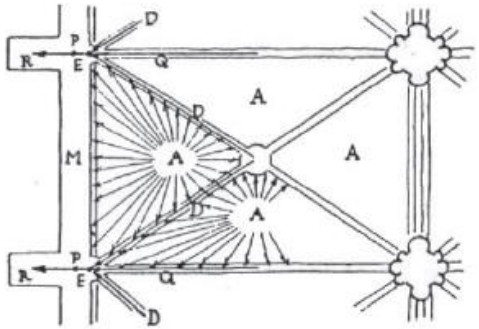
Theories:



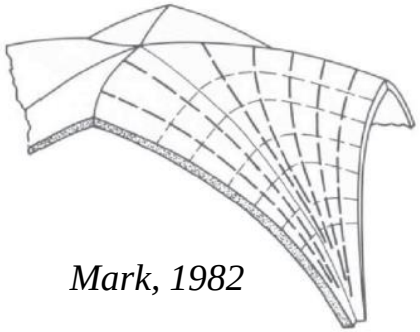
Ungewitter, 1890



Abraham, 1934



Rave, 1939



Mark, 1982

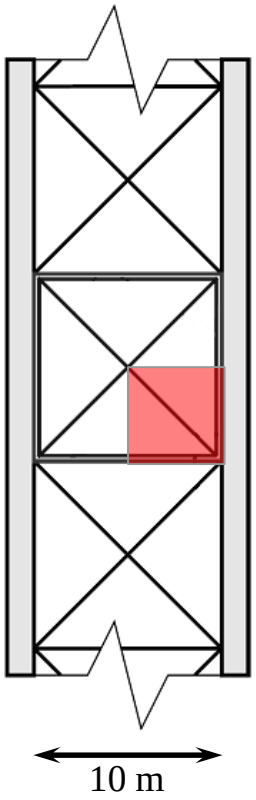
Role of ribs ???

decorative ↔ structural

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

CROSS VAULTS

Lengyel and Bagi, 2015

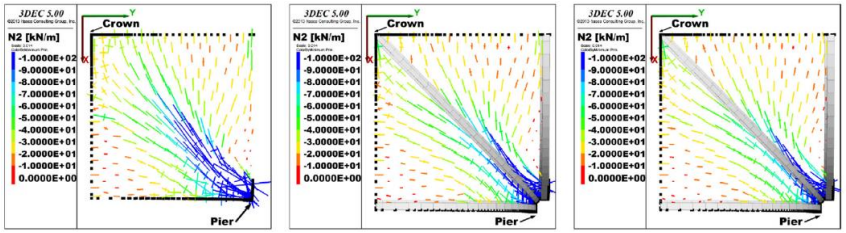


Internal forces in coss vaults:

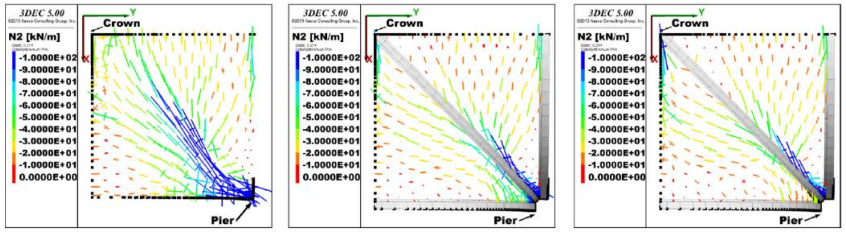
Outwards support displacement:

NO RIB *THIN RIB* *THICK RIB*

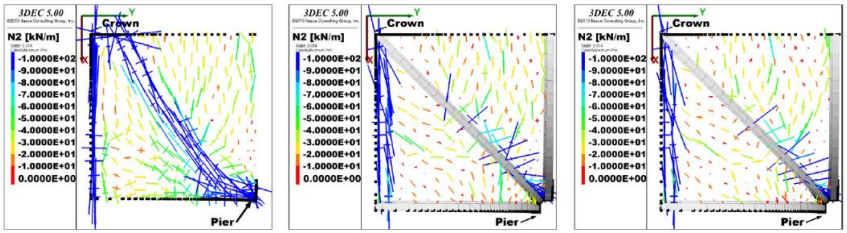
0 cm →



1 cm →



20 cm →



Suggested reading: Huerta (2009) ; Lengyel and Bagi (2015)

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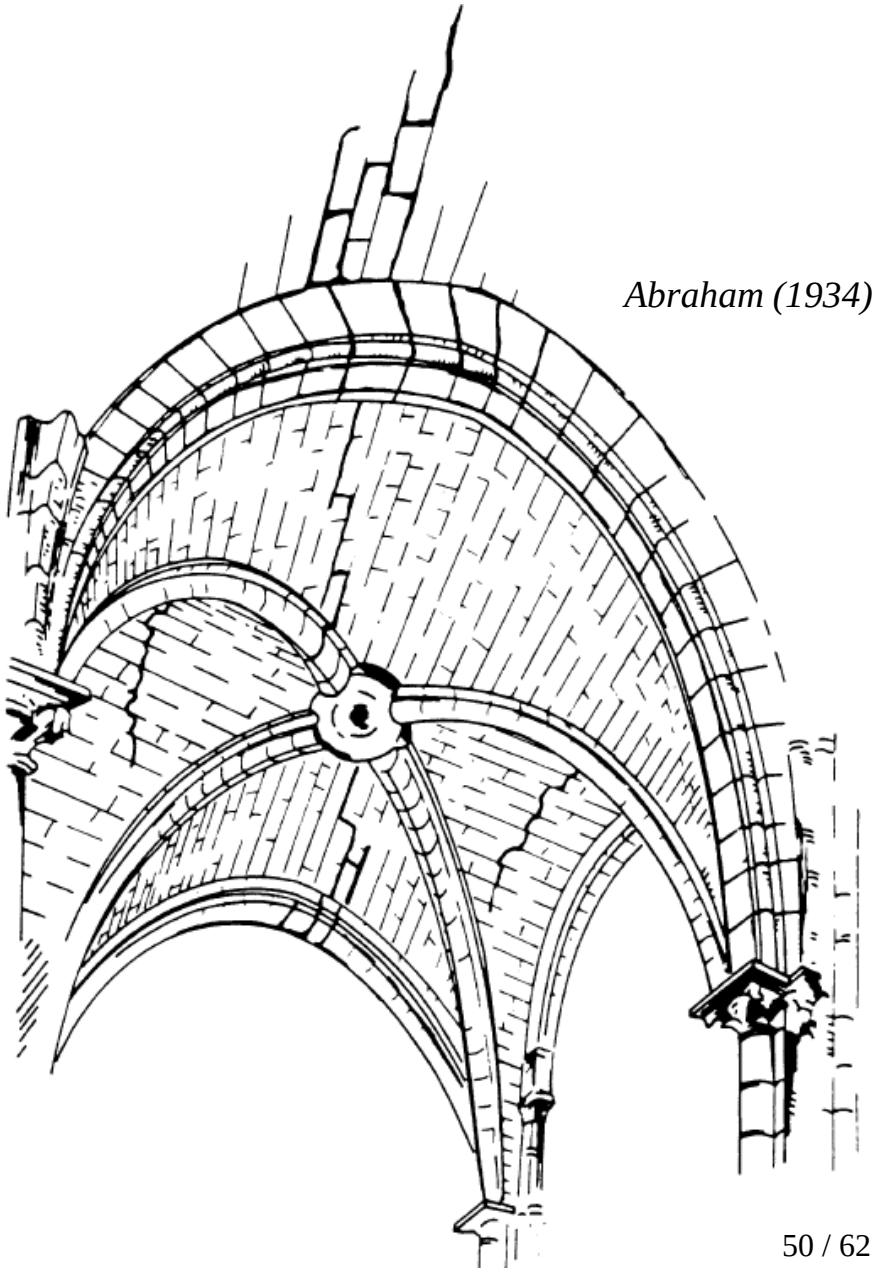
CROSS VAULTS

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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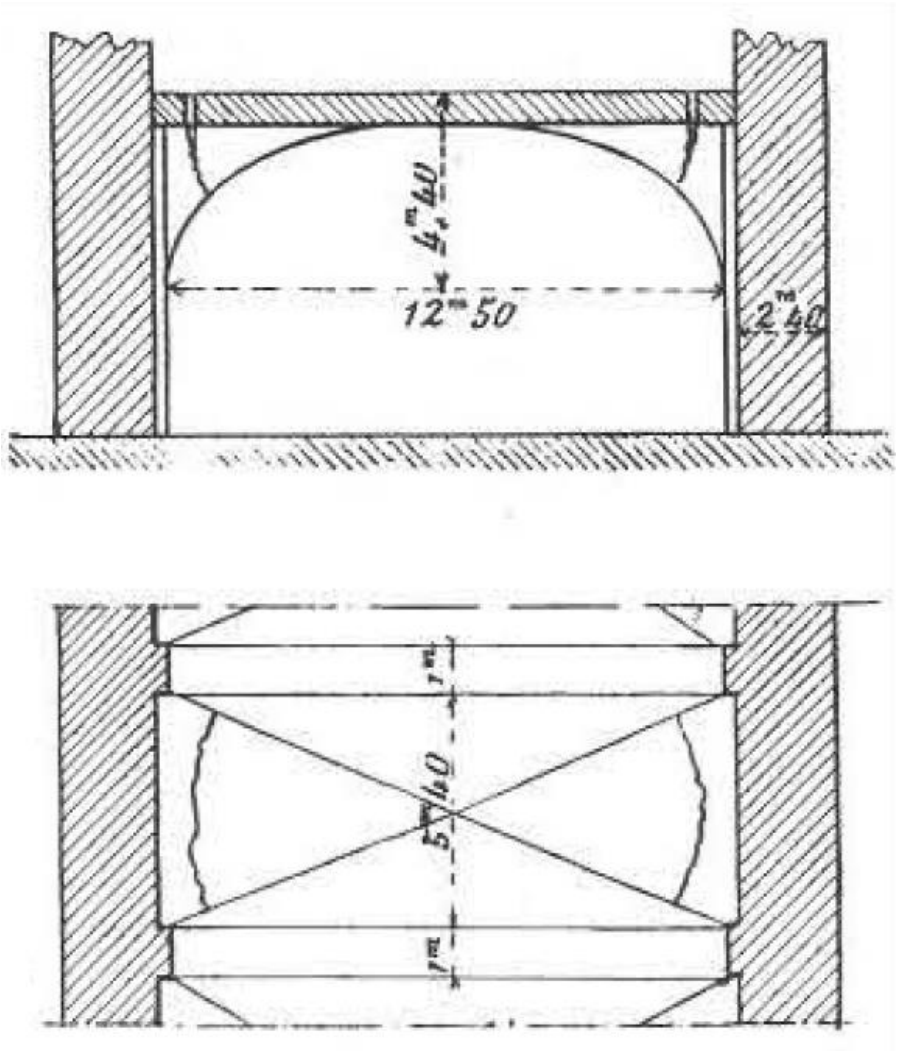
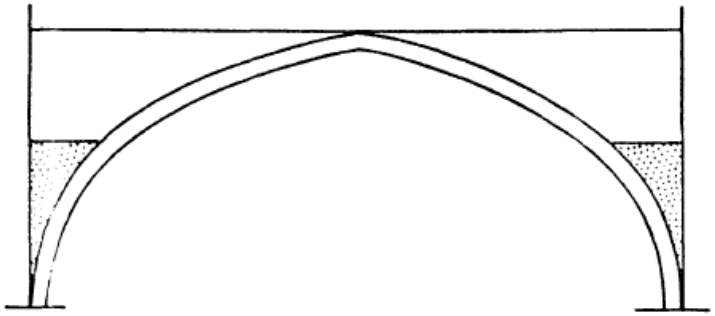
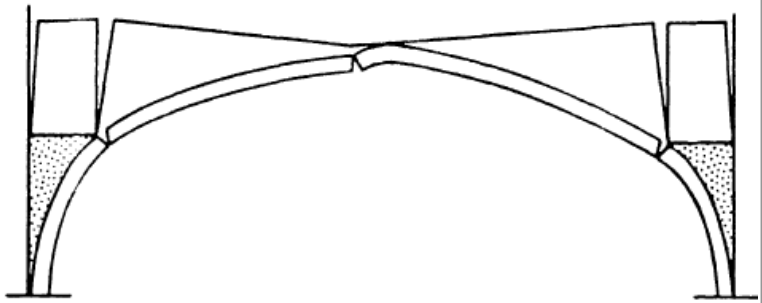


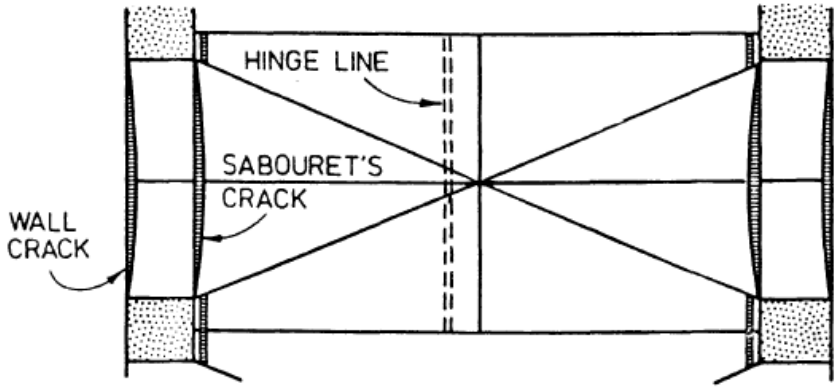
Sabouret (1928)

CROSS VAULTS

Heyman (1983)







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McInerney and DeJong (2015)

CROSS VAULTS

Strengthening:

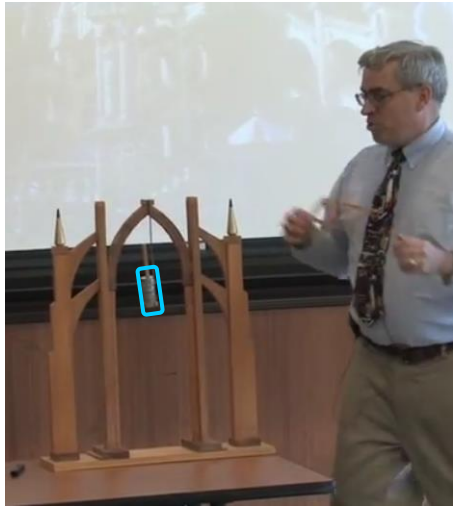
REMEMBER:

→ 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:

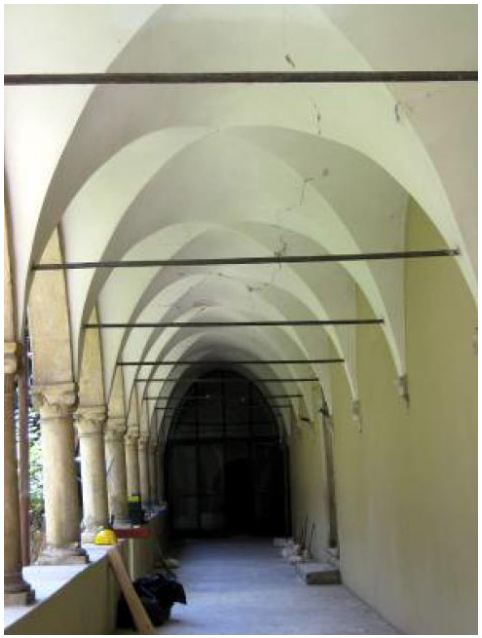
Basilica St. Magdalene, Vezelay, France thoughtco.com/what-is-a-flying-buttress-4049089

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:

OPEN ISSUE!

grid arrangement

annular arrangement

Foraboschi (2004)

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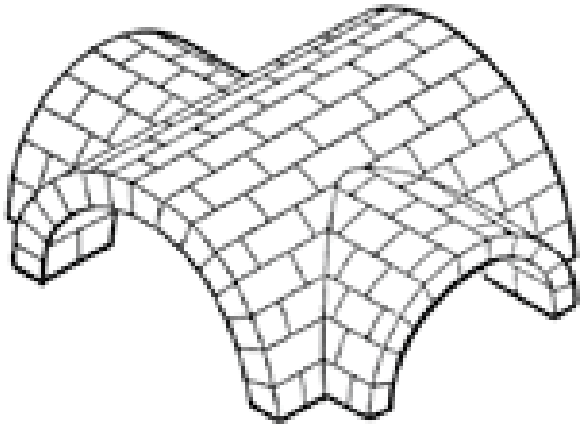
UNDERPITCHED VAULTS

Definition: „Welsh vault” ;

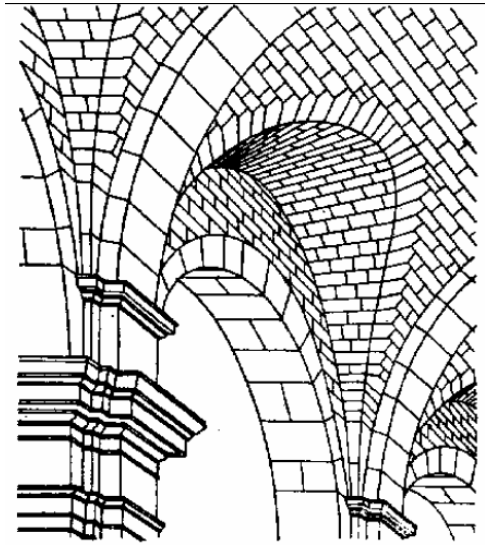
→ A construction formed by the penetration of two barrel vaults of unequal size, springing from the same level

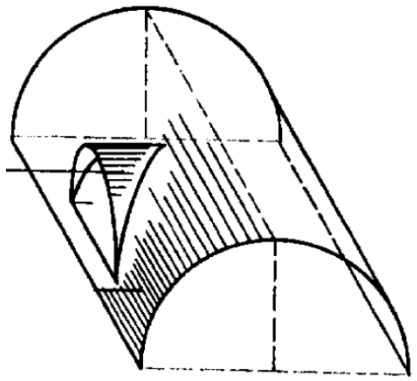
→ A barrel vault intersected by lower vaults

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

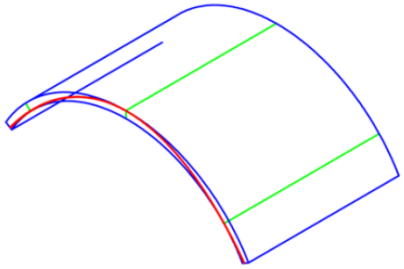
Church of St. Agnes, Lublin, Poland lublinarchitecture.pollub.pl/?p=514

hardly any analysis exist on the mechanics! → OPEN ISSUE

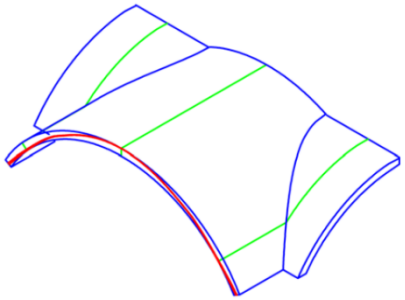
UNDERPITCHED VAULTS

Crack patterns:

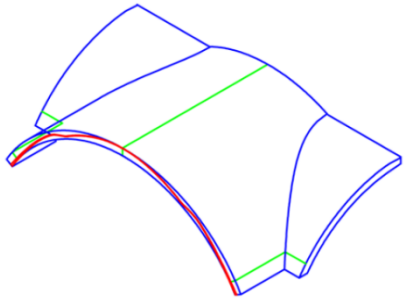
Holzer, 2013: (FEM & LSA)



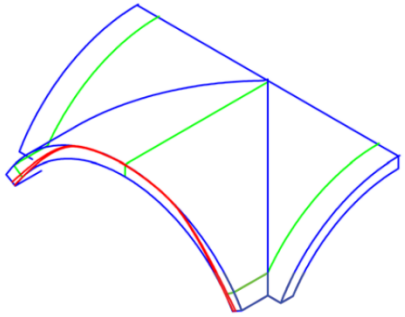
barrel vault



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)

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

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. What methods do you know to protect a cross vault against cracking?