Heritage Problems, Causes and Solutions

Calogero Bellanca and Susana Mora Alonso-Muñoyerro

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This material is didactic, to be used in education. The graphic material although fundamentally is made by the authors, includes photographs and drawings compiled from material used by the authors in their lessons in ETSAM (UPM) (*Construction and Heritage Courses*), Sapienza University of Rome (*Course of Theory and Practice of Conservation* and *Laboratorio di Restauro*) and other european university.

In this volume have collaborated specially these architects:
Ignacio Mora Moreno, Alejandro Iniesta Munoz, Magdalena Prieto de la Lastra

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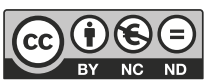


In copertina | *Cover image*: *Colosseum*, detail. Photo by Susana Mora and Calogero Bellanca.

Dedicated to our parents

Maria and Antonino
Consuelo and Justo

Index

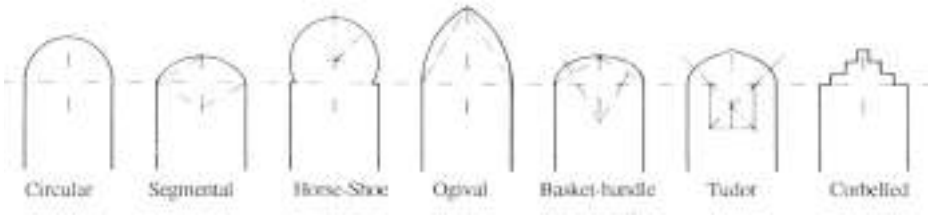
PART III – CONSTRUCTION APPLIED TO HERITAGE

CHAPTER 9. VAULTS: CONSTRUCTIVE SYSTEMS, PROBLEMS, CAUSES AND SOLUTIONS

> "Vaults are usually constructed of stone or brick masonry, as these are good materials when used in compression, but other materials such as timber and plaster can be used. The ceilings of York Minster are an interesting example of a stone vault reproduced in laminated timber. Vaults such as Neuman used at Baroque Neresheim were constructed of tufa reinforced with iron tie bars. The complex cutting of stones with two curves to form vaults was avoided in Roman construction by the use of mass concrete. Later, brick ribs were introduced into the groin, as in the Baths of Diocletian where clear spans of up to 20 m were achieved. Such heavy construction demanded heavy centring, which was overcome by building the ribs first and then filling in the webs vistually freehand with a light curved centring".
>
> From FEILDEN, B. M., *Conservation of Historic Buildings*, Butterworths, London, 1982, p. 40.

FORM OF ARCHES

There are many shapes of arches. These are mainly characterized by the curve of the intrados and the ratio of height to span. Most arches are connected to the wall by the extrados. The corbel arch, built using courses gradually jutting further out, and monolithic arches, whether poured, tamped or cut out, have no extrados and continue directly on from the wall.



TYPES OF VAULTS

– Formal
– Constructive

There are a great many forms of vault. The simplest are barrel vaults which in fact consist of a succession of identical arches. Barrel vaults can have steeper or flatter profiles: semicircular, segmental, ogival, etc. The catenary vault is very common as its form gives maximum stability for a minimum use of material.

Combining two barrel vaults with the same profile allows two other types to be defined: the "groined vault" and the "dominical vault". By prolonging one of the two barrel vaults, the "dominical vault" becomes a "trough vault". Combining barrel vaults with different profiles forms a "lunette vault".
A "dominical vault", the ribs of which are rounded in the form of cones starting from the corners, becomes a "squinch vault". Similarly the "trough vault" can evolve into a "boat vault".

FORMAL

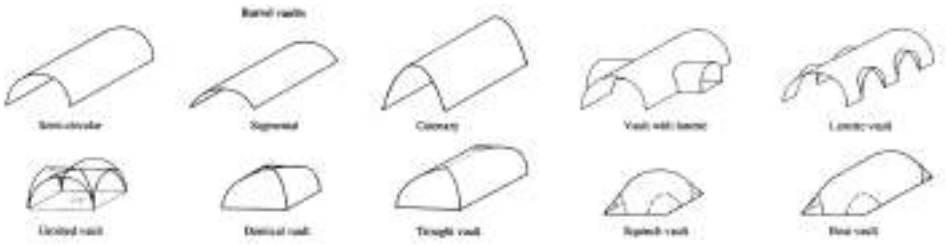


Fig. 1. Design by Susana Mora.

CONSTRUCTIVE

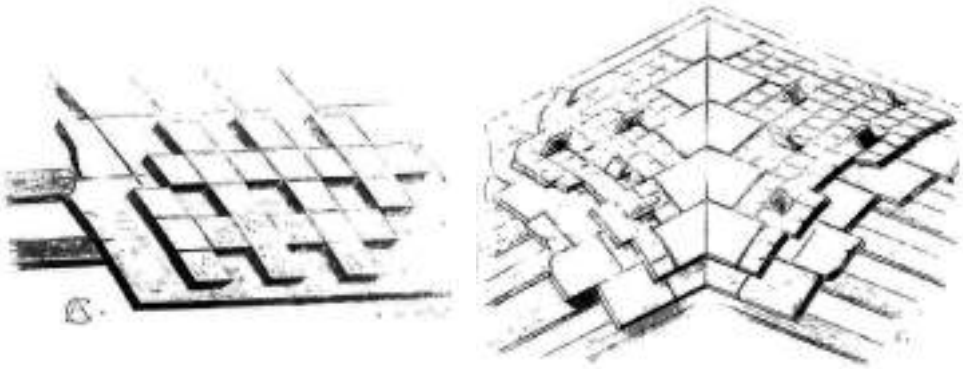


Fig. 2. On the left: Bonded. On the right: Poured. From G. Giovannoni, *L'Arte di costruire presso i romani*, 1925. Reprinted: Roma 1994.

Fig. 3a. Roman vault. Fori Imperiali, Rome. Photo by Susana Mora, 2017.

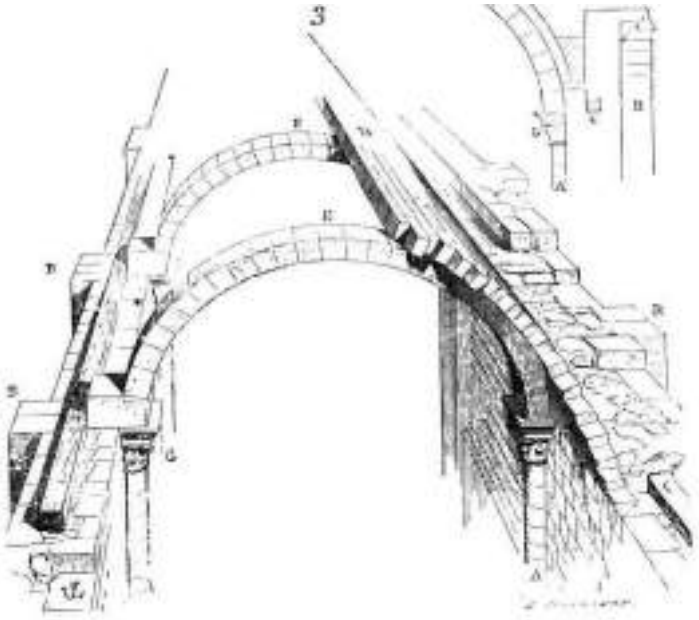


Fig. 3b. Medieval vault. From L. Palaia, E. Abdilla, *Técnica de intervención en arcos, bóvedas y cúpulas*, UPV, 1996.

FORMS OF DOMES

Domes are obtained by rotating an arch, except for faceted domes which more closely resemble the Dominical vault. A dome can be semi-circular, segmental, ogival, conical, etc.

Domes are circular in plan. They can, however, be used to cover square or rectangular rooms by using pendentives or squinches. Domes on pendentives can be used to cover any kind of polygonal shape in plan.
It is possible to combine several cupolas or to combine domes with vaults.

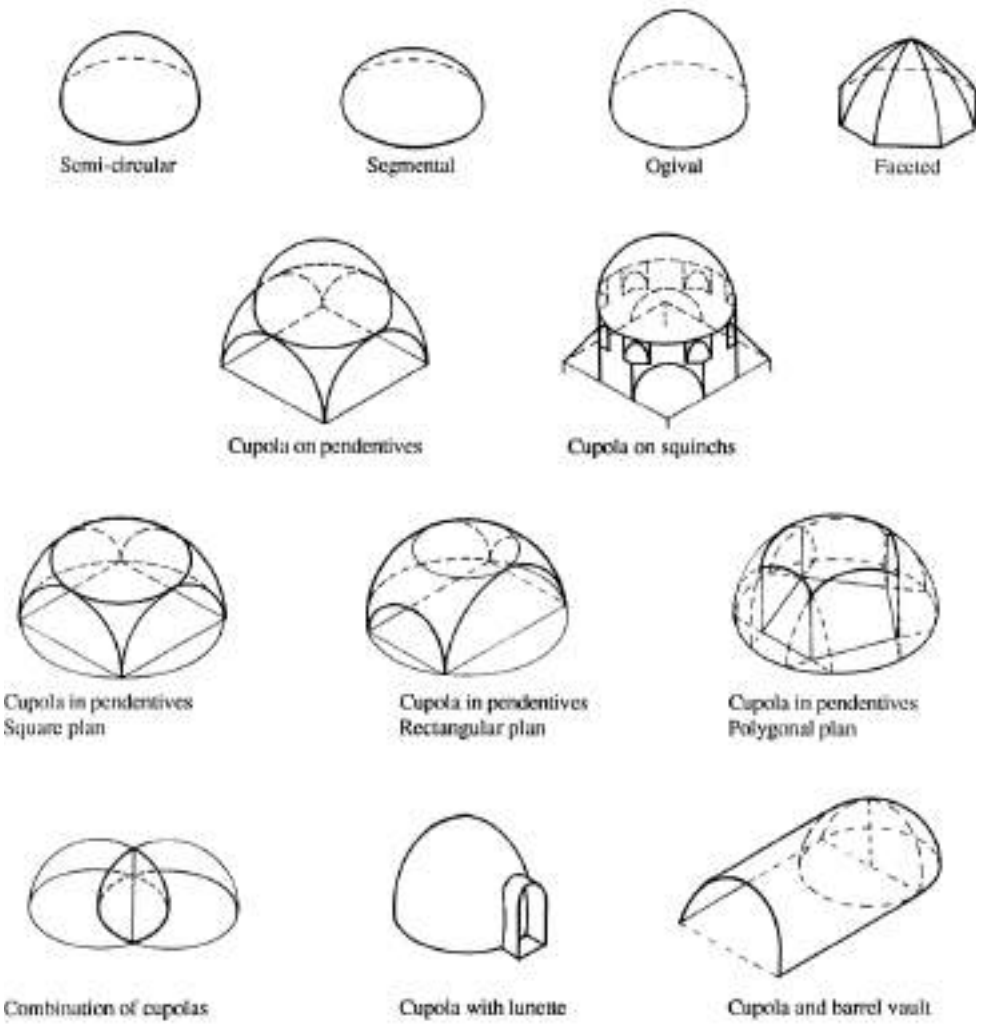
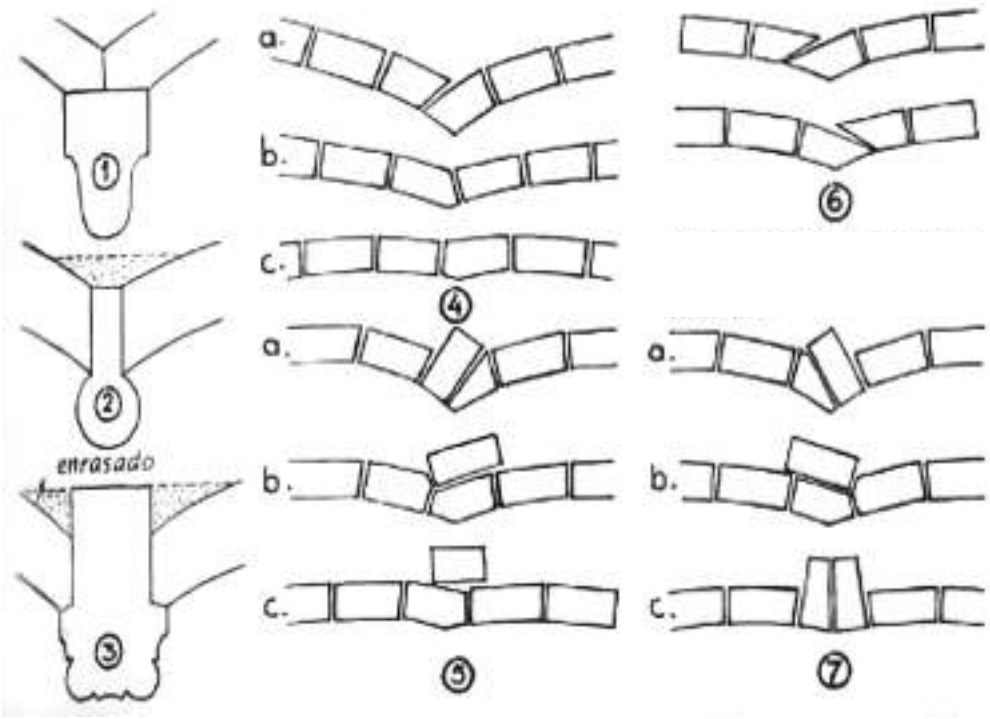
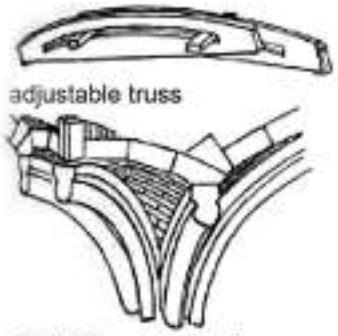


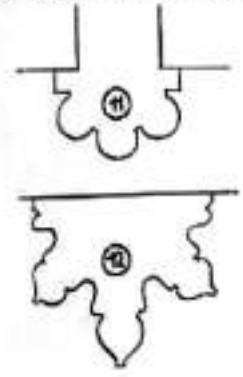
Fig. 4. From H. J. W. Thunnissen, *Bóvedas: su comportamiento y empleo en la arquitectura*, Instituto Juan de Herrera, ETSAM, Madrid 2012, p. 7, lam. 1.

GROIN AND RIB VAULTS. DETAILS OF RIBS





Springing of the vault. The nerves are reinforced by the interior



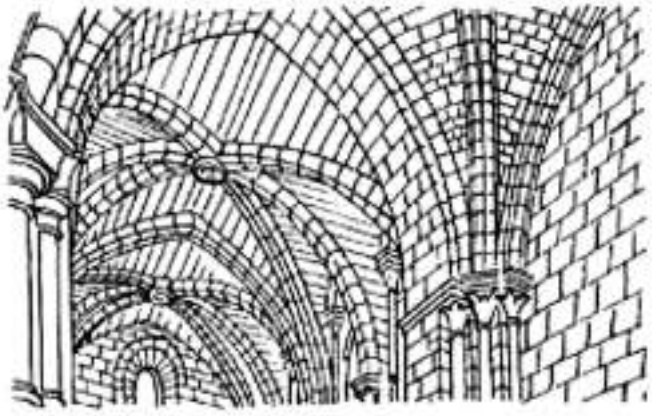


Fig. 5. From H.J.W. Thunnissen, *Bóvedas: su comportamiento y empleo en la arquitectura*, Instituto Juan de Herrera, ETSAM, Madrid 2012, p. 161, lam. 53.

CONSTRUCTIVE SYSTEMS OF ROMANESQUE AND GOTHIC VAULTS

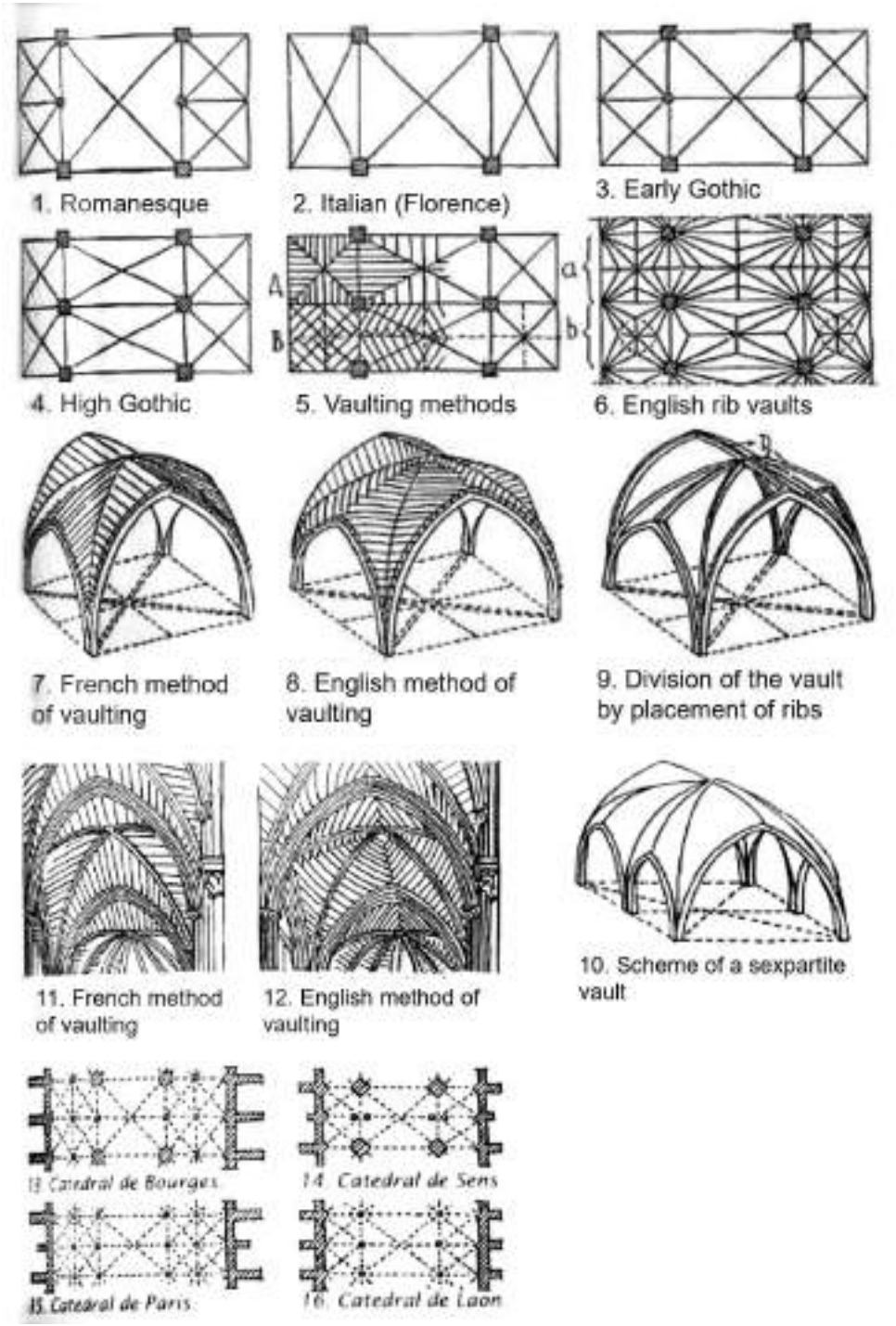
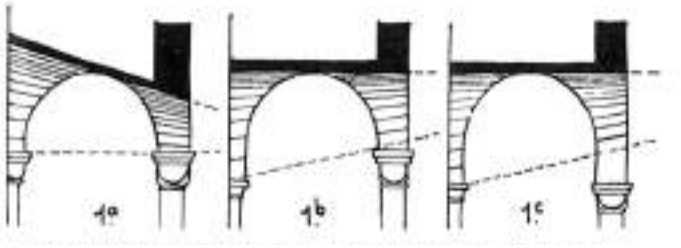


Fig. 6. From H.J.W. Thunnissen, *Bóvedas: su comportamiento y empleo en la arquitectura*, Instituto Juan de Herrera, ETSAM, Madrid 2012, p. 163, lam. 54.

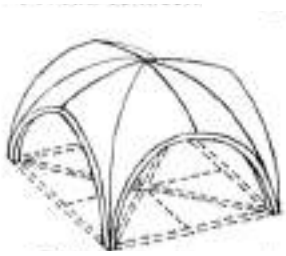
MEDIEVAL GROIN AND RIB VAULTS. LAYOUT OF THE KEYSTONE LINES

Partial plan of an apse aisle.

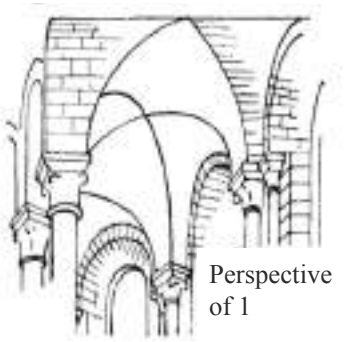


1. Different ways in which cylindrical annular corridor can intersect with a semi-conical vault (according to Ungewitter).

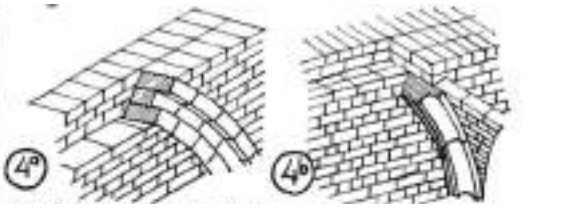
2. Groin vault with straight key lines. The front vaulting has been placed higher.



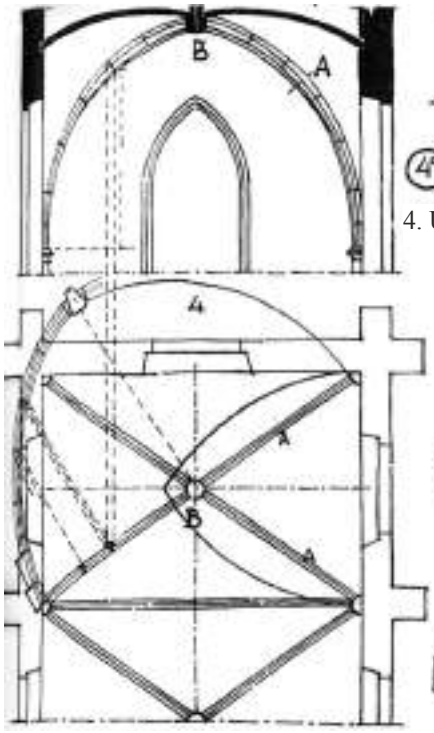
3. Ditto with curved lines and unevenly shaped edge arches.



Perspective of 1



4. Union of vaults and walls (according to Wanderley)



4. Groin vault with domed panels; one of the diagonal arcs has been absorbed.

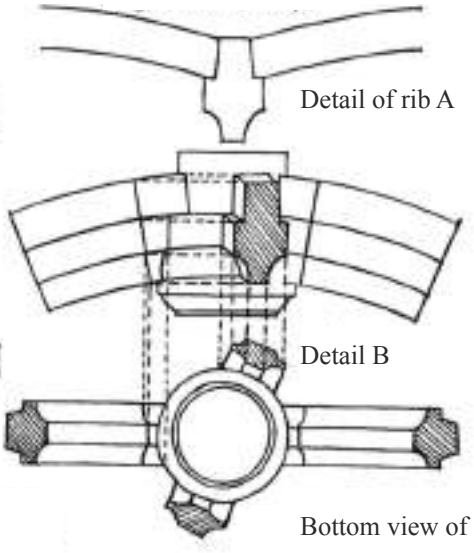
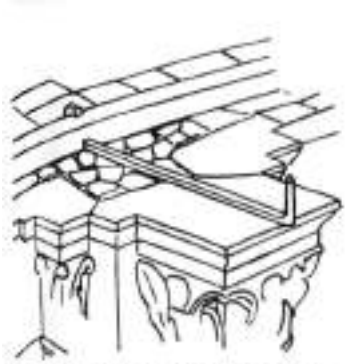
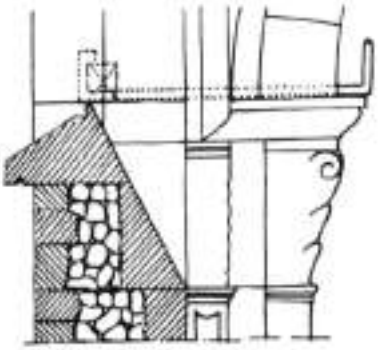


Fig. 7. From H.J.W. Thunnissen, *Bóvedas: su comportamiento y empleo en la arquitectura*, Instituto Juan de Herrera, ETSAM, Madrid 2012, p. 167, lam. 55.

STAYED VAULTS. CONSTRUCTION OF FORMWORKS

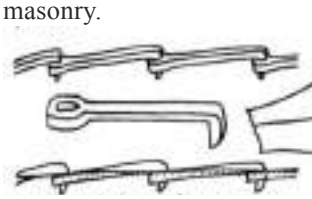


1. Wrench for temporary tie anchored to a beam within the masonry.

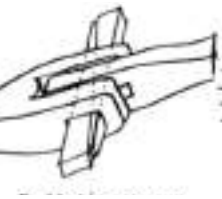


2. View of the anchor embedded in the factory.

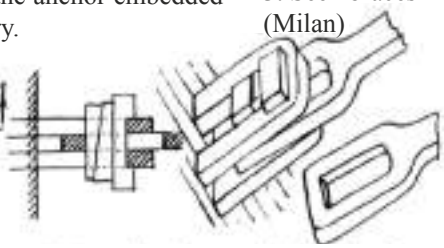
3. Seen braces (Milan)



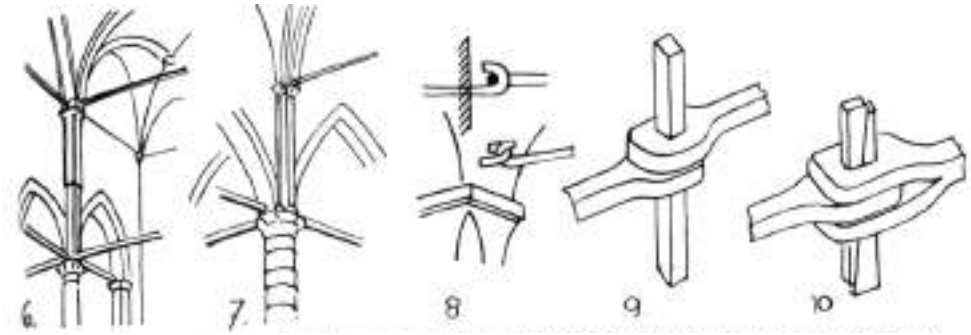
4. Chain ties used within the factory to absorbe tensile stresses.



5. Braces/ties union



3ª. Anchor union detail. The iron wedges action tensions the braces.



Cable-stayed systems in various churches. 6. Venice 7. Ferrara 9. Pistoia 10. San Pietro di Roma

11. Rib vault falsework

Fig. 8. From H.J.W. Thunnissen, *Bóvedas: su comportamiento y empleo en la arquitectura*, Instituto Juan de Herrera, ETSAM, Madrid 2012, p. 215.

DAMAGES AND BACKGROUND

- Historical references:
  - · Photographs, documents, testimonies
- Existence of previous buildings
- Structural or architectural modifications
- Damages: earthquakes, flooding…
- Modifications of the environment:
  - · Excavations, paving, sanitation, wells, cellars…

ANALYSIS OF OBSERVED PATHOLOGY

- Verify the origin of damages
- Typology of problems:
  - · Fissures
  - · Cracks
  - · Damages and deformation
  - · Inclination
  - · Deterioration
  - · Loss of material
  - · Patina, color change, vegetation, salts, efflorescences

TYPOLOGY OF PROBLEMS

DAMAGES AND DEFORMATIONS IN A VAULT STRUCTURE

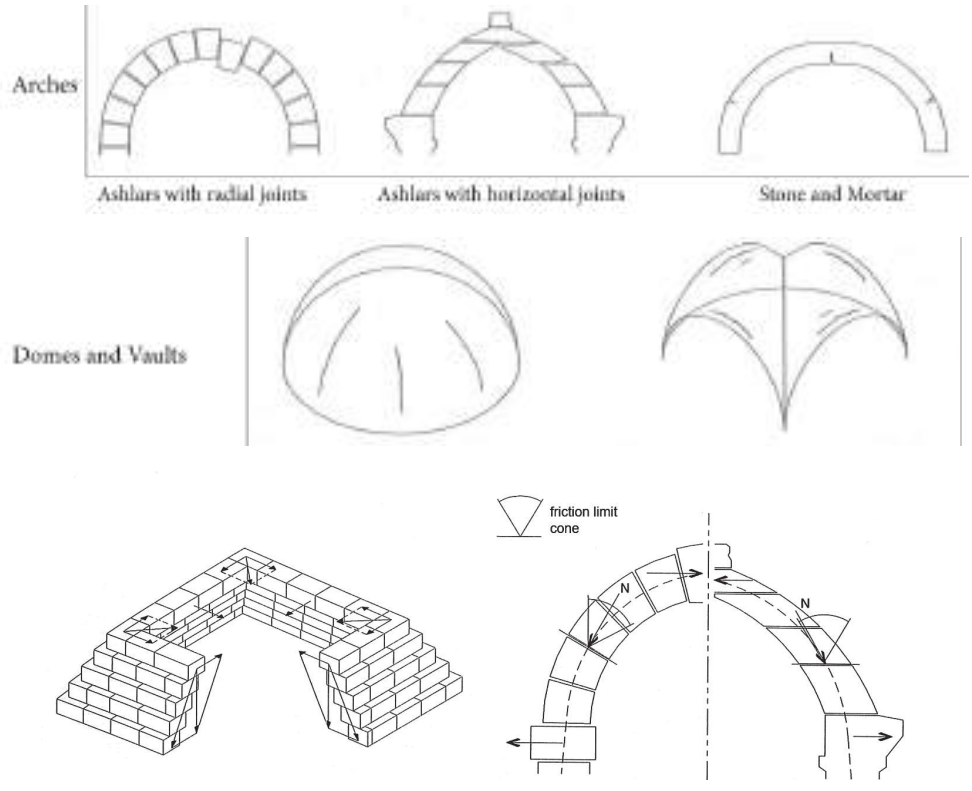


Fig. 9. From G. Croci, *Conservazione e restauro strutturale dei beni architettonici*, Utet, Torino 2011, pp. 47, 121.

CAUSES

– INCOMPATIBILITY (CONSTRUCTIVE) (1)

– GROUND
  · Soil Settlement
  · Changes

– LOADS

– STRUCTURAL
  · Originally
  · Joints

– HUMAN ACTION

– MATERIALS
  · Degradation
  · Oxidation

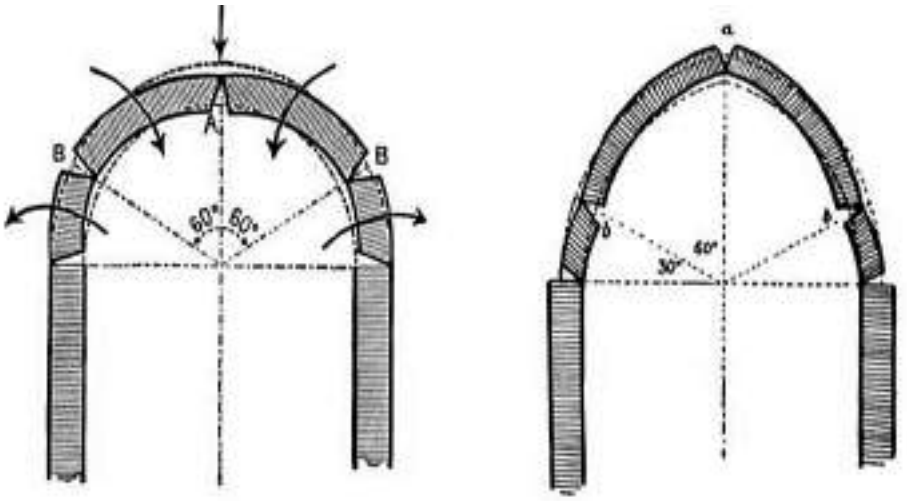


Fig. 10. From R. Di Stefano, *Il consolidamento strutturale nel restauro architettonico*, Edizioni Scientifiche Italiane, Napoli 1990, p. 96, fig. 51.

If vertical loads dominate, the arch opens at five points (on the left). If, instead, lateral loads are the dominant ones (on the right), each one of the five cracks manifests in the opposite direction.

HYPOTHESIS

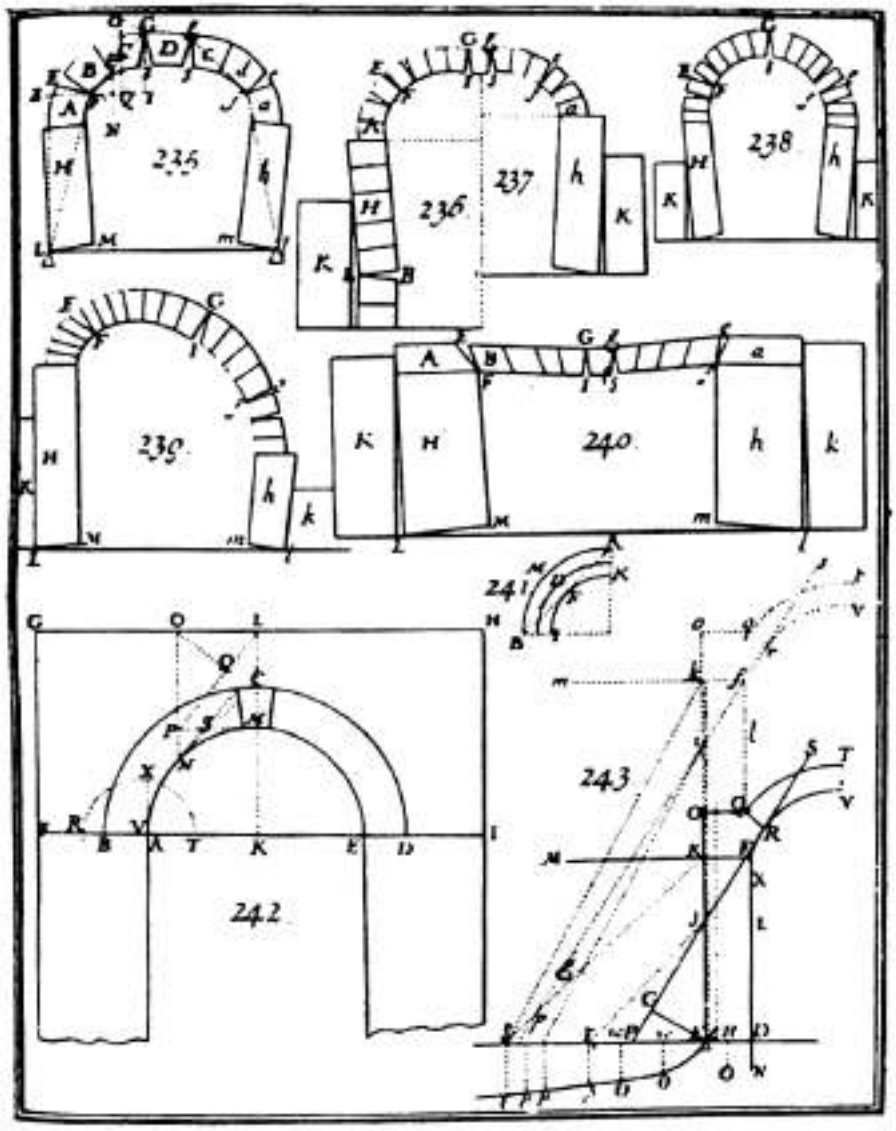
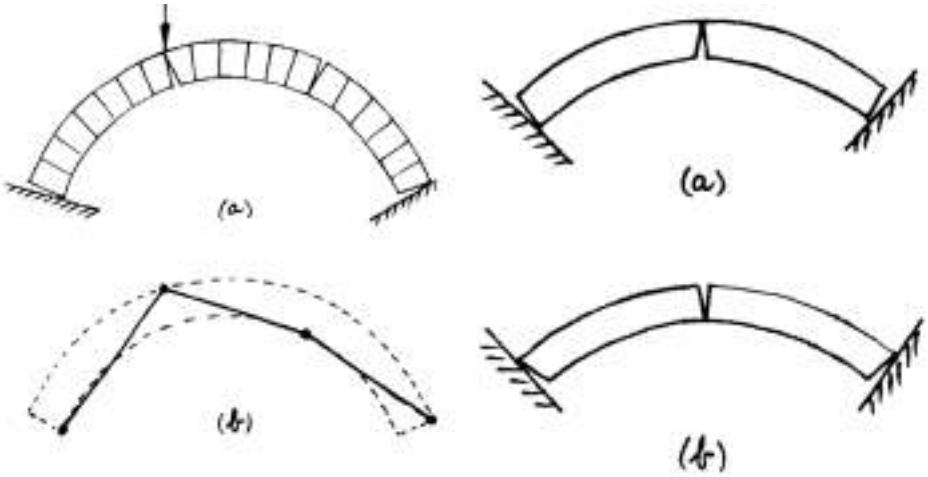


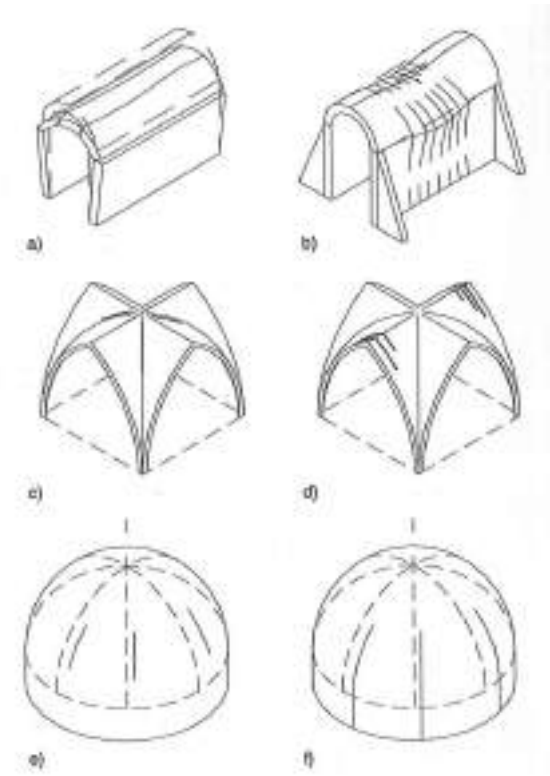
Fig. 11. From *The collapse of archs*, published by Frezier, in A. Giuffrè, *Monumenti e terrremoti, aspetti statici del restauro*, Roma 1988, p. 80.



Collapse mechanism
for a voussoir arch.
Four hinges are necessary

Voussoir arch fitted between abutments
of slightly the wrong span;
(a) too large, and (b) too small.
In either case the arch cracks
in three places

Fig. 12. Mainstone R. From L. Palaia, E. Abdilla, *Técnica de intervención en arcos, bóvedas y cúpulas*, "Stability concept from Renaissance to today", UPV, 1996, p. 71.



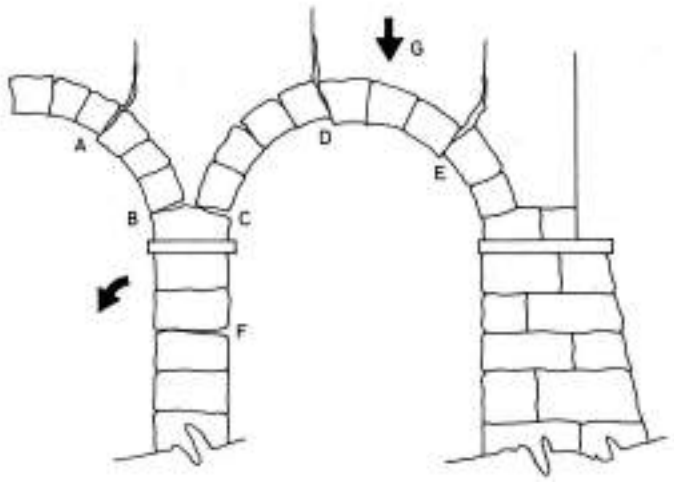


Fig. 13. On the left: from G. Croci, *Conservazione e restauro strutturale dei beni architettonici*, Utet, Torino 2011.

HUMAN ACTION

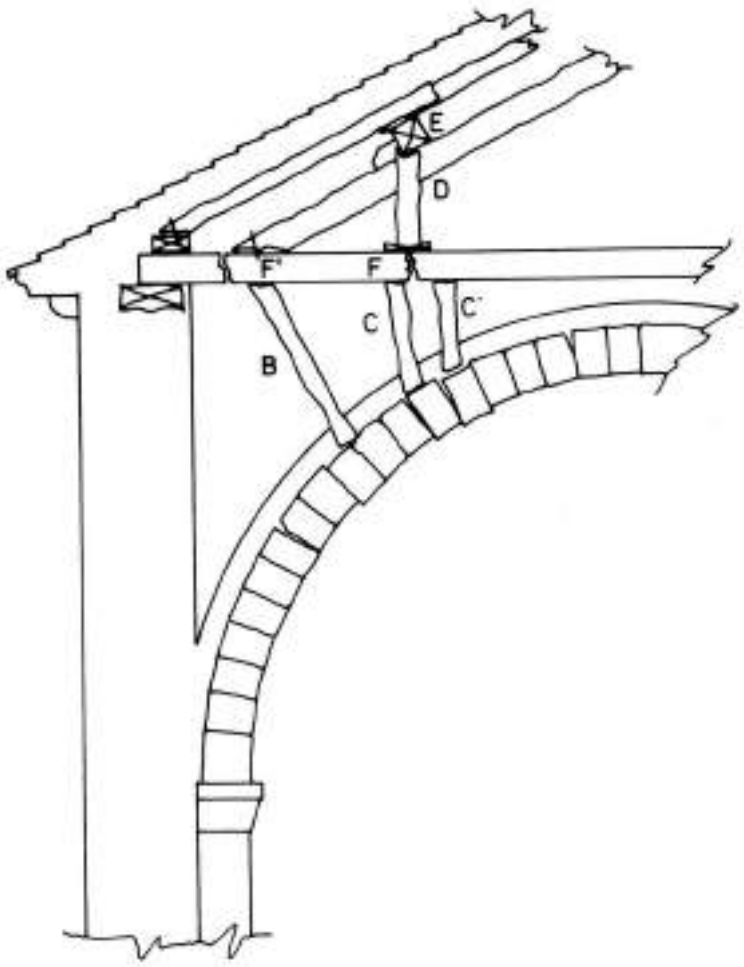


Fig. 14. On the right: from G. López Collado, *Las Ruinas en Construcciones Antiguas*, Miján, Artes, Gráficas, Ávila 1975, p. 72.

Fig. 15. From G. López Collado, *Las Ruinas en Construcciones Antiguas*, Miján, Artes, Gráficas, Ávila 1975, p. 233.

DEFECTS IN MASONRY VAULTS: SABOURET'S CRACKS

Typical cracks in Gothic vaults. Pol Abraham distinguished between the tensile cracks near the vault crowning, 'Sabouret cracks' parallel to the wall ribs, and the separation of the vault from the walls.

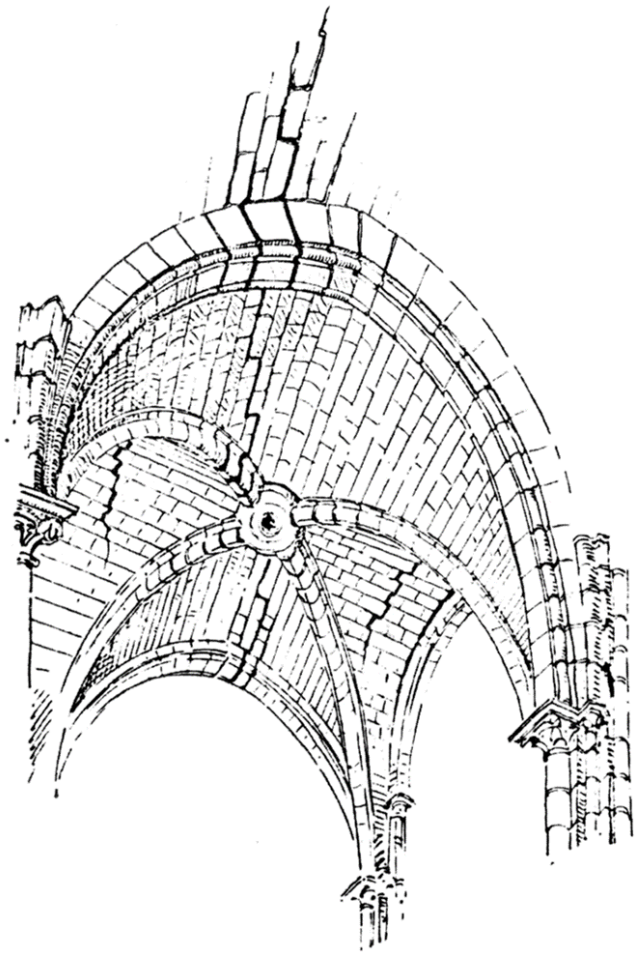


Fig.16. From J. Heyman, *The masonry arch*, Ellis Horwood serie in Engineering Science, 1982, pp. 3-19.

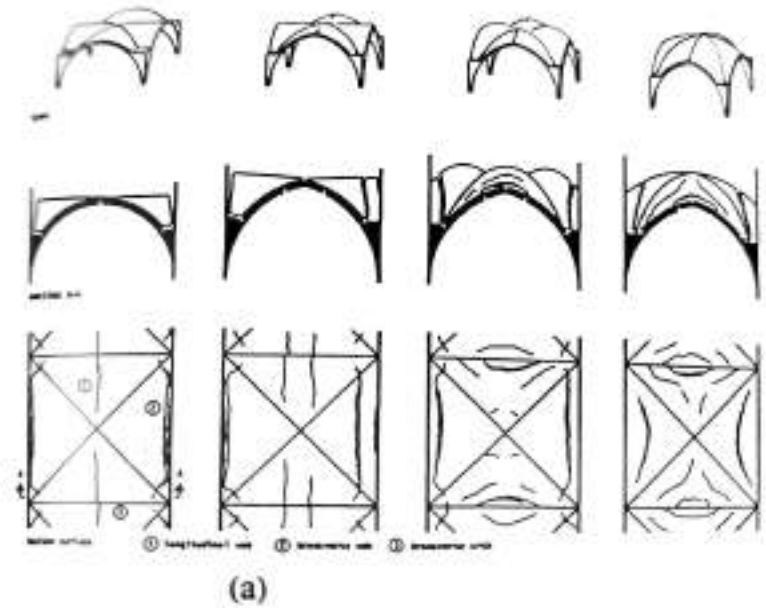


Fig.17. From J. Heyman, *The masonry arch*, Ellis Horwood serie in Engineering Science, 1982.

CONSOLIDATION OF VAULTS

– Reconstruction of lacunae (2)
– Sealing of cracks
– Overlay:
  · Upper reinforcement
  · Upper structure
– Anchoring
– Restore the shape to the vault
– Shoring

RECONSTRUCTION OF LACUNA

Fig. 18. Cáceres, Spain. Photo by Susana Mora, 2014.

SEALING OF CRACKS

Fig. 19. Vault in the cloister of Carracedo Monastry, Spain. Restoration by S.P. Arroyo and S. Mora. Photo by Susana Mora.

OVERLAY

UPPER REINFORCEMENT

– Poured or Shell

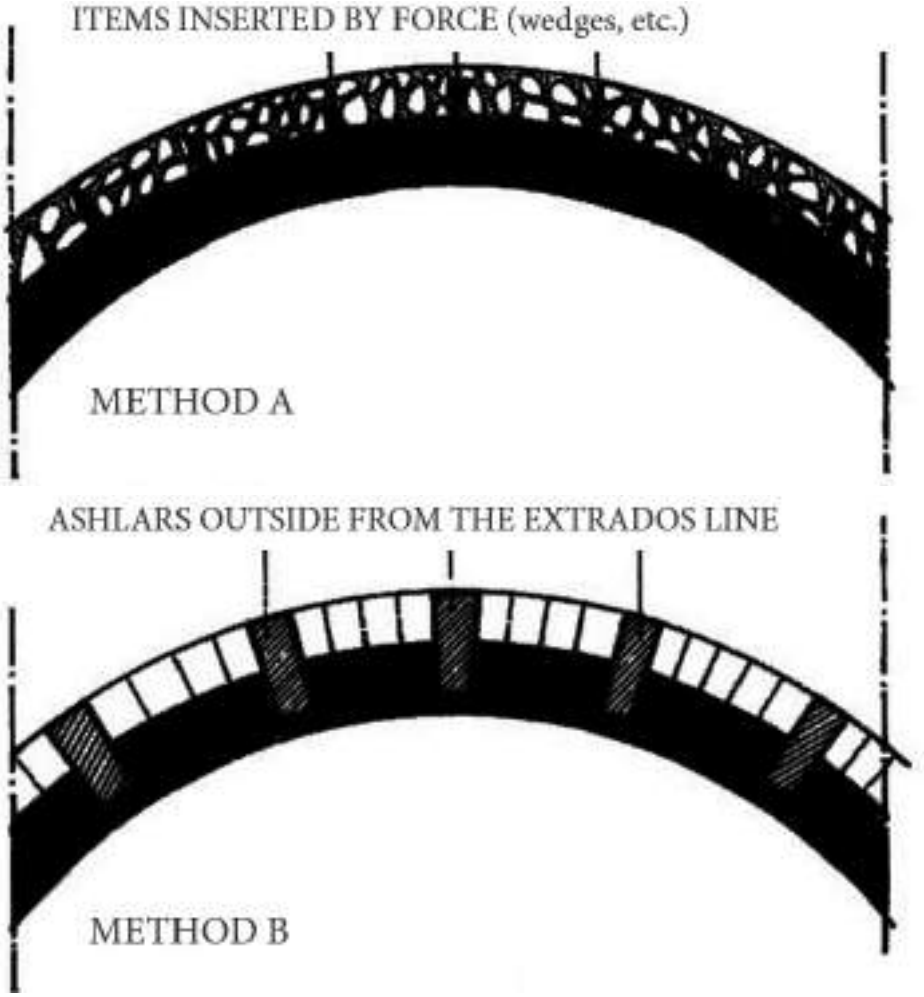


Fig. 20. From C. Piccirilli, *Consolidamento critico*, Multigrafica editrice, Roma 1989, p. 68.

– Reinforcement with metalic/glass fiber frame

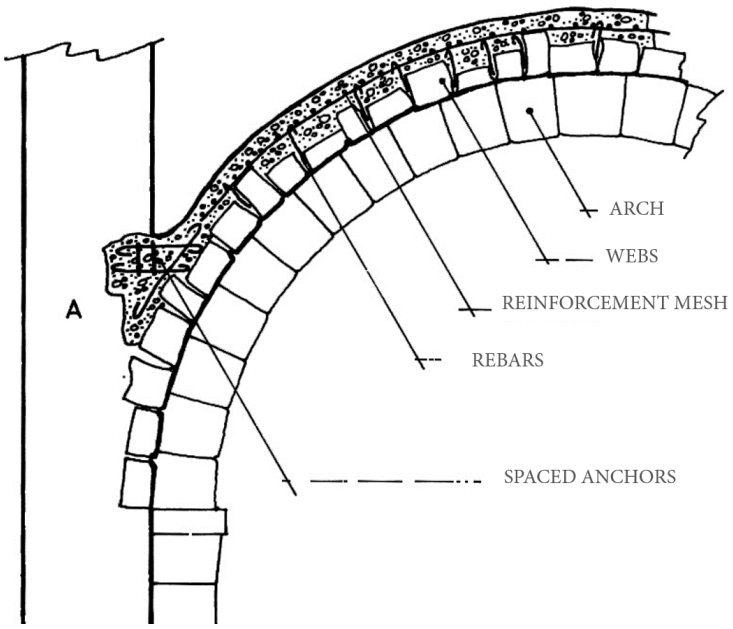


Fig. 21. From G. López Collado, *Las Ruinas en Construcciones Antiguas*, Miján, Artes, Gráficas, Ávila 1975, p. 251.

– Reinforcement with metalic frame.

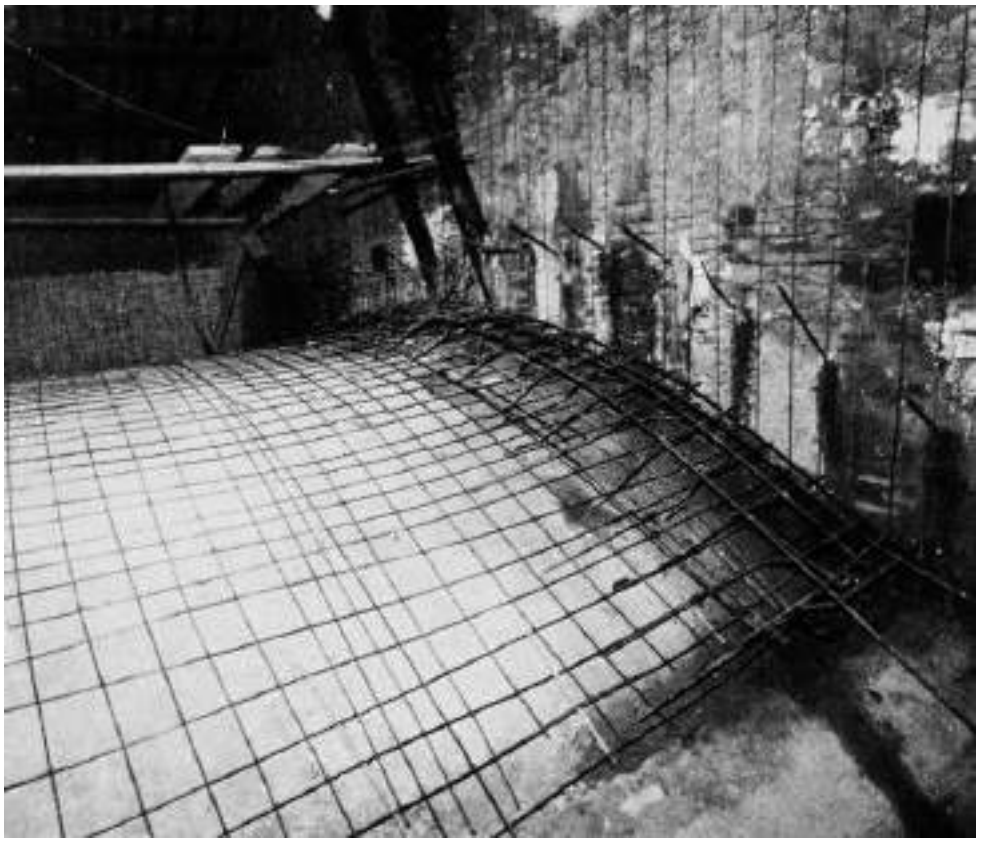


Fig. 22. San Silvestro in Capite, Roma. F. Lizzi Method. From F. Lizzi, *The static restoration of monuments*, Sagep Publisher, Genova 1982, p. 24.

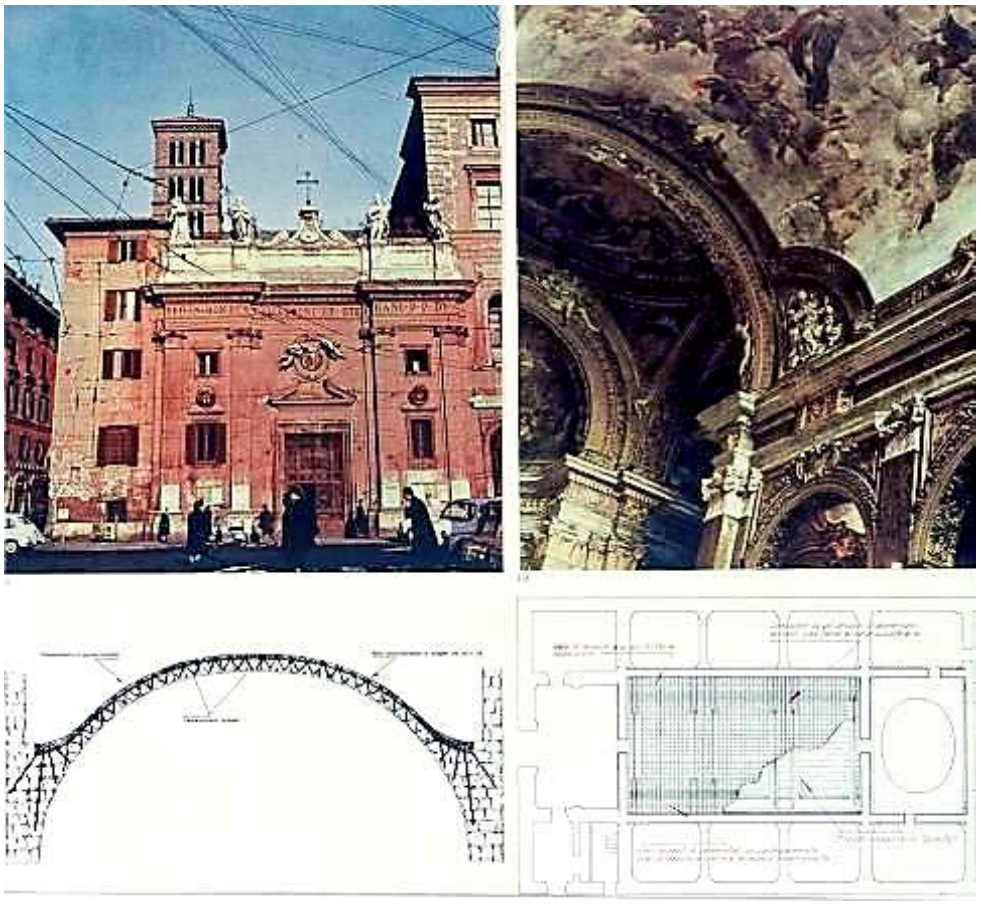
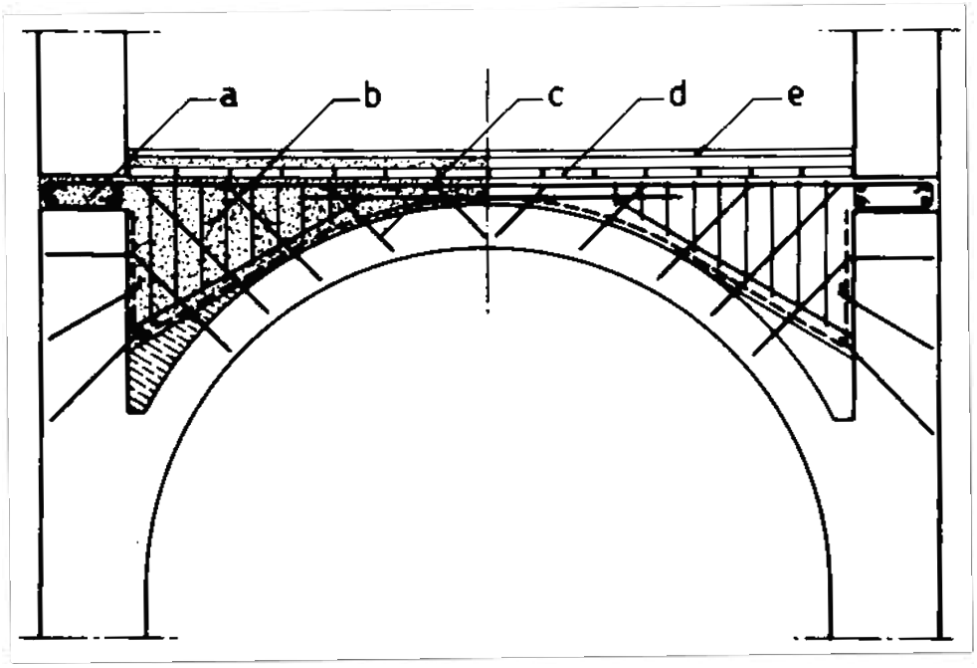


Fig. 23. San Silvestro in Capite, Roma. From F. Lizzi, *The static restoration of monuments*, Sagep Publisher, Genova 1982, p. 23.

– Reinforcement with carbon fibers.

UPPER STRUCTURE



– Hanging

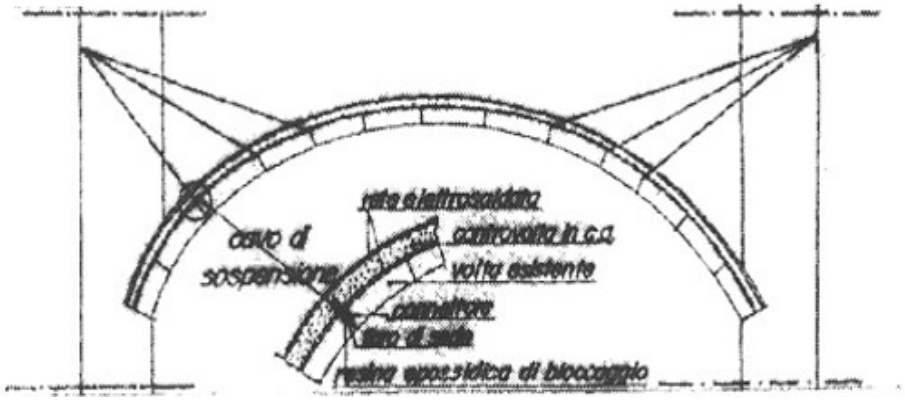


Fig. 24. From C. Piccirilli, *Consolidamento critico*, Multigrafica editrice, Roma 1989, p. 71.

ANCHORING

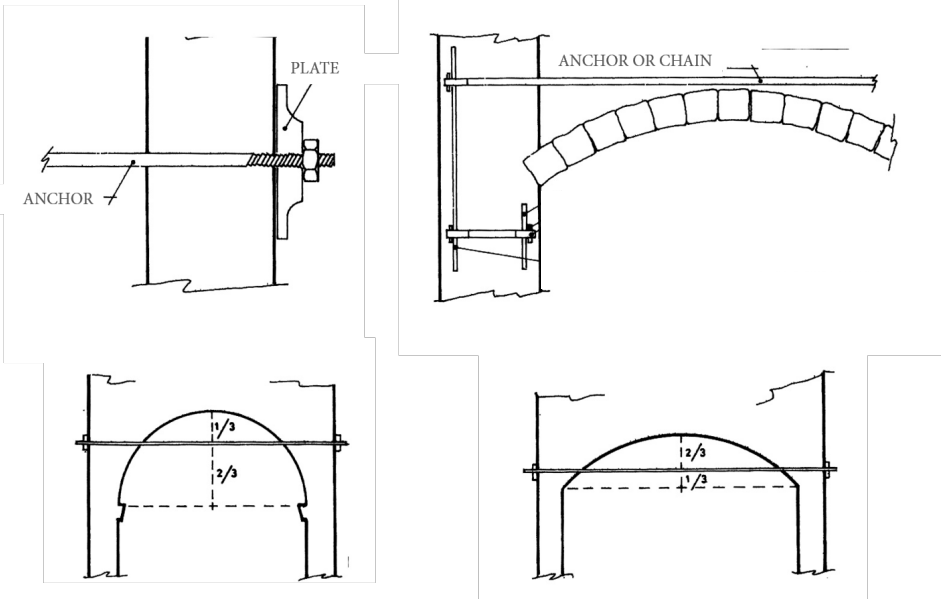


Fig. 25. From G. López Collado, *Las Ruinas en Construcciones Antiguas*, Miján, Artes, Gráficas, Ávila 1975.

RETURN THE SHAPE TO THE VAULT

REINFORCED ARCH

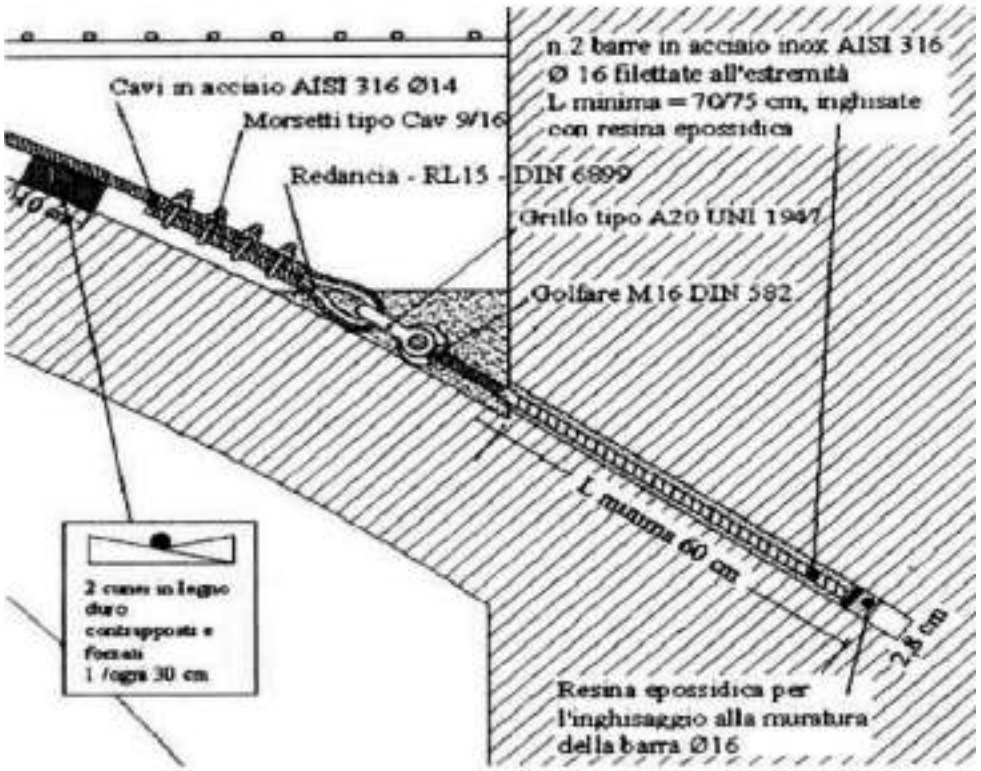


Fig. 26. Castello Mediceo. Intervention carried out by Lorenzo Jurina using the "reinforced arch" method, applied to the extrados of the vault. Details of the anchoring of the ties to the masonry, with post-tensioned by wooden wedges. From L. Jurina, *Evoluzione e declinazioni nell'uso dell'"Arco Armato"*, Politecnico di Milano 2013.

Figs. 27-29. From G. Carbonara, *Atlante del restauro architettonico,* vol. II, Utet, Torino 2004.

Fig. 30. Castello della Manta. Lorenzo Jurina used the "reinforced arch" method, applied to the extrados of the vault. Details of the anchoring of the tie-rods to the masonry and of a crossing of tie-rods, with post-tensioned by tensioners. From L. Jurina, *Evoluzione e declinazioni nell'uso dell'"Arco Armato"*, Politecnico di Milano 2013.

Fig. 31. Villa S. Carlo Borromeo. Lorenzo Jurina used the "reinforced arch" method, applied to the intrados of the vault. View of the intrados. Details of the anchoring of the tie-rods to the masonry, with post-tensioned by tensioners. From L. Jurina, *Evoluzione e declinazioni nell'uso dell'"Arco Armato"*, Politecnico di Milano 2013.

SHORING

Support constructions or parts of constructions in order to structurally stabilize and transfer loads to the ground.

Fig. 32. Monastero Olivetano. Lorenzo Jurina used the "reinforced arch" method, applied to the extrados of the vault. Details of the anchoring of the tie-rods to the masonry and of a crossing of tie-rods, with post-tensioned by wooden wedges. From L. Jurina, *Evoluzione e declinazioni nell'uso dell'"Arco Armato"*, Politecnico di Milano 2013.

Fig. 33. Santa Maria di Collemaggio, L'Aquila. Photo by Susana Mora, 2012.

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