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
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

Origins of barrel vaulting:

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)

[Greks 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)
BARREL VAULTS

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BARREL VAULTS

Temple of Sulis Minerva, Bath, UK: ≈ 1st ct AD „Aquae Sulis”, hot water spa
Celtic goddess of wisdom (≈ Minerva)

How it may have looked like:

How it looks today:

wikivisually.com/wiki/Aquae_Sulis

wikivisually.com/wiki/Aquae_Sulis
BARREL VAULTS

The Basilica of Saint Sernin, Toulouse, France: end of XIth century
[largest Romanesque church]

the main nave vault:

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

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

„banded barrel vault”

https://www.medart.pitt.edu/image/france/Toulouse/SSernin/Plans/de0130tss.jpg
BARREL VAULTS

Lisbon Cathedral, Portugal: the Romanesque nave from XIIth century
[ several earthquakes in the region ⇒
⇒ Gothic, Baroque, etc parts also ]

the nave vault:

from outside:

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

pinterest.ca/pin/166211042478736763/
BARREL VAULTS

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

from outside:

the nave vault:

arts.st-andrews.ac.uk/corpusofscottishchurches

imagedatabase.st-andrews.ac.uk/images
BARREL VAULTS

Cracking and failure modes

Typical load: selfweight & support displacements

(\textit{the barrel only, as an arch})

Failure: together with the supporting structure

Remark:
Failure modes under lateral ground accelerations:

\textit{Alexakis and Makris, 2017}
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:

Lancaster, 2009

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

Baths of Caracalla, Rome, Italy; 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:**
  Roman invention,
  from ≈ 2nd century AD
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. \( \approx 1400 \text{ kg/m}^3 \)) instead
  of stone (e.g. \( \approx 2600 \text{ kg/m}^3 \))
  ✓ formulate coffers („indentations”):

Ressler (2011), 11. The Glory of Rome
BARREL VAULTS

How to resist the lateral thrust?

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→ earth pressure ✓

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→ heavy, thick walls under the barrel
→ walls supported by buttresses
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→ make the vault easier
→ neighbouring barrels: [ ≈ arcade ]
BARREL VAULTS

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Freestanding barrel vaults on higher walls:

→ heavy, thick walls under the barrel
→ walls supported by buttresses
→ iron tie bars
→ make the vault easier
→ neighbouring barrels [≈ arcade]
→ crosswise barrels:

TOWARDS THE CROSS VAULT!
BARREL VAULTS

How to resist the lateral thrust?


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

crosswise barrels:

TOWARDS THE CROSS VAULT!
BARREL VAULTS

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

Lancaster, 2015
BARREL VAULTS

Constructional issues

Romano & Grande (2008):

→ vertical concentrated load
  in the middle point:

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

STRONGER
THIS LECTURE

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Underpitched vaults

Questions
VAULTS IN GENERAL

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

History:
Moorish origin, found from XIIth century spread in the Mediterranean 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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- 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

Constructional issues

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

→ Rafael Guastavino: e.g. Boston Public Library:

e.g. NY Queensboro Food Emporium: e.g. City Hall Station, NY subway:

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

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:

Suggested reading:
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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
SKEW BARRELS

Construction geometries:

the developed surfaces:

False skew construction:

coursing joints parallel with the springings
SKEW BARRELS

Construction geometries:

the developed surfaces:

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:

Logarithmic construction:

coursing joints are \( \perp \) to the arch face

\( \Rightarrow \) 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
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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

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]
CROSS VAULTS

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  \[ \approx 223 \text{ BC, in Delphi, Greece} \]
→ Roman architecture: [ semicircular ]
  public buildings: baths; churches
  e.g. Baths of Caracalla:

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

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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)

Fall of Gothic architecture:
Beauvais Cathedral, France
(1225…1573; two collapses)

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

CROSS VAULTS

Main types of cross vaults:

→ unribbed („groin vault“):
  construction:
  centring is needed;
  problem at groins

→ 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:

→ equal pointed cylindrical barrels:

→ higher at centre:

→ lower at centre:

Gaetani et al, 2015

MECHANICS: OPEN ISSUE
CROSS VAULTS

Bond patterns:

French coursing: [longitudinal]

English coursing: [diagonal]

OPEN ISSUE: its mechanical effect?

Fitchen, 1961

Viollet-le-Duc, 1854–1868
CROSS VAULTS

Terminology:

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

Terminology:

One bay:

- webs
- diagonal ribs
- transverse ribs
- wall ribs

pitt.edu/~medart/menuglossary/
CROSS VAULTS

Terminology:

- pinnacle
- boss

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

Terminology:

tas-de-charge:

Top face of top drum perpendicular to arch curvature in correspondence of arch bands

Arch band voussoirs

Tas-de-charge top drum

Tas-de-charge drums

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

Questions
CROSS VAULTS

Internal forces in cross vaults:

Theories:

Role of ribs ???

decorative ↔ structural

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

Abraham, 1934

Ungewitter, 1890

Rave, 1939

Mark, 1982

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

Internal forces in coss vaults:

Outwards support displacement:

0 cm →

1 cm →

20 cm →

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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
CROSS VAULTS

Characteristic crack patterns:

(1) Longitudinal hinging cracks near the crown

(2) Sabouret’s cracks

(3) Complete separation from the lateral walls

Sabouret (1928)
CROSS VAULTS

Characteristic crack patterns:

(1) Longitudinal hinging cracks near the crown

(2) Sabouret’s cracks

(3) Complete separation from the lateral walls

McInerney and DeJong (2015)

Heyman (1983)
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

→ flying buttresses:

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

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:

→ FRP strips:

**OPEN ISSUE!**

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

*Foraboschi (2004)*

grid arrangement  annular arrangement
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Questions
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

![Diagram of underpitched vaults](encyclopedia2.thefreedictionary.com)

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

hardly any analysis of the mechanics! → OPEN ISSUE
UNDERPITCHED VAULTS

**Definition:** „Welsh vault” ;

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→ A barrel vault intersected by lower vaults

spread: XVI.-XVIII. century Europe

![Image of Cathedral of the Immaculate (Bosa, Italy)](wikimapia.org/31232881/Interior-of-the-Cathedral-of-the-Immaculate)

![Image of 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://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=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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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?