ARCHITECTURAL DESIGN PRINCIPLES AS EVIDENCED IN GOTHIC ARCHITECTURE

by

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Committee Chairman: Dayton E. Egger,
Architecture and Urban Design

(ABSTRACT)

Three specific architectural design principles are identified and documented through a study of gothic architecture.

The comparative method is used to show progressive change in gothic architecture and to illustrate how these design principles are evident in this change.

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ACKNOWLEDGEMENTS

I would like to take this opportunity to thank some of the many people who have encouraged and aided me in this task.

To my wife for her patience and beautiful typing.

To the members of my committee,
for their help, and especially for his patience and insight.

To my parents for their long-suffering faith.

To my friends for their encouragement.

And most importantly to God for his strength.

GLOSSARY OF TERMS

Abbey Church: The church, governed by an abbot, which was usually associated with a monastery

Abutment: A general term covering various masonry members intended to resist lateral thrusts from an arch or vault

Aisle: The colonaded passageway flanking the nave. Also the lower portion of the wall which seperates the nave and the aisle proper

Ambulatory: The arch between the apse and the radiating chapels generally used for walking

Apse: A projection to a church floor plan, usually at the east end of the nave

Arch: A curved masonry structure, usually constructed of separate stone elements which is used to span an opening and support the upper wall

Barrel Vault: A vault in the form of a half cylinder

Bay: The portion of a wall encompassed by two major structural elements

Blind: A reference to an opening which has been filled with masonry

Centroid: The center of gravity of a mass

Chapel: A small chamber, often located around an apse, used for small-scale services and meditation

Choir: The area of the nave occupied by the clergy and the choir

Clerestory: The upper portion of a wall which is pierced by windows

Corbel: A stone, or series of stones, which projects from a wall to give support to the succeeding courses of stone

Cruciform Plan: Laid out in the shape of a cross

Crown of Vault or Arch: The highest point of a vault or arch

Dynamic System: A structural system which can absorb movement within that system without failing

Flying Buttress: A light masonry half arch between the clerestory wall and the great buttress, which transmits the thrusts of the vault to the great buttress

Gothic: That architectural style in common use in western Europe from the twelfth through sixteenth centuries which succeeded the Romanesque and was in turn succeeded by the Renaissance. This style was characterized by the development of articulated structure and the use of strong vertical elements and pointed arches.

Gothic Vault: A vault formed by four pointed arches with corresponding ribs forming pointed arches

Groin: The V which is generated by two intersecting vaults and thin ribs

Haunch: That portion of an arch or vault which is roughly between the crown and the springing

Line of Force: The resultant of the compressive forces in the individual voisseurs of an arch or vault

Lintel: A horizontal structural member which spans an opening and supports the upper portion of the wall

Nave: The main interior space of a church usually between the aisles

Pier: A free-standing column or collection of columns which convey the load of the upper portion of the wall to the foundation

Pialaster: A thickening of a wall to reinforce it in the vertical direction

Rib: A stone arch which projects below the surface of and acts to support a vault

Rose Window: A large circular window, usually located in a prominent location, which is filled with radiating stained glass panels

Spring Point: The point on an arch where the curvature of the arch begins

Static System: A structural system which cannot absorb movement within that system without failing

Trancept: The two lateral arms which project from the nave of a church built on a cruciform plan

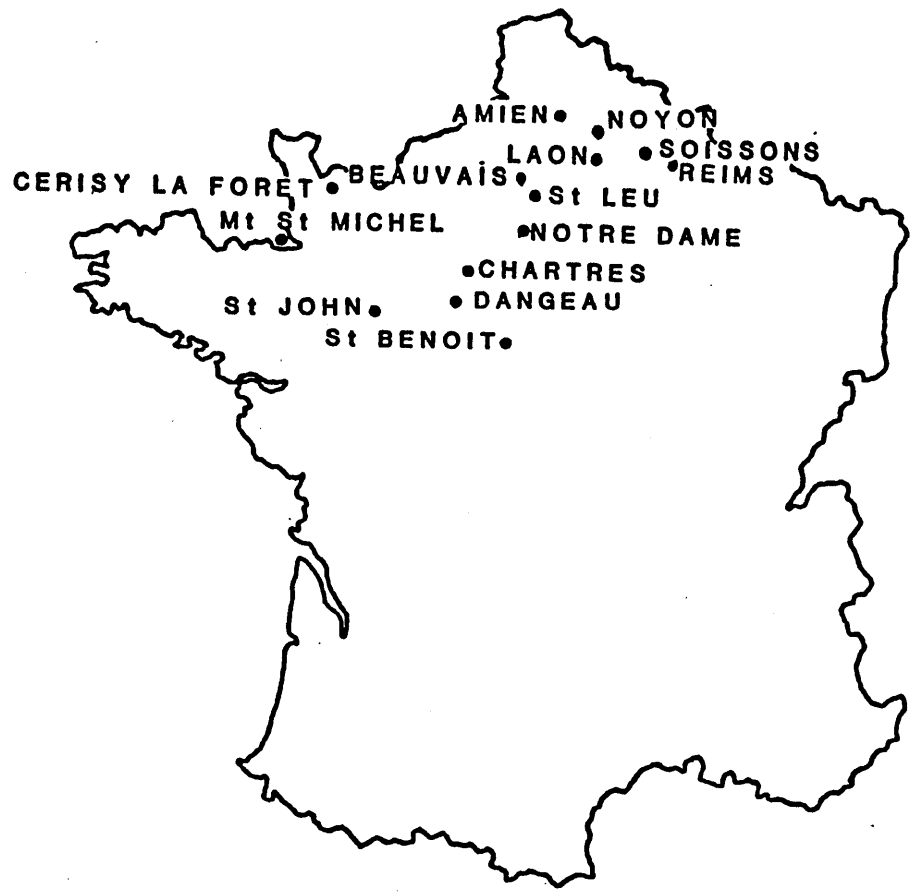
Triforium: A shallow gallery in the aisle wall below the clerestory

Thrust: The force in an arch or vaulted structure which tends to force the sides outward or to overturn the supports of the arches

Vault: The curved surface generated by mutually supporting masonry units acting as an arch

Voisseurs: Individual wedge-shaped stones which make up an arch or vault

Wall Buttress: The thickening of a wall at a specific location which is intended to stabilize a wall and allow it to resist thrusts



LOCATION MAP

INTRODUCTION

There are many ways to study architecture. In many cases, however, these ways are difficult to identify. One way to gain understanding is to study examples of architecture which are recognized as exemplary and search for trends and patterns.

One period which is especially well suited for this type of study is the Gothic. Between the years of 1100 and 1400 AD, there was a virtual explosion of church building in Europe. This monumental construction effort left a legacy that is ideally suited for comparative study. First, there are many structures which are still in existence. This allows for a broad base of study and the identification of common elements, problems and solutions. Second, those structures were intended to perform a single function. As a result many of the elements and symbols remain constant throughout the period. Third, the structures were constructed with limited materials; therefore, changes in technology are easy to identify and evaluate.

The following drawings document the Gothic period and seek to identify some of the factors which make these buildings significant.

The development of these drawings has brought to light three aspects of Gothic architecture which are valid even today.

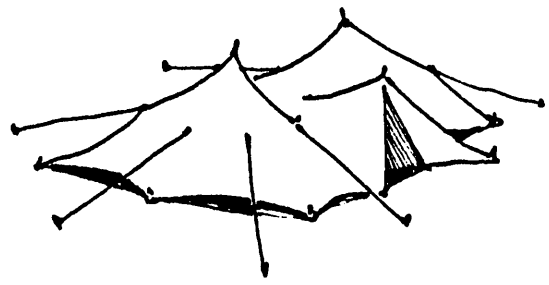
Simply stated, they are:

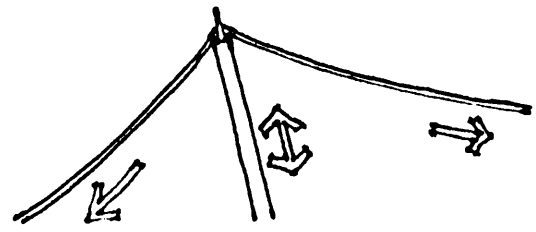
1. The use of repetitive elements
2. The use of varying solutions to a common problem
3. The refinement and application of technology to enrich space

As a precedent to studying Gothic architecture, some basis in the available technology is necessary since in large measure the manner in which space is enclosed is determined by the properties of the available materials.

Two problems must be addressed when enclosing space; first, how to hold up the roof, and second, how to penetrate the enclosure.

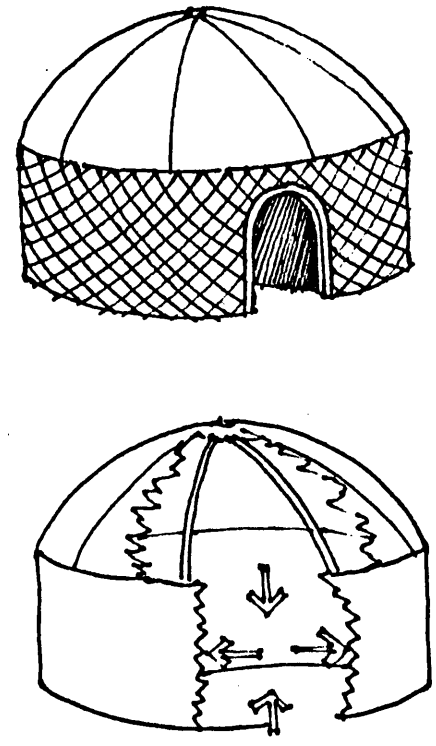
In non-rigid structures a flexible membrane is simply supported with light compression members.





The membrane is placed in tension while rigid members act in compression.

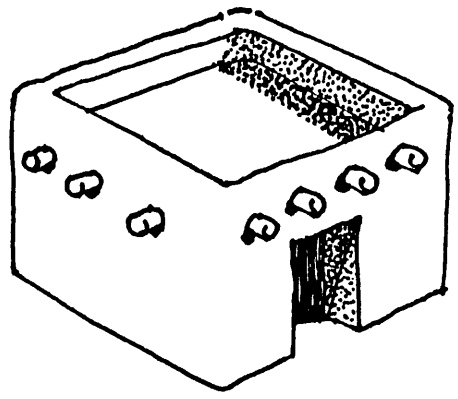
Semi-rigid structures require parts of the structure to function both in tension and compression.

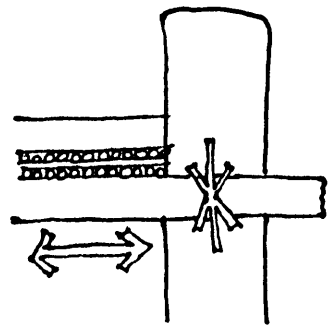


The membrane continues to function in tension while the lower frame acts under vertical compression and horizontal tension. The tension forces result from the weight of the membrane and its supports pressing downward and tending to push the lower frame outward.

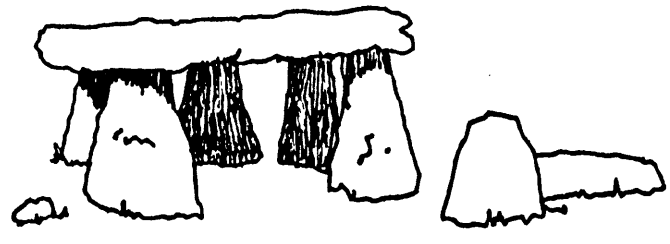
In this condition, the ability of the structure to remain erect depends in large part upon the ability of the lower frame to act both in tension and in compression.

Rigid structures place increased demands on their constituent parts because they tend to enclose larger spatial volumes and to utilize heavier materials. Heavier roof systems produce greater resultant forces on walls and points of connections.

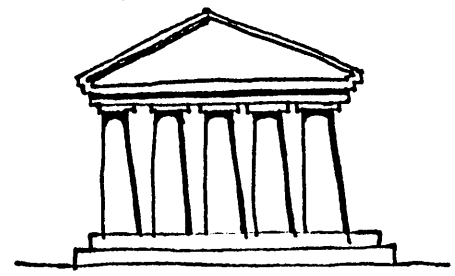




Stone is one of the most durable building materials. Until the advent of steel, stone was the material of choice for almost all large-scale buildings.



Stone has relatively little ability to function in tension, a limitation that directly affected the ways in which it was utilized.



The second problem coincident with that of enclosure is how to penetrate the enclosure itself. Enclosing space implies that that space will be used for some purpose, hence the need for access.

The penetration of an enclosure involves many of the same problems encountered when constructing the enclosure; however, they tend to be more simple.

Therefore, considering some of the aspects of penetrations in walls is a good introduction into enclosures.

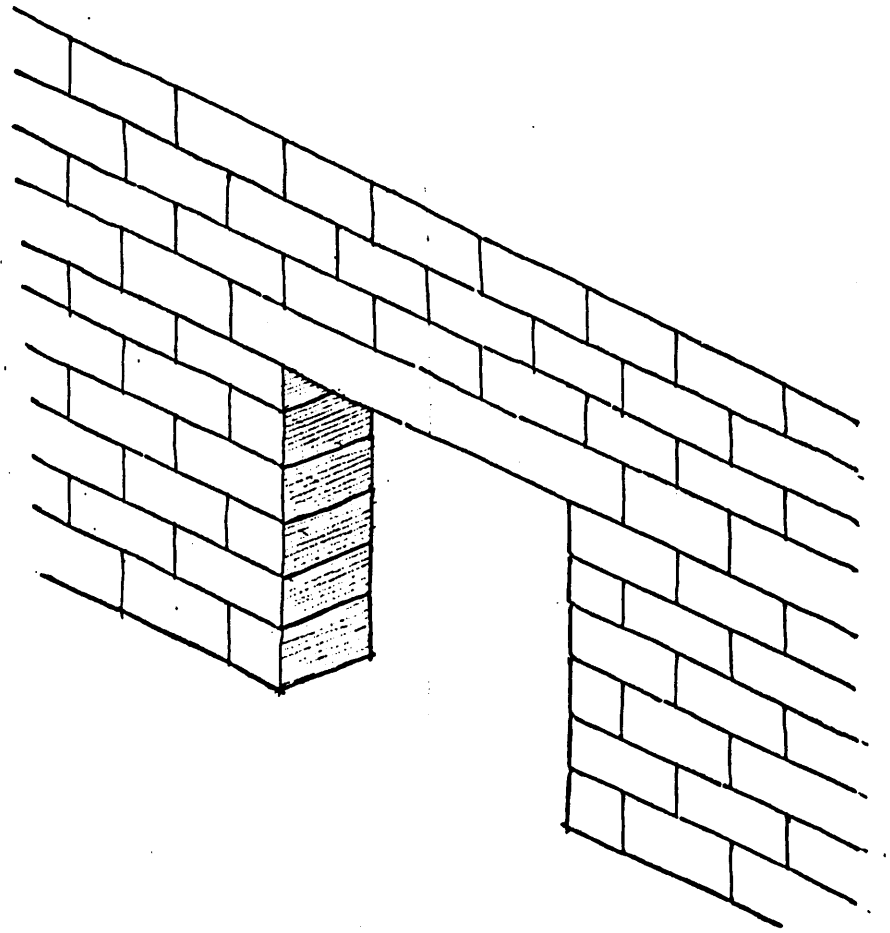
TECHNICAL FUNDAMENTALS
(WALL)

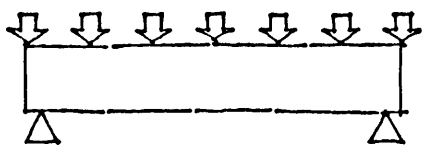
The limitations of stone were well understood by the Gothic masters. The knowledge available to them had been accumulated through centuries of practical application in many types of buildings.

The drawings which follow are intended to convey some of the complexities of stone construction. This knowledge is fundamental to recognizing: how repetitive elements were utilized as structural members and as a means of establishing patterns and subdividing space; how different solutions to a common problem create complexity and interest; and how technological improvements in stone construction changed the nature of the space itself.

LINTEL

The simplest way to support a penetration in a stone enclosure is with a lintel. A lintel acts to span an opening and to transfer a distributed load to supports at each end.(figure 1). The forces on the lintel result in tension and compression forces acting on the member at the same time.(figure 2). The net effect on the lintel is to place the bottom surface in tension which can result in the failure of the member (figure 3).due to stone's poor tensil characteristics.[1]





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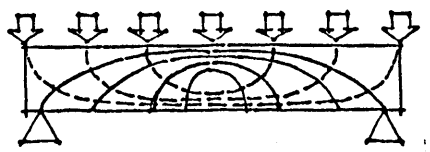

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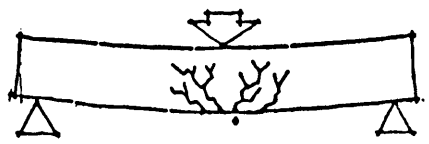


3. FAILURE

LINTEL

Simple technology

Static system

Opening limited in width

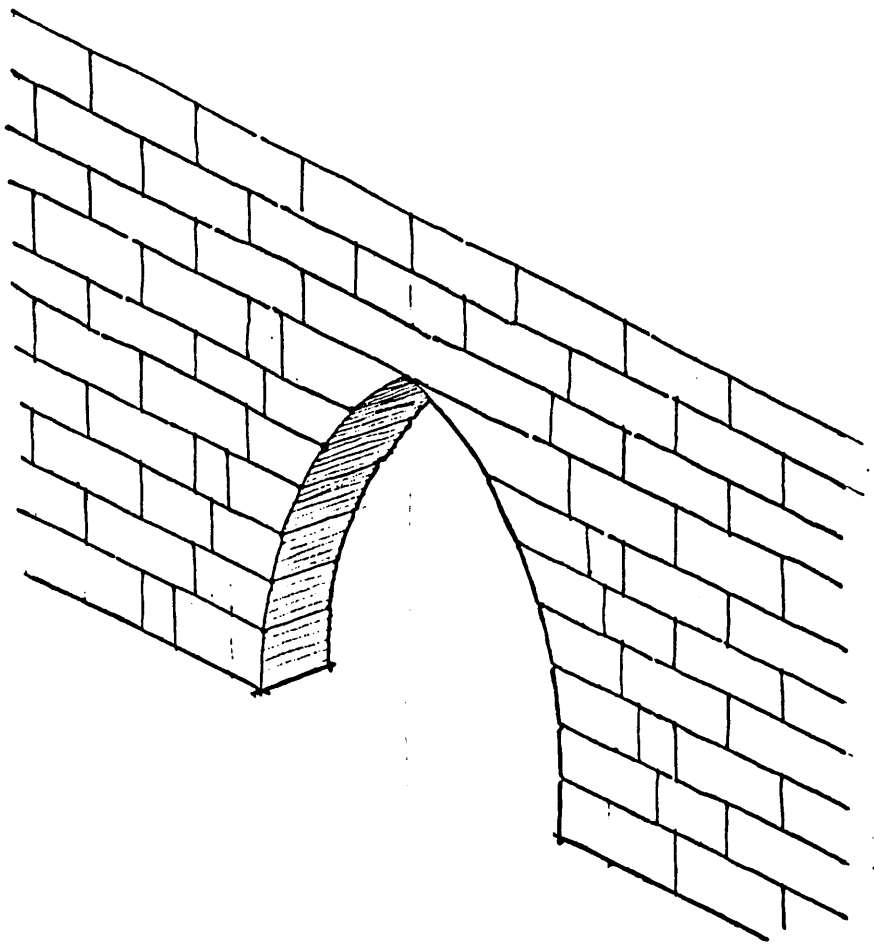
Repetitive use requires large pier/cols between penetrations

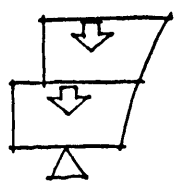
CORBEL ARCH

The poor tensile strength of stone requires a means of penetration which allows the materials to function in compression.

An early attempt to achieve this condition resulted in openings formed with corbeled stones. Each successive member places its predecessor in compression (figure 1). The resultant line of force, however, falls inside the centroids of the units (figure 2), which can result in failure of a unit (figure 3).

This construction has limited practical application since the size of openings which can be accommodated are small and cannot readily be expanded or effectively used repetitively.[2]





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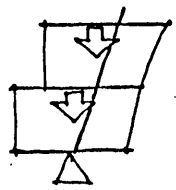

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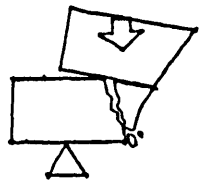


3. FAILURE

CORBEL ARCH

Improved technology

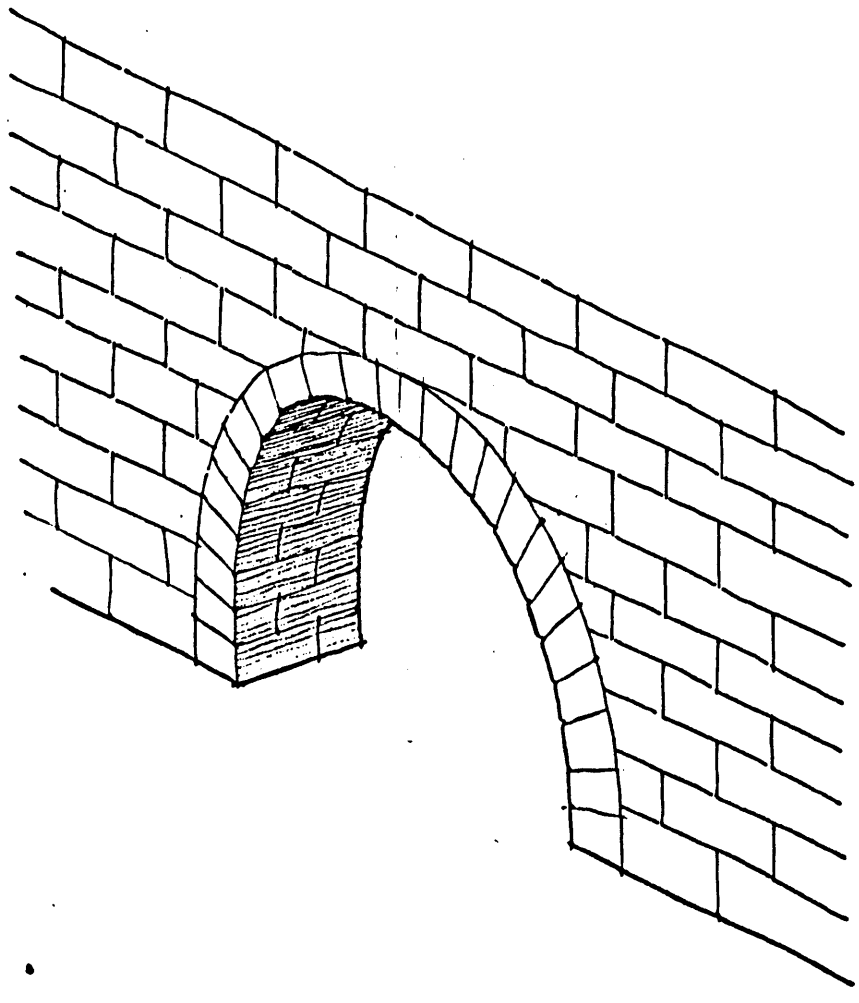
Static system

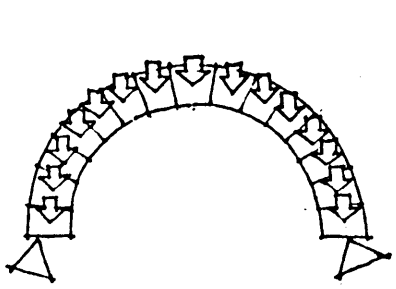
Opening limited in width

Repetitive use requires large piers/cols between penetrations

ROUND ARCH

The round arch is a more effective means of supporting a wall at a penetration. The individual stones or voisseurs all act as though under a point load (figure 1). This action places all of the voisseurs in pure compression. Unfortunately, the line of pressure, that is, the resultant of all the compressive forces, again fails to align itself with the centroids of all the stones (figure 2). The result is a tendency for the arch to fail by collapsing if the sides are allowed to expand outward (figure 3).[3]





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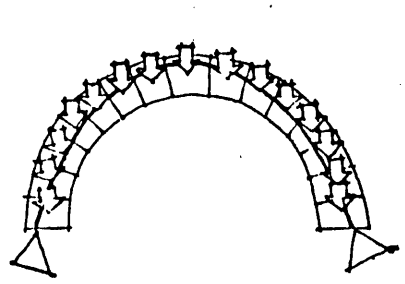

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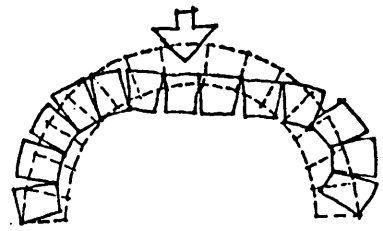


3. FAILURE

ROUND ARCH

Complex technology

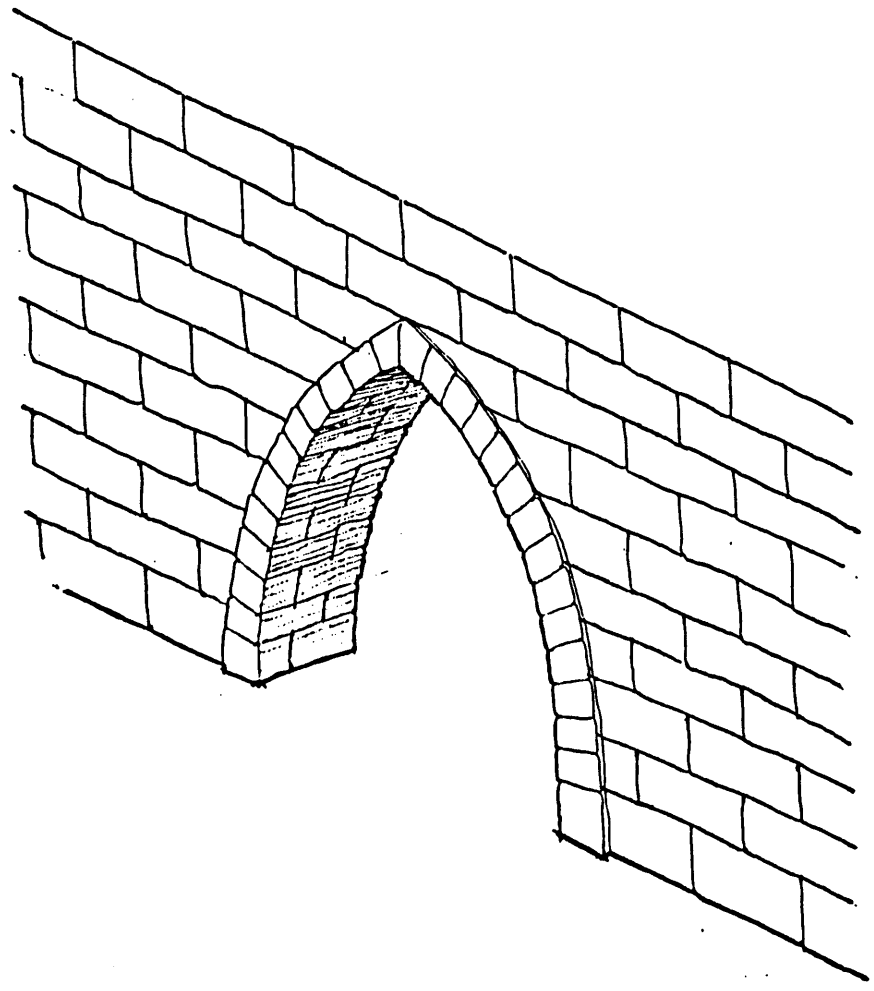
Static system

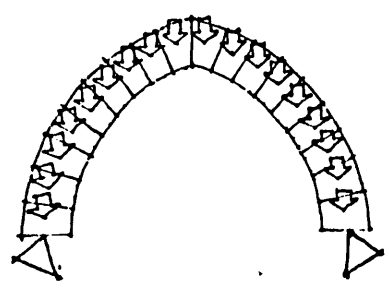
Opening can be varied in size

Repetitive use requires lighter pier/cols due to concentration of forces

POINTED ARCH

A pointed arch is inherently more stable than the round arch. The voisseurs still act as though loaded at their centroids (figure 1), but the structure of the arch causes the line of pressure to be more nearly coincident to the centroids of the stones (figure 2). This results in the arch being able to distribute the forces imposed upon it more effectively. The pointed arch also has a certain capacity to absorb movement in the structure as a whole with failure being dependent on imbalanced loading rather than the poor distribution of the resultants (figure 3).





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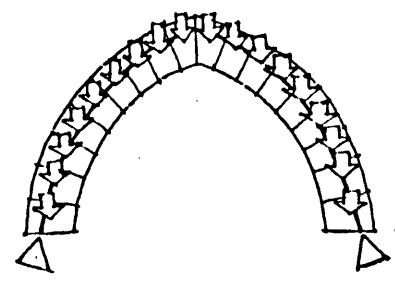

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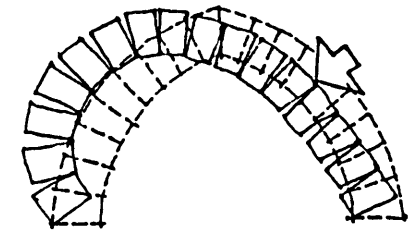


3. FAILURE

POINTED ARCH

Highly complex technology

Dynamic system—arch can absorb shifts in wall

Opening can be varied in size

Repetitive use requires only light piers/cols due to concentration of forces

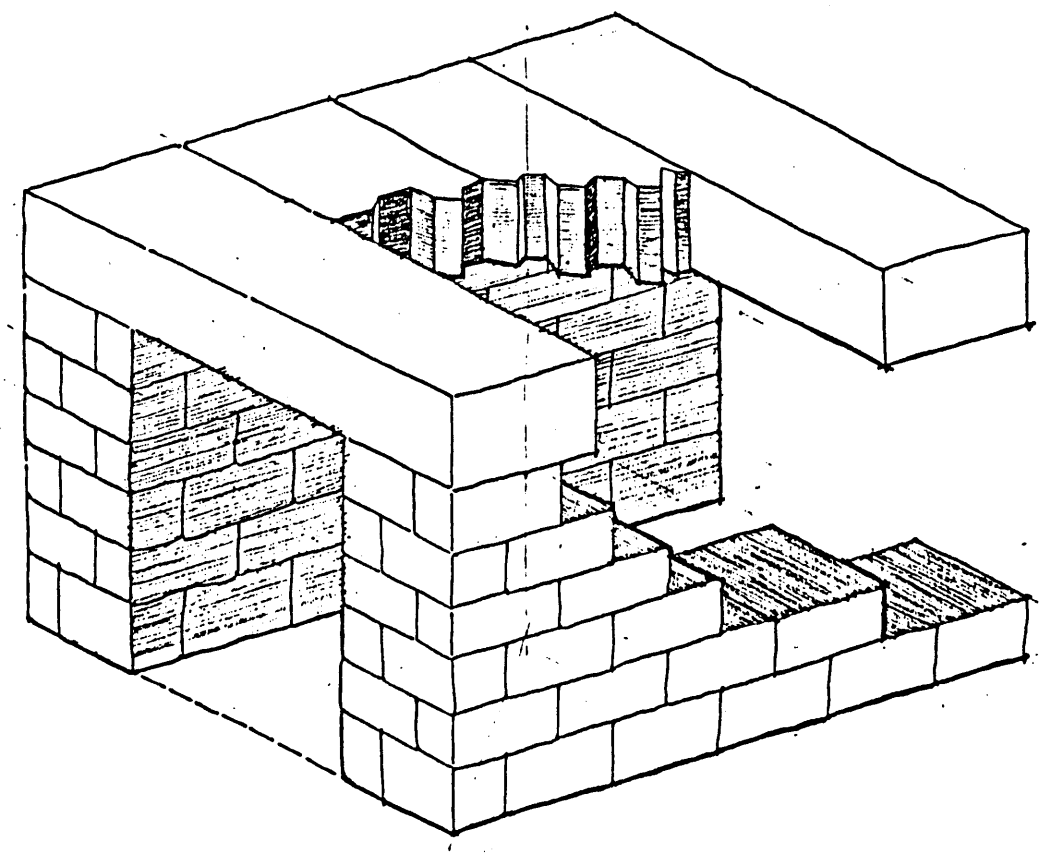
TECHNICAL FUNDAMENTALS
(ENCLOSURE)

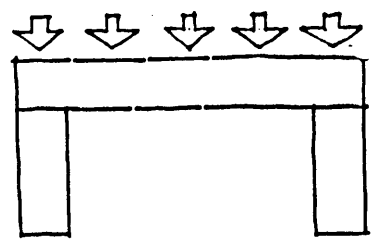
The technology employed in the penetration of the stone wall can be applied to the enclosure of space.

This next series of drawings deals with the expansion of wall penetrations into enclosures.

SLAB VAULT

The lintel can be extended into the third dimension to become an enclosure. The distribution of forces is identical to the wall lintel when considered in section (figure 1). Failure can occur in one of the stones or the entire lintel system for the same reasons evidenced in the wall condition (figure 2). The forces are uniformly collected and transmitted to the walls (figure 3), but the restrictions on span, combined with the massive side walls required to support the heavy lintels, minimize the potential of the enclosed space.[4]





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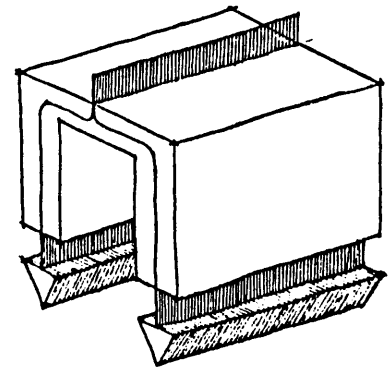

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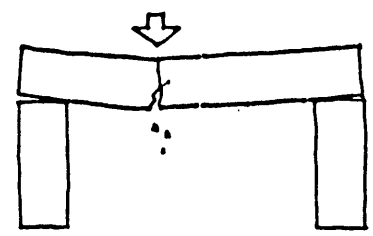


3. FAILURE

SLAB VAULT

Simple technology

Static system

Massive structure

Vault span limited by slab strength

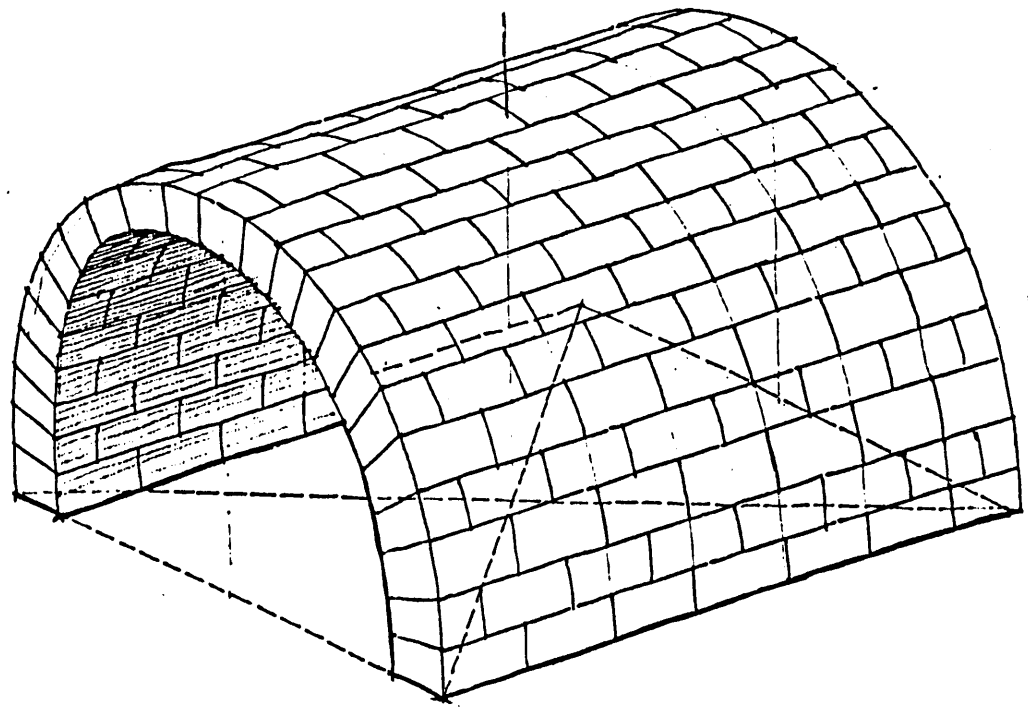
Vault can be expanded on only one axis

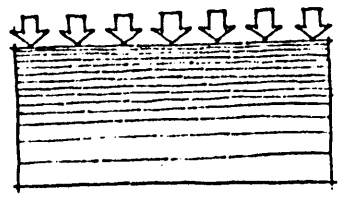
BARREL VAULT

The extension of the round arch about a perpendicular axis to form a barrel vault generates a space with fewer constraints than that enclosed by the lintel/wall system.

Unfortunately, however, loading a barrel vault (figure 1) places the spine of the vault in tension, which can result in saddle failure of the vault.(figure 2). This failure results from the flat section of the vault being unable to distribute a load in the direction of its long axis.

In addition, the loading of the vault tends to force the lower portions of the vault outward (figure 3) due to the lack of coincidence between the line of pressure and the centroids of the vault stones.[5]





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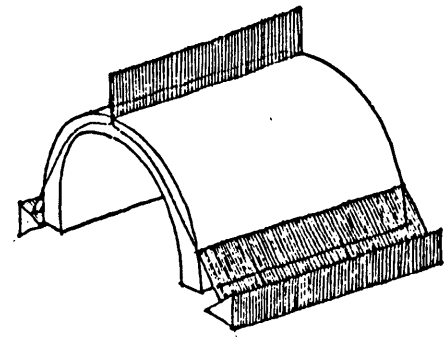
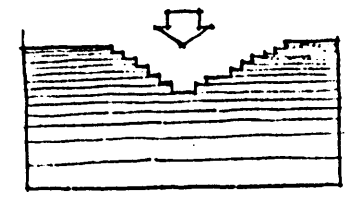


2 FORCES



3 FAILURE

BARREL VAULT

Complex technology

Static system

Massive structure

Vault height is limited by wall mass

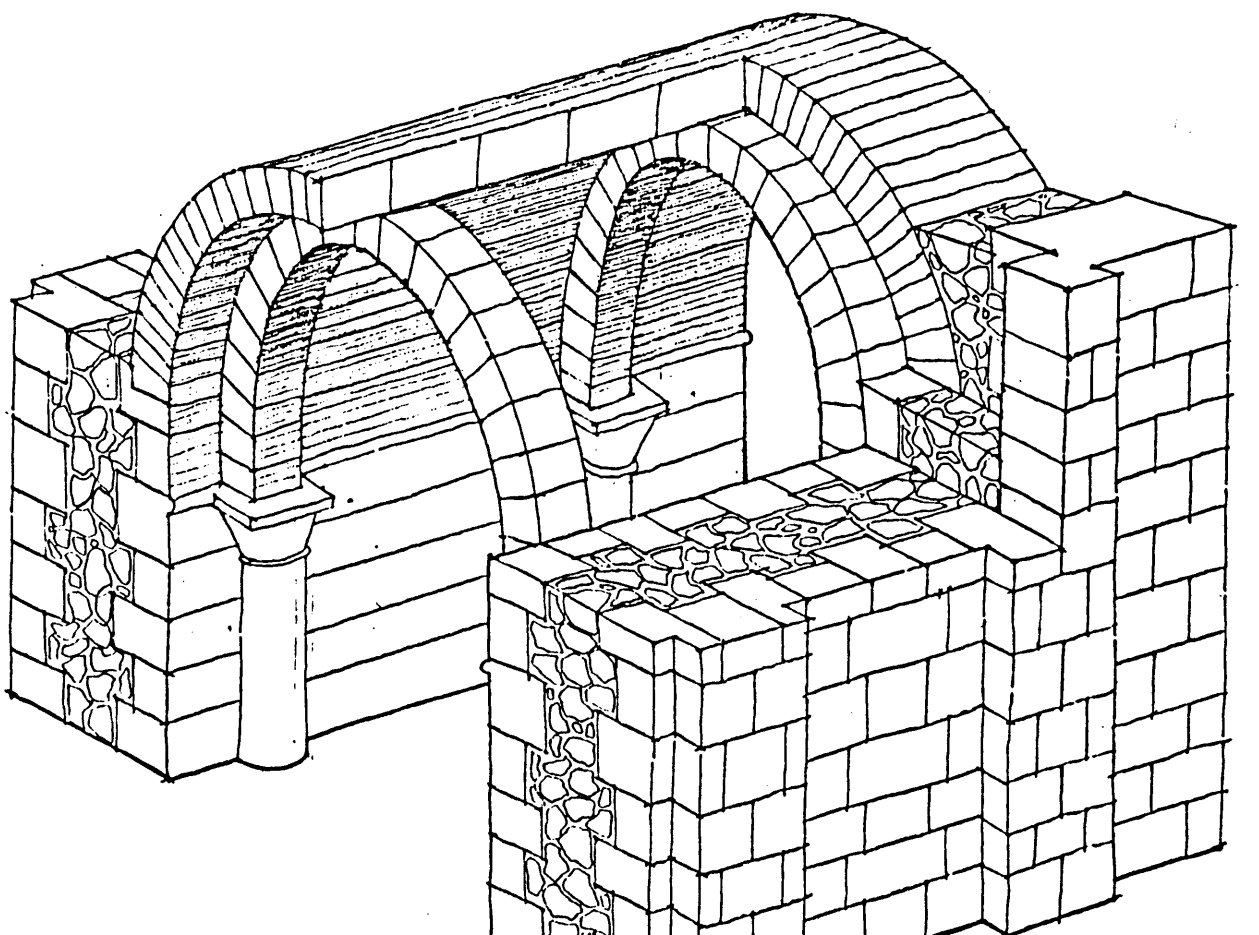
Vault can be expanded on only one axis

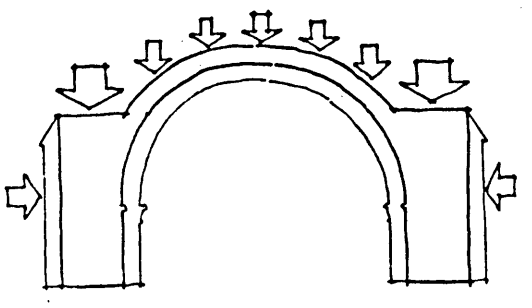
REINFORCED VAULT

The inherent weakness of the simple barrel vault resulted in several additive corrective measures.

In order to allow the structure to withstand the outward thrust of the arch (figure 2), mass was added to the outside of the arch near its point of origin or springing (figure 1).

To stiffen the vault against saddle failure, it was necessary to add internal arches and exterior pialaster strips. These had the effect of decreasing the active span of the vault and increasing the wall mass (figure 3).[6]





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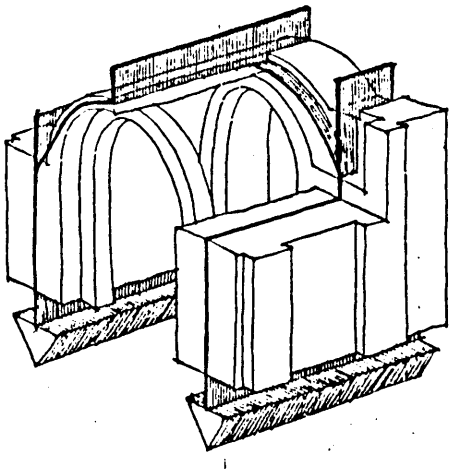

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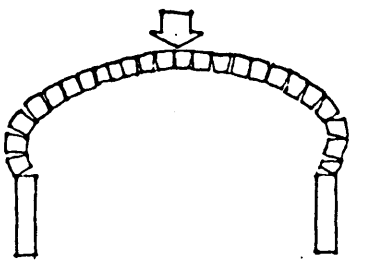


3. FAILURE

REINFORCED VAULT

Complex technology

Static system

Massive structure

Vault size limited by reinforcing's ability to resist thrusts

Vault can be expanded on only one axis

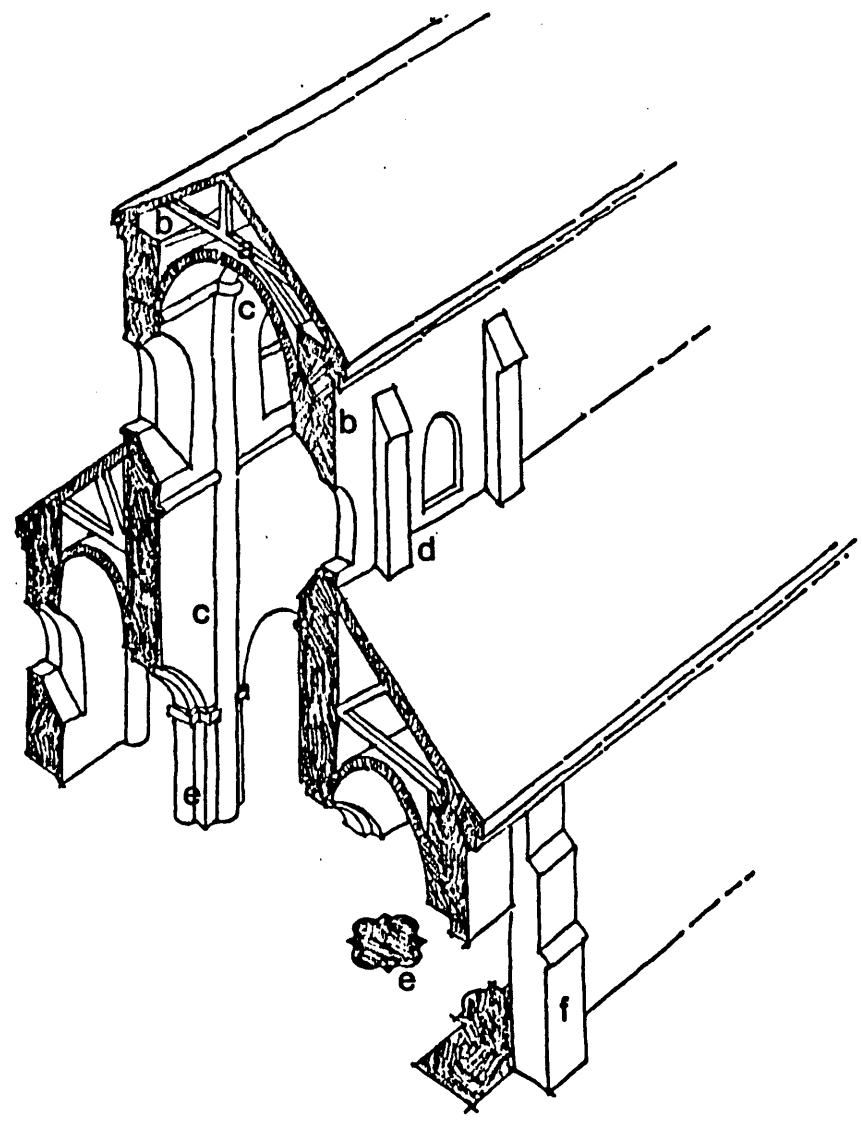
The structural characteristics of the barrel vault limit the volume which can be enclosed.

The stone vaults (a) are resisted by concentrated mass, (b) In addition, the vault is supported along its axis by piers and arches (c).

The clerestory wall is reinforced on its exterior by pialaster strips (d) which act in conjunction with the piers (c).

The mass of the aisle wall is transmitted to the foundation by the piers (e).

Along the aisle wall pier buttresses (f) are required to contain the aisle vaults.



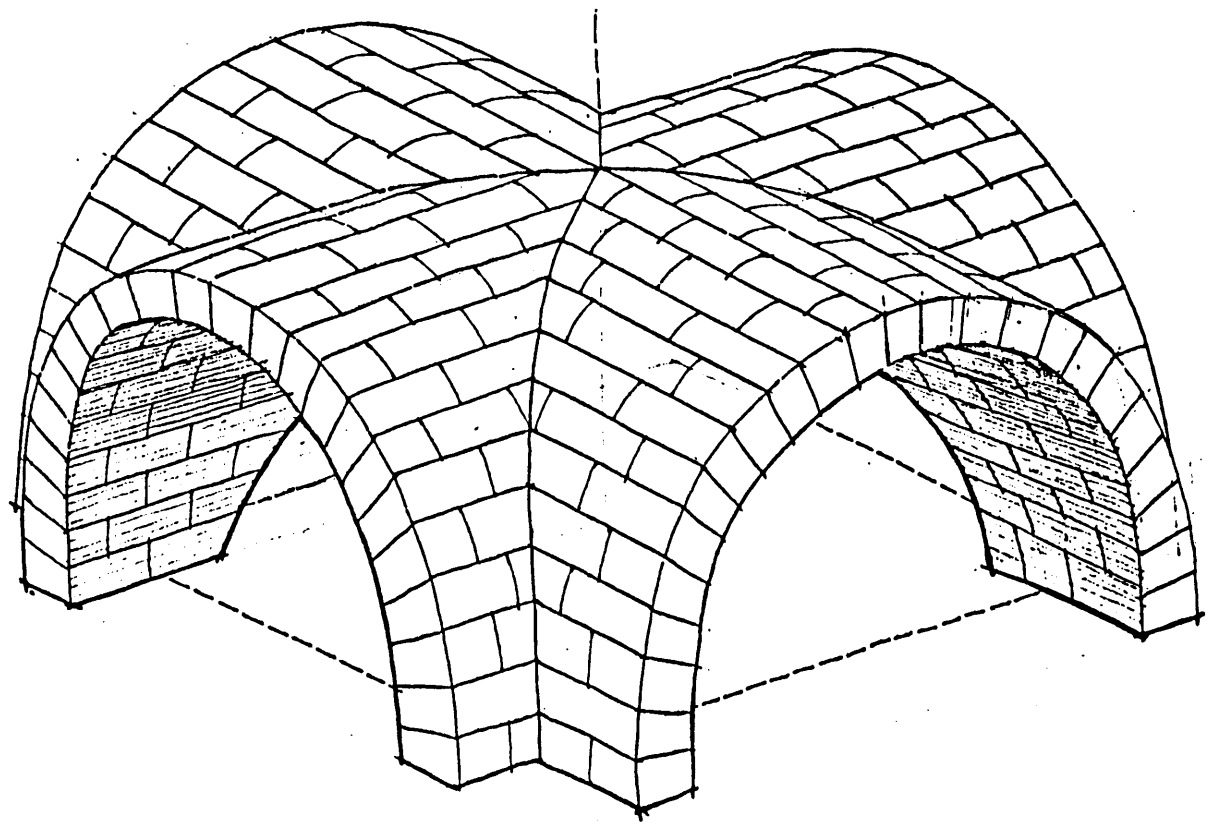
St.BENOIT SUR LOIRE

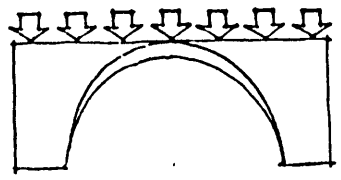
GROIN VAULT

The juxtaposition of two barrel vaults and the subsequent elimination of material greatly reduces the portions of the vault which are placed in tension.

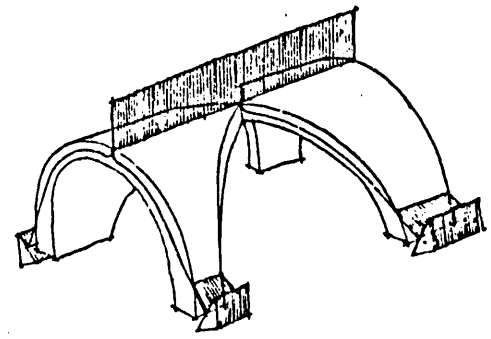
Even this arrangement, when under load (figure 1), is still prone to failure along the long axis of the vault (figure 2).

One advantage is the somewhat more effective concentration of the forces transmitted by the vault to the adjacent structure (figure 3). This concentration of force simplifies the structure required to restrain the base of the vault.[7]

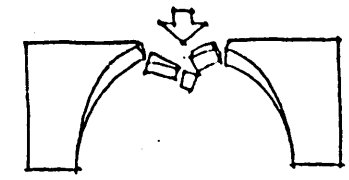




1. LOADING



2. FORCES



3. FAILURE

GROIN VAULT

Complex technology

Static system

Undefined structure

Forces partially concentrated

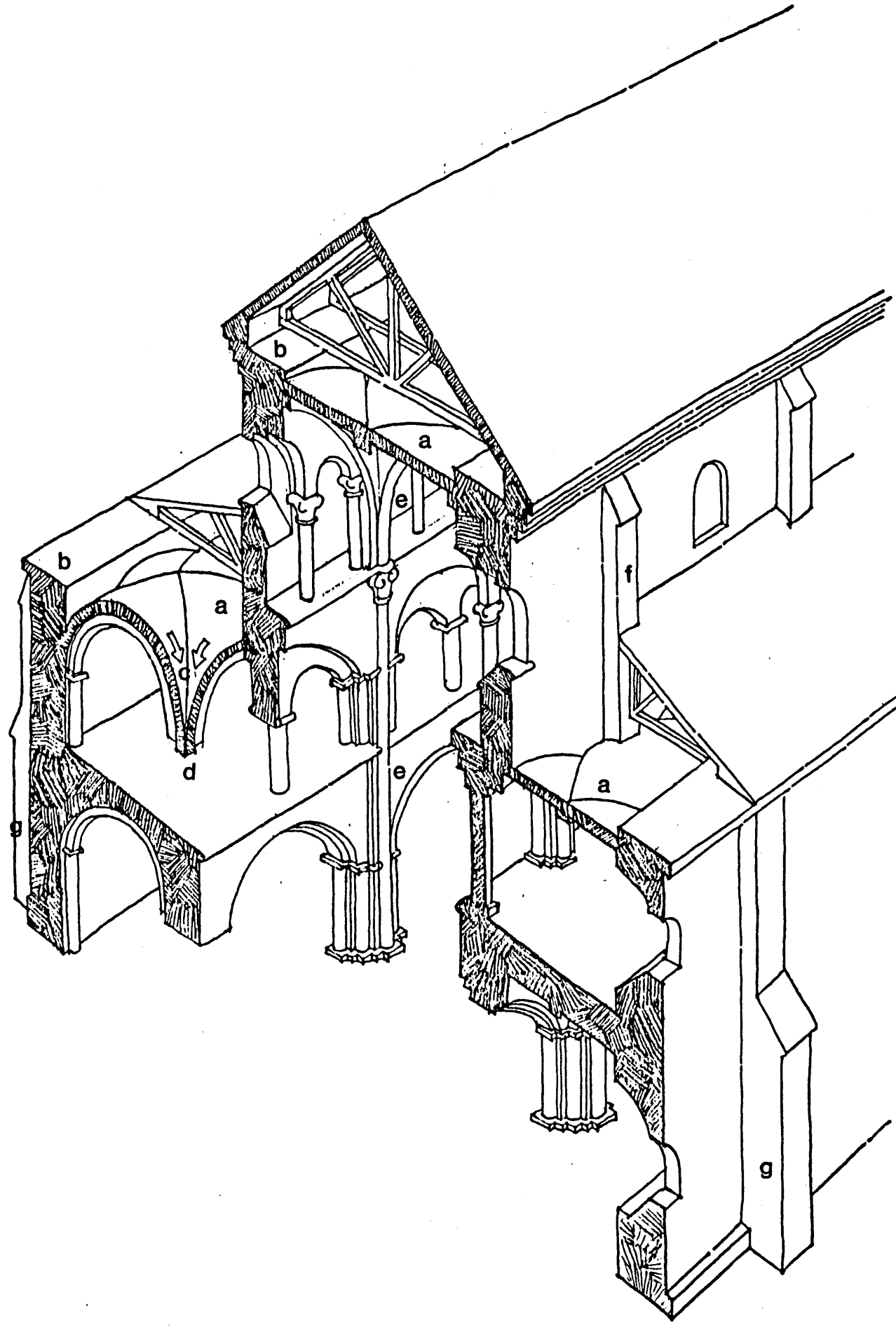
Large mass required at corners

Vaults can be repeated

The use of multiple groined vaults allowed an increase in the size of stone structures.

The vaults (a) are still partially restrained by local mass (b), but some collection of the forces (c) at points (d) is now possible.

The vault is still somewhat prone to saddle failure and requires reinforcing piers and arches (e). The exterior walls are reinforced with pialasters (f) and pier buttresses (g).



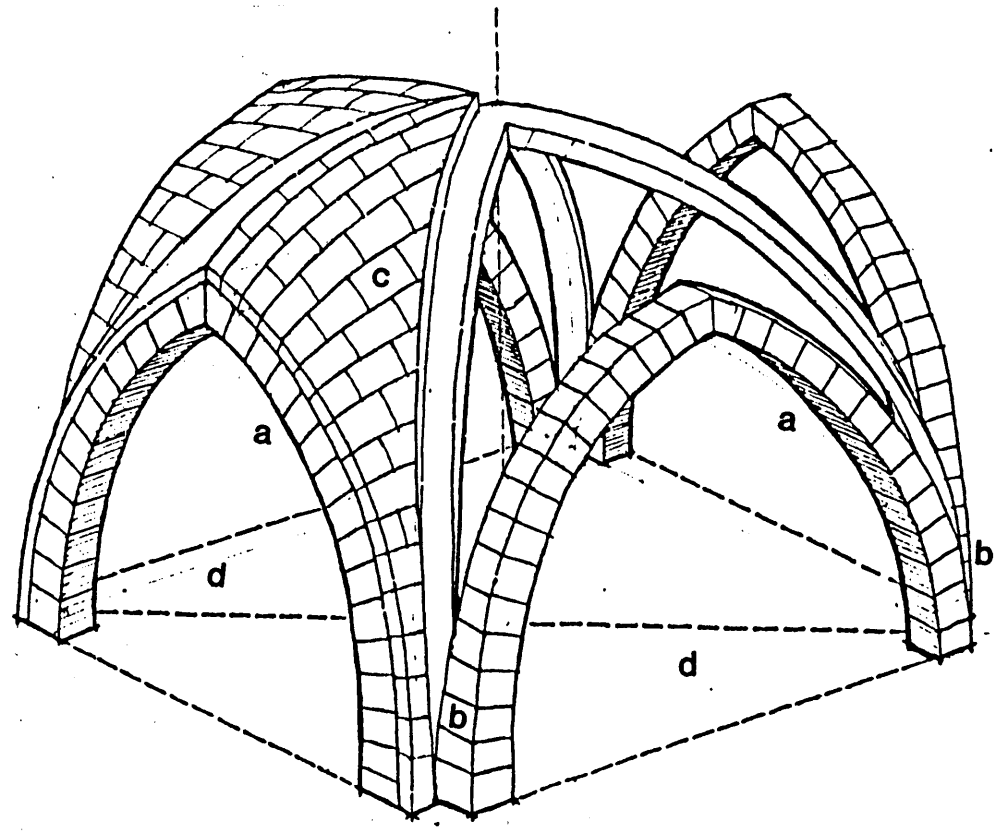
CERISY LA FORET

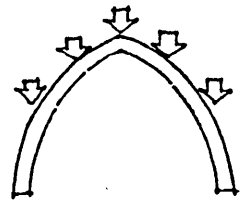
GOTHIC VAULT

The use of the pointed arch represents a radical departure from the previous systems of constructing vaults.

The most significant feature of the vault created with four pointed arches is the ability of the structure to dissipate resultant forces in two directions.

The arches (a) receive forces and transmit them effectively to the spring points (b) (figure 1). In addition, the skin of the vault, or shell (c), is curved (figure 2), unlike the shell of the barrel vault, thus allowing the individual stones to act more completely in compression. Consequently, the forces are effectively collected and concentrated at the common spring points of the arches (b) (figure 3). This concentration has several advantages. First, the areas below the arches need not be filled with heavy masonry (d). Second, by constructing repetitive vaults, the forces on one vault can be opposed by the forces of the vaults adjacent to it rather than with masses of masonry. Finally, the arches can be of different sizes, allowing for the enclosing of spaces which are not square as with interesting barrel vaults.





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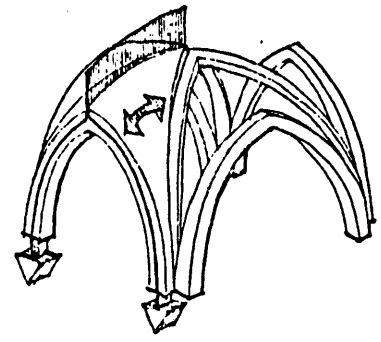
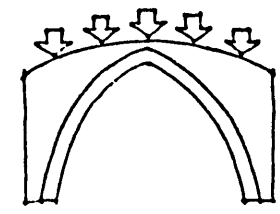


2. FORCES



3. DISTRIBUTION

GOTHIC VAULT

Highly refined technology

Dynamic system

Defined structure

Force resisted by force

Reduced mass

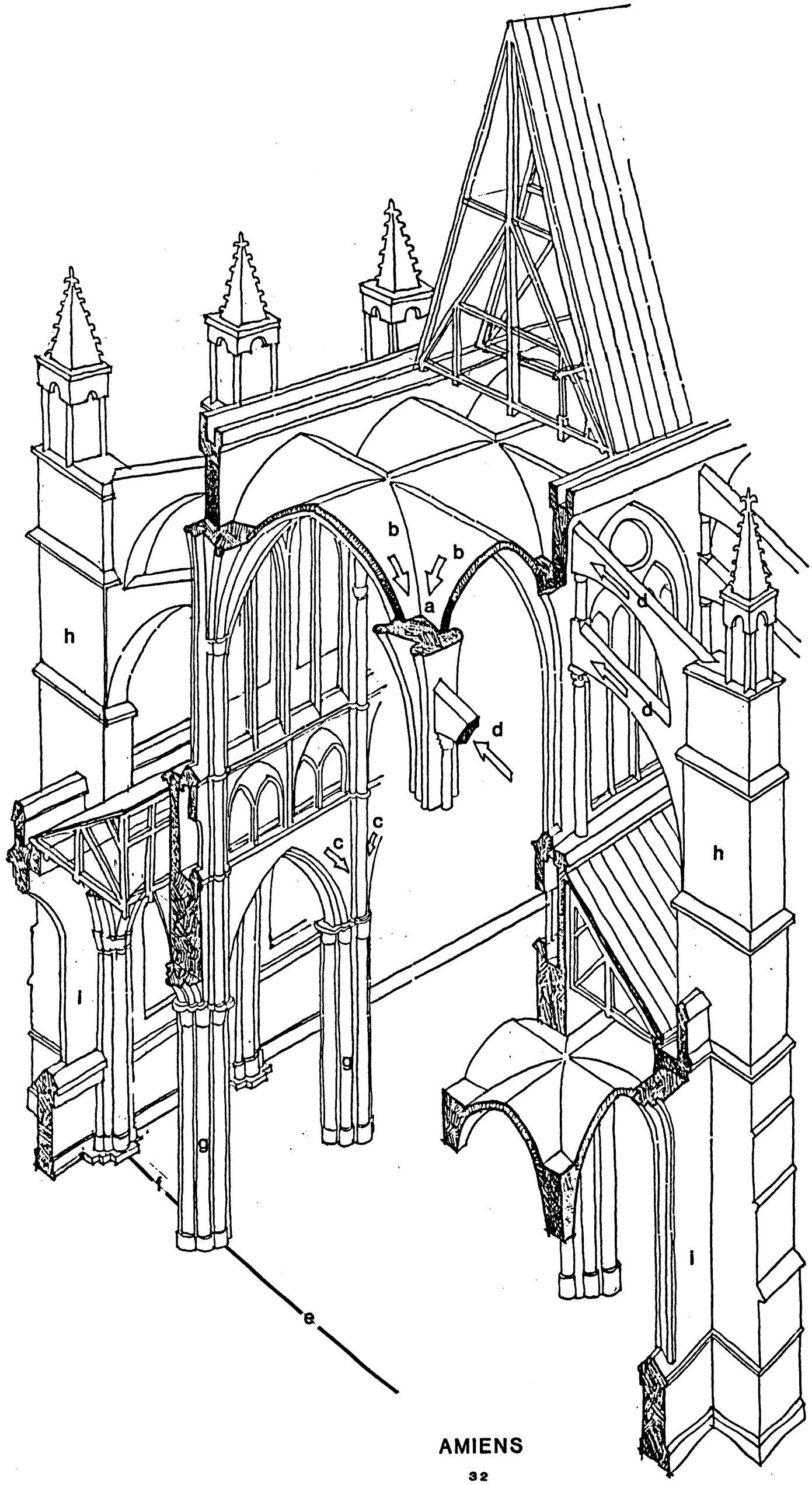
Vault height can be varied

Vaults can be repeated in both directions

The Gothic cathedral represents the quintessential use of the pointed arch and vault. The cathedral is compled by the judicious collection of vault forces at precise locations (a) by the action of the vaults themselves (b). These forces are then either balanced by the action of counter forces (c), or resisted by remote mass via half arches (d).

The application of the unequal vault and the arch results in the subordination of spaces as in the nave (e) and aisle (f). The concentration and articulation of structure at the interior columns (g) and the main buttresses (h), the reduction of mass in the perimeter walls (i), the minimization of wall mass in the triforium gallery (j) and the virtual elimination of the wall in the cleristory windows (k).

All of these features combine to produce a structure which utilizes technology to maximize spacial volume, to minimize mass and to define structure.



AMIENS

INTERIOR ELEVATIONS

The buildings in the next series of drawings represent a range in scale from small to monumental. The drawings are at the same approximate scale so that a comparison can be made more easily.

An overview will show the increase in complexity of the different structures; and by studying the drawings, it is possible to develop some understanding of the changes taking place.

While none of the structures possess clear evidences of all concepts, the aggregate of the drawings shows:

1. The use of repetitive elements
2. The use of varying solutions to common problems
3. The application of technology to enhance space

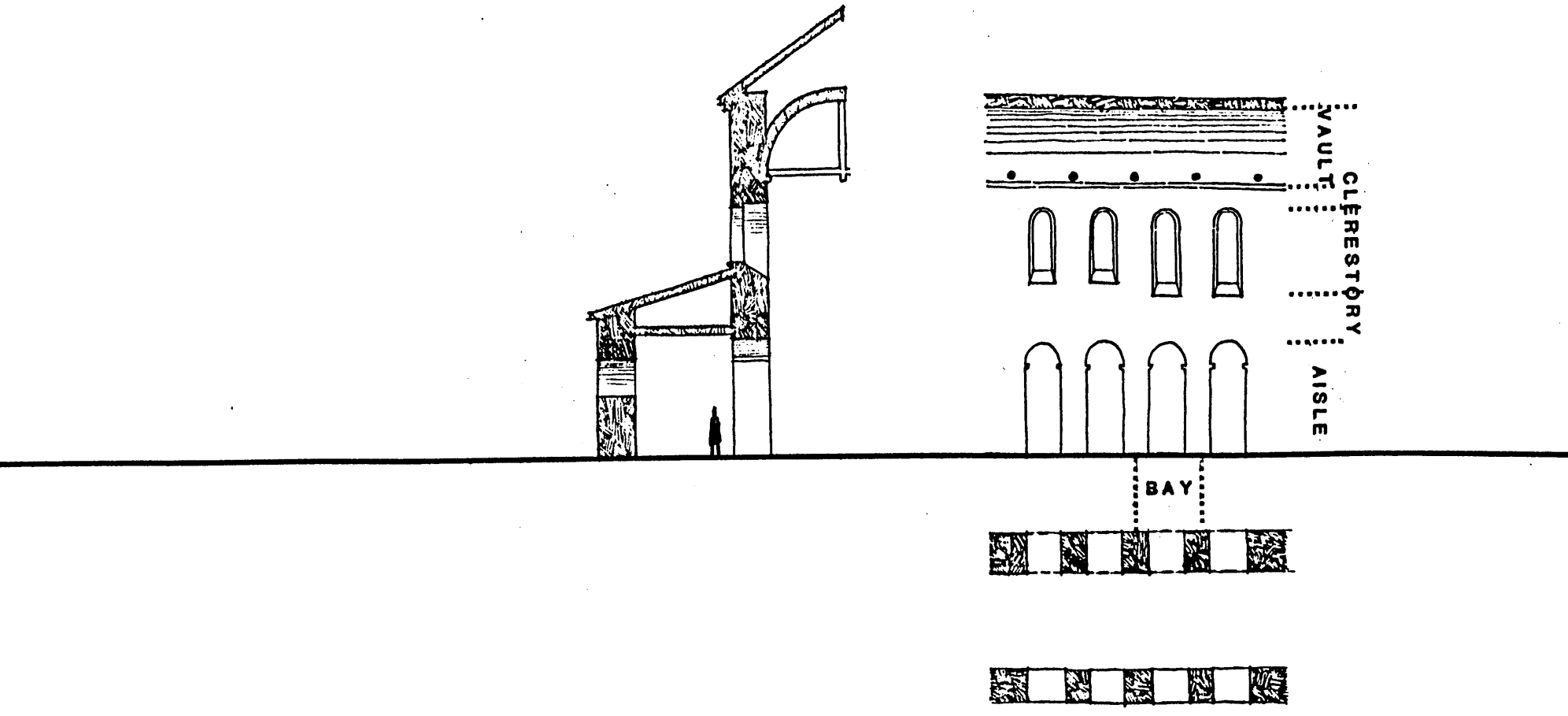
CHATEAU GRONTIER St.JEAN

Saint Jean is a small church which is built on a cruciform plan.

The nave is covered with a wooden barrel vault which is restrained by the mass of the exterior walls and timber cross ties. The cross ties also support vertical timber crutches designed to help the vault resist saddle failure. The side aisles are narrow with a flat ceiling.

The penetrations in the nave walls are narrow and deep due to the thickness of the wall. The aisle windows are set high in the wall and are even smaller than the nave openings.

This little church is spartan in character. While there is some repetition of the window and arch elements, there is minimal ornament. The small scale of this church, quite naturally, results in a small bay size.



Repetitive Elements:	Window penetrations Door penetrations
Varying Solutions:	Door penetrations Square--window Penetrations angled
Technology:	Massive structure Braced barrel vault

St. JEAN

ABBEY DANGEAU

Daugeau is another small church. In this instance, however, an ambulatory has been added to the cruciform plan.

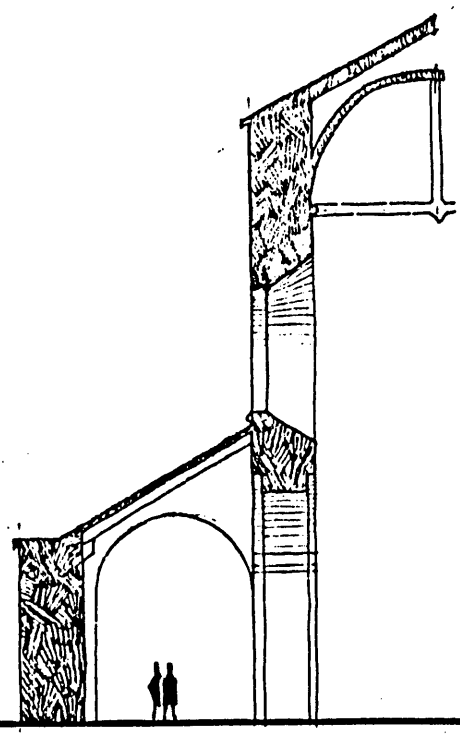
As in Saint John, the vault at Daugeau is framed in wood with timber cross ties. The aisle ceiling is also framed in wood, but in this case the structure is pitched with stone corbels receiving the roof members at the aisle walls.

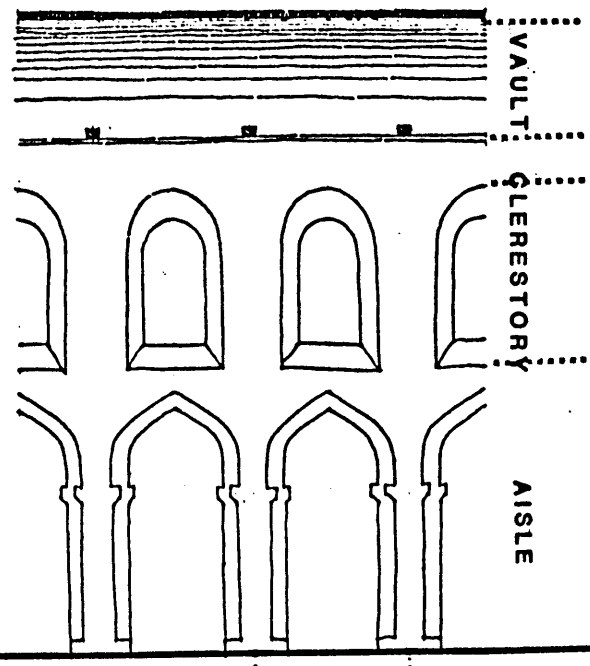
The main wall is abutted by arches over the aisle which help transfer the thrusts in the nave wall to the aisle wall. The action of the supporting arches and the roof are not, however, integrated.

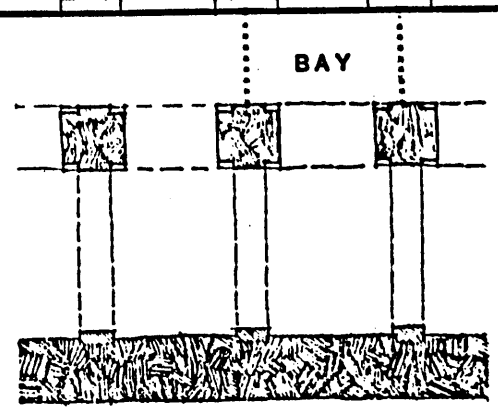
The penetrations in the nave wall evidence improvements over those used at Saint John. While the wall thickness is still great and the window openings remain small, the recesses for the windows are angled. The net effect is to reflect light and visually increase the size of the penetration.

The penetrations through the nave wall at floor level have also been improved. The pointed arches allow the opening to become wider while the revealed edge to the opening, again, causes it to seem larger than it is.

The use of repetitive elements at Abbey Daugeau is limited in much the same manner as St. John. The scale of the church in terms of size and funds expended are reflected in the restrained interior.







Repetitive Elements: Window penetrations
Door penetrations

Varying Solutions: Round arches--pointed arches
Angled/stepped penetrations
Plain/articulated arches

Technology: Massive structure
Braced barrel vault
Reinforcing arches over aisle

DANGEAU

St. BENOIT SUR LOIRE

Saint Benoit is a large church serving a substantial parish south of Paris.

The main vault is of stone, faced in plaster, and is reinforced at widely spaced intervals with double reinforcing arches. The aisle is capped with a half barrel vault which leans against the nave wall and acts to prevent outward collapse.

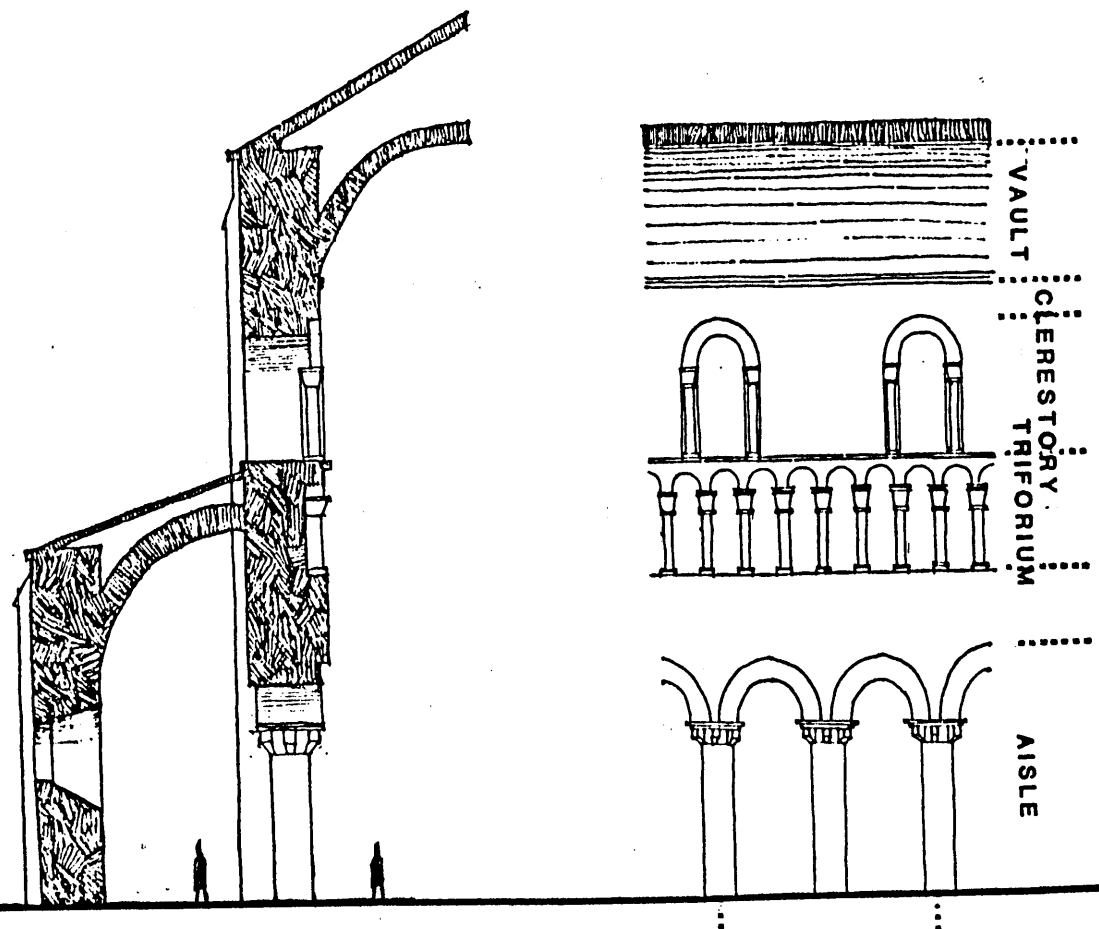
The penetrations of the nave and aisle walls continue to be narrow and limited both in size and in number. But, in an attempt to lighten the nave wall above the columns, the builders introduced a band of pialasters and relieving arches.

With this addition of what will eventually become the triforium gallery, several things can be noted. First, the use of repetitive elements has become more explicit. There are three different column/penetration patterns which modify the interior surfaces. Second, as will be typical in most of the examples shown, diverse solutions are most obvious in the changing penetrations and attendant detailing of the nave walls.

Saint-Benoit evidences most of the technical characteristics of the reinforced barrel vault, heavy walls, reinforcing arches, and pialasters. This structure, though proven to be sound by the passage of nearly eight hundred years, is heavy, relying almost totally on massive masonry walls to restrain the vault.

As previously noted, this reliance on heavy masonry places severe limitations on the space. Penetrations of the upper wall are limited in order to maintain the continuity of the wall, and the intersection of the aisle half vault is necessary to support the nave wall and permits some lightening of the lower mass.

This combination is representative of one of the least sophisticated of the structures shown. As the structures become more refined, through improvements in technology, there is a dramatic transformation of the elements in the structure.



Repetitive Elements:	Window penetrations Pialasters Wall penetrations 3 sizes of col/pialaster
Varying Solutions:	Penetration sizes Column sizes Column capitals/bases Column spacing
Technology:	Mass concentrated Reinforced barrel vault Half arch over aisle

St. BENOIT

MONT St. MICHEL

Saint-Michel stands upon a rock in a tidal flat off the Norman coast. Its emote location and its fortress like construction are testimony to the turbulent state of the region where the church was constructed.

The vault at Saint Michel is less adorned that Saint Benoit in that it is constructed of wood with wooden tie beams and crutches. This simplicity of the vault has been more than offset by the richness of the nave wall.

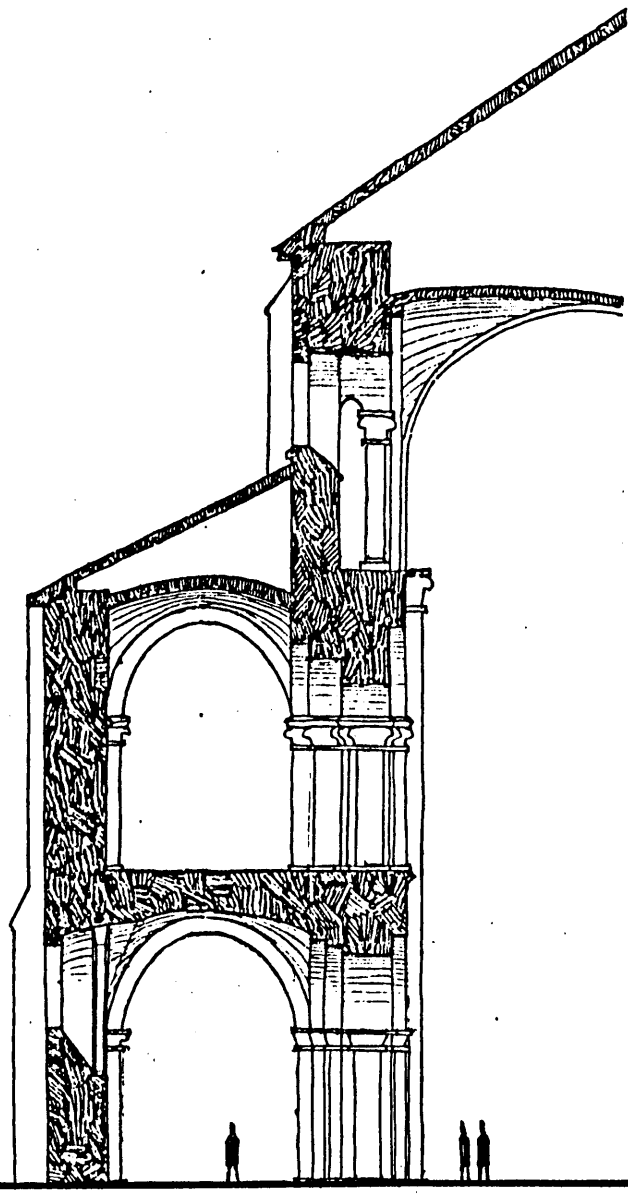
The nave wall is divided into three sections, clerestory, triforium, and aisle, as in Saint Benoit, and each of these divisions has been enhanced by the use of copings which define the areas and form horizontal repetitive elements. The copings appear again at the springing of the arches and intersection vertical reinforcing. From a practical standpoint, these copings served the master architect as a tool to assist in maintaining level throughout the structure.

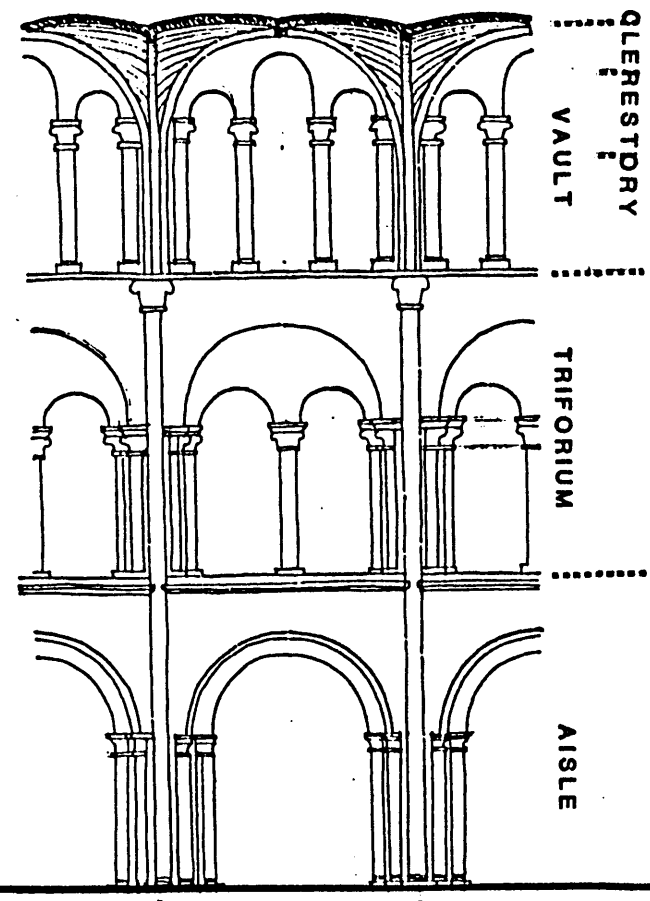
One of the most obvious aspects of the wall is not just the presence of multiple columns or multiple openings, but that these multiple elements combine with divergent solutions to structural and decorative requirements. For example, the four most obvious column conditions, the vault reinforcing columns, the aisle columns, the triforium columns, and the columns which frame the clerestory, all have different aspect ratios: 1:35, 1:11, 1:7, and 1:12.

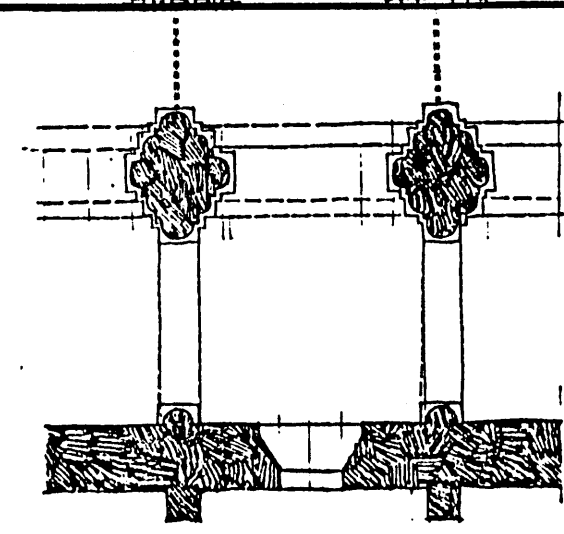
This combination of repetitive elements in the form of round arches and columns combined with diverse wall penetrations adds a new complexity and interest to the nave wall.

Along with the increasing complexity of the wall, the structure has also been improved.

The aisle vault has been raised, lightening the clerestory wall and allowing the triforium to be transformed from a pialaster strip into a gallery. The aisle vault has been strengthened by round arches which reinforce the aisle columns and absorb a portion of the thrust from above.







Repetitive Elements:	Main/sub arches Cols/piers Col patterns Penetration patterns Vertical subdivisions
Varying Solutions:	Arch subdivisions Arch detailing Clerestory arches Column clusters
Technology:	Mass concentrated at col/pier locations Wall sections deepened at col Double arches over aisle

St. MICHEL

CERISY LA FORET

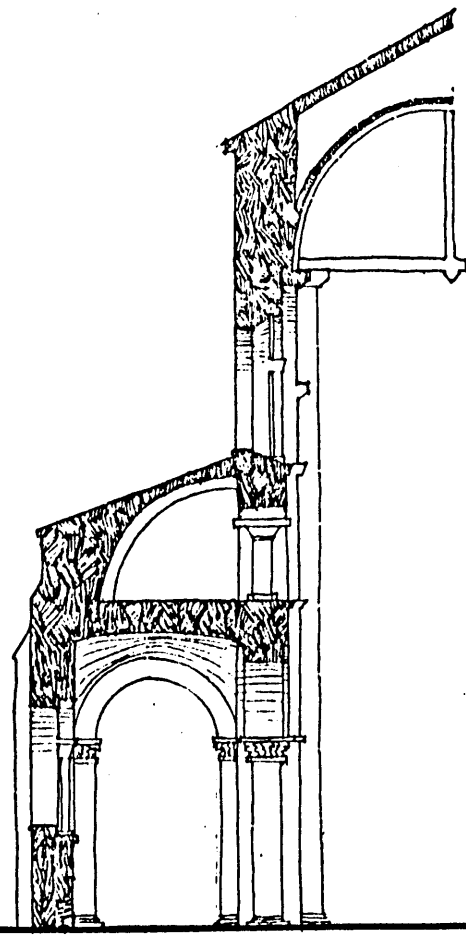
Cerisy-La-Foret, built in Normandy around 1050 by a Duke Robert as a house for his religious relics, is more technically advanced than Mont-Saint-Michel, but it is also more restrained.

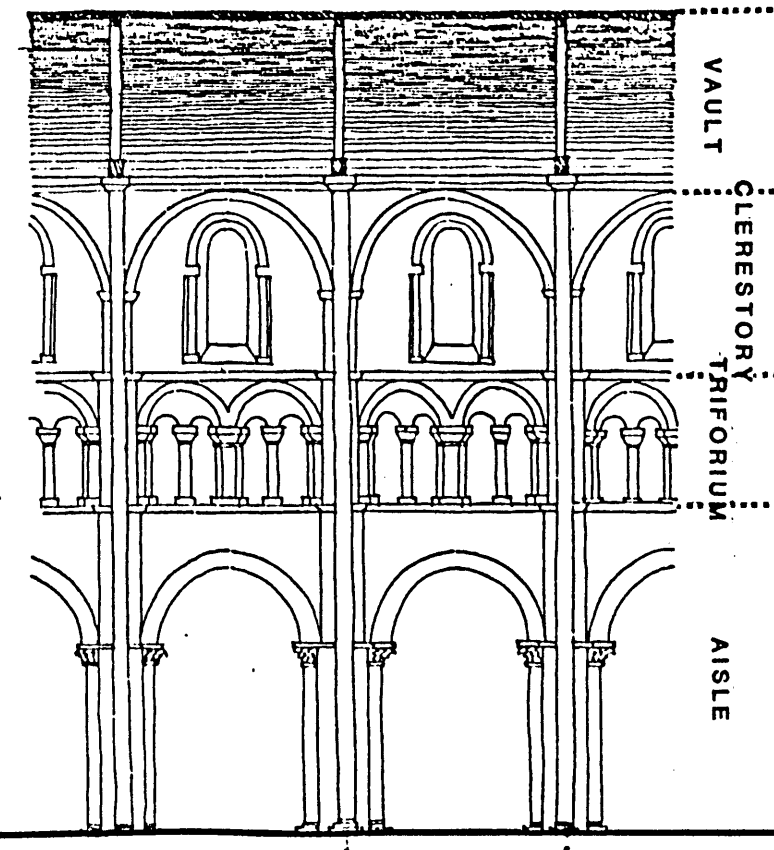
The technical refinement is evidenced in the structure by the ribbed stone vaults, the enlarged triforium gallery with more delicate columns, the decreased reliance on vault reinforcing columns, and the increased bay size.

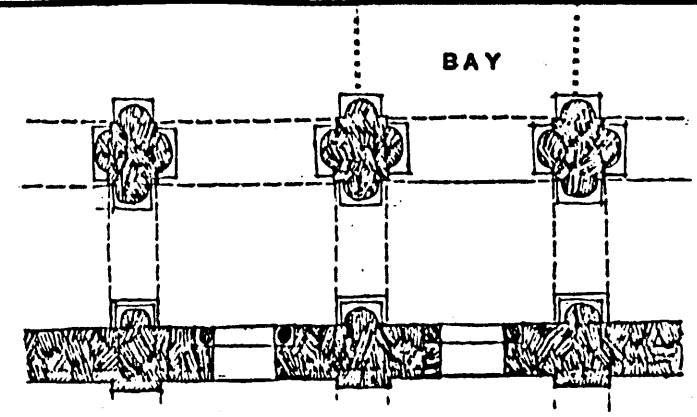
There is one especially enjoyable evidence of divergent solutions in the wall. The three levels of the wall are defined with similar major arches, but the large arches themselves are subdivided with totally different sub-arches. This is combined with a complexity in the detailing of the arches themselves which is the inverse of the structural complexity.

The structure of the building has also continued to evolve. The mass of masonry is still largely present, but it is more effectively concentrated at points of thrust. In addition, the triforium is generated with a full arch and piers to better absorb the vault thrusts, which have been increased due to the weight of the stone vault.

At Cerisy, the evidence of repetitive elements is increasingly clear. There is a profusion of column acting singly, in consort to form the main piers, and in colonades. The arches too have become more significant as repetitive elements with major and minor arches being repeated on the different levels.







Repetitive Elements:	Round arches Triforium cols Aisle cols Penetrations Cols/piers Arch detailing
Varying solutions:	Col aspect ratios Gallery divisions Penetration detailing Col spacing Col capitals/bases
Technology:	Half arch raised for better wall support Mass reduced at upper levels

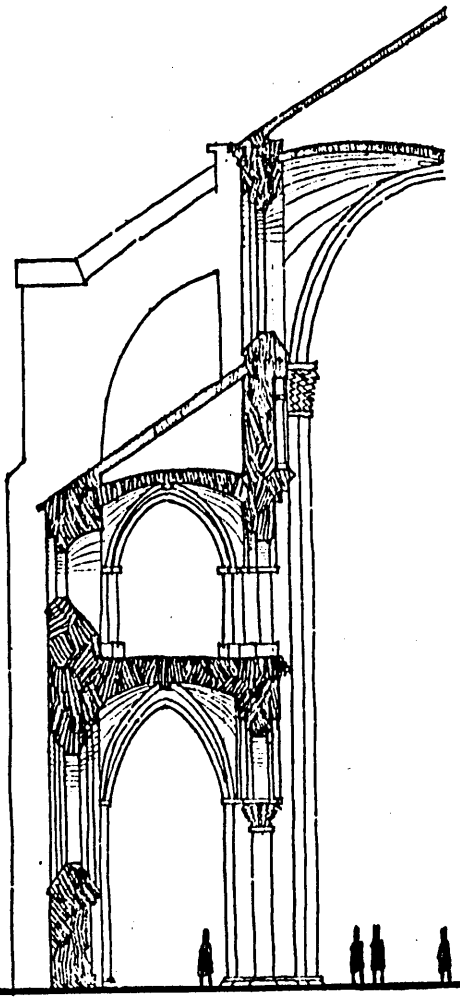
CERISY LA FORET

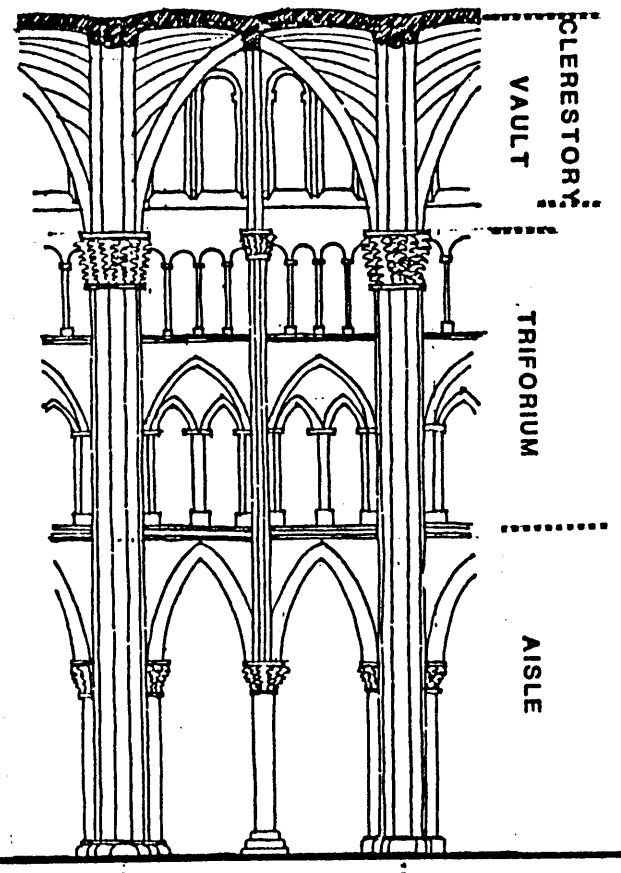
NOTRE DAME de NOYON

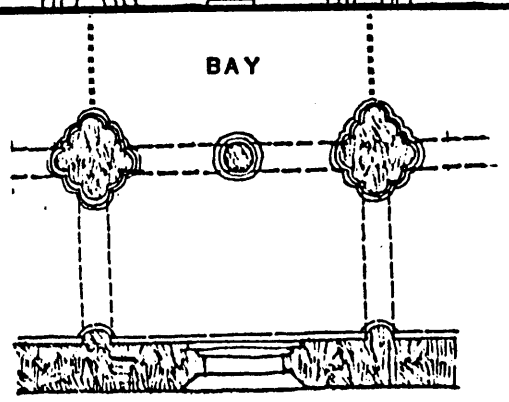
The Cathedral at Noyon demonstrates increasing complexity in the nave wall. This is the first example which makes extensive use of the pointed arch, but the combination of round and pointed arches raises the question of whether the pointed arches are used for visual or technical reasons.

Noyon, which is also cited in the following series on the flying buttress, has four bands of columns in the wall. Two of the bands have pointed arches while the upper arches have round arches.

The row of columns directly below the clerestory is actually a blind arcade; that is, a row of pialasters intended to minimize the surface of the upper wall.. This is a new treatment of that portion of the wall which reflects the desire to minimize the visual aspect of the enclosure. The structure of Noyon, while technically more highly developed than those shown previously, was not capable of supporting a lightened clerestory wall, which was to become such a striking element in later cathedrals and hence the application of the blind arcades.







Repetitive Elements:	Arch patterns Col patterns Penetration patterns Vertical elements
Varying solutions:	Round/pointed arches Arch detailing Arch subdivision Pier clusters
Technology:	Gothic vault resists thrust Flying buttress resists thrust at haunch of vault Aisle vault resists thrust at springing of vault

NOYON

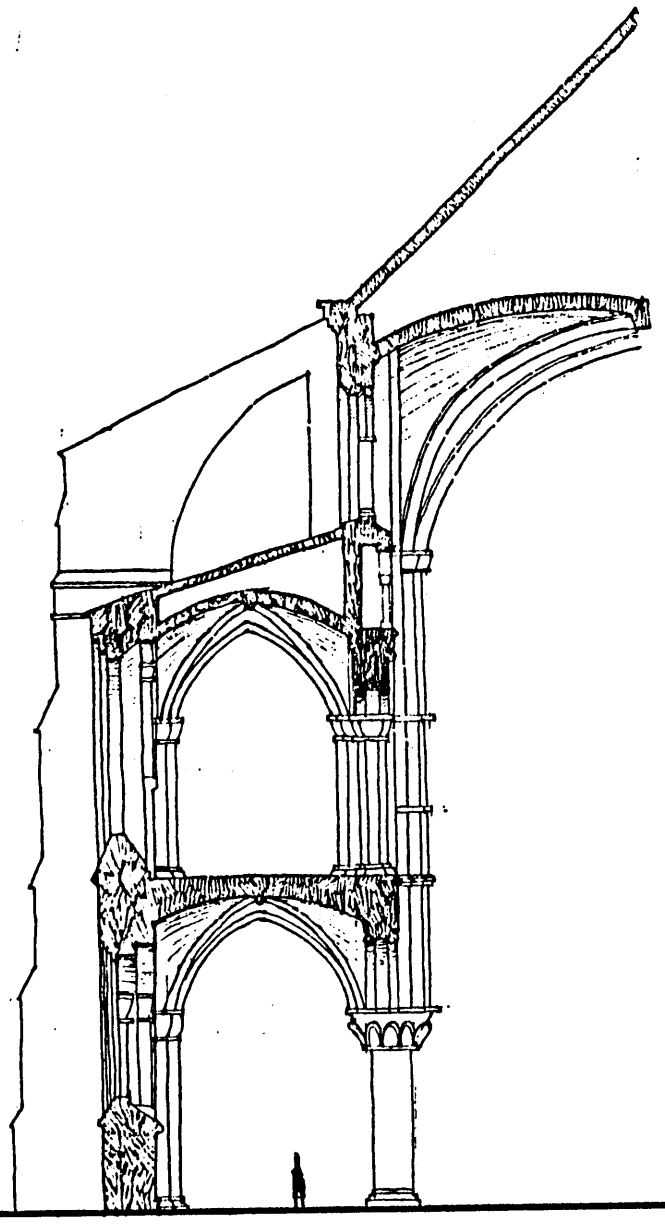
NOTRE DAME de LAON

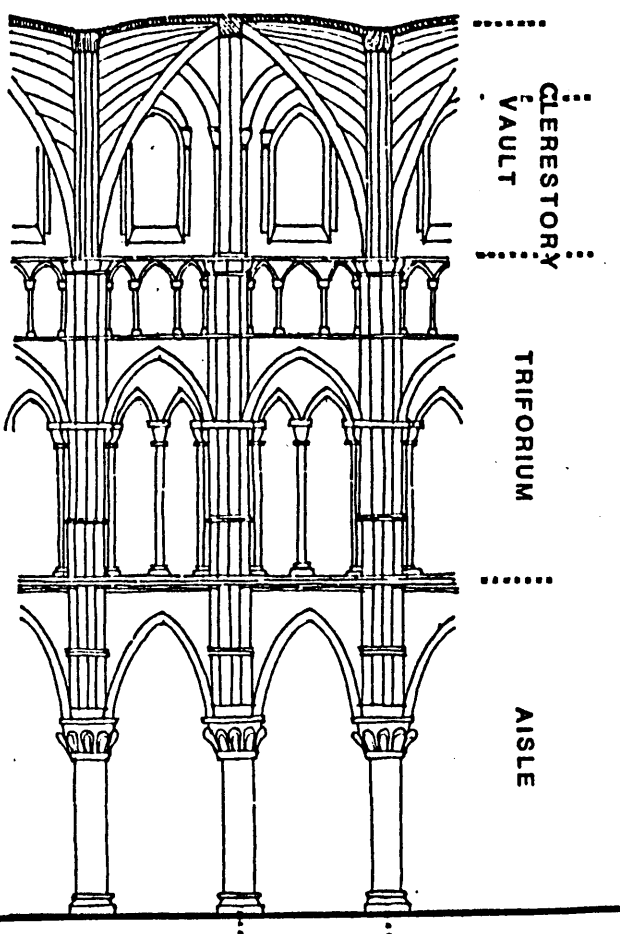
The Cathedral at Laon shows only modest development over Noyon. The changes which are evident tend to be more in the nature of refinements and adjustments.

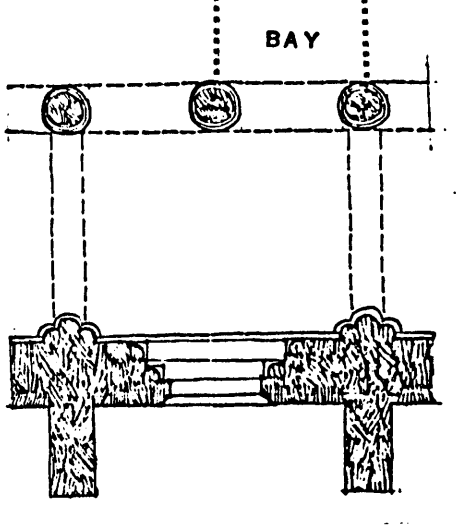
The first refinement is the complete utilization of the pointed arch. In Noyon some of the penetrations were accomplished with round arches; at Laon all of the openings are capped with pointed arches. Second, the pier at the midline of the bay has been increased in size as the vault continues to increase in height and span. Third, the triforium has been surmounted by a narrow gallery as opposed to the row of pialasters at Noyon. Fourth, the flying buttress has undergone a further improvement with a reduced cross section intersecting the vault at its haunches. This allows the buttress to meet the vault thrust with less mass but a more effective structure. Fifth, the great buttress has been modified with numerous offsets. These offsets serve to concentrate the mass of the buttress so that the imposed forces can be controlled more efficiently, as well as helping to shed the elements and to adorn the great buttress.

The nave wall, by now almost 23 meters in height, has the typical division into aisle, triforium and clerestory. Here, however, is the last example which shows essentially equal divisions. The examples which follow demonstrate an evolving hierarchy which is the result of the structure's increasing ability to function without need of walls.

Laon also demonstrates one of the more complex applications of repetitive elements. Virtually all of the major elements have been subdivided and differentiated. In addition, the various horizontal bands have been repeatedly subdivided and differentiated. In addition, the various horizontal bands have been repeatedly subdivided with columns and piers which has the effect of giving the wall a large vertical component.







Repetitive Elements:	Arch patterns Pointed arches Penetration patterns Vertical elements
Varying Solutions:	Penetration aspect ratios Arch subdivision Col/arch detailing Col clusters
Technology:	Gothic vault resists thrust Flying buttress resists thrust at haunch of vault Aisle vault resists thrust at springing of vault

LAON

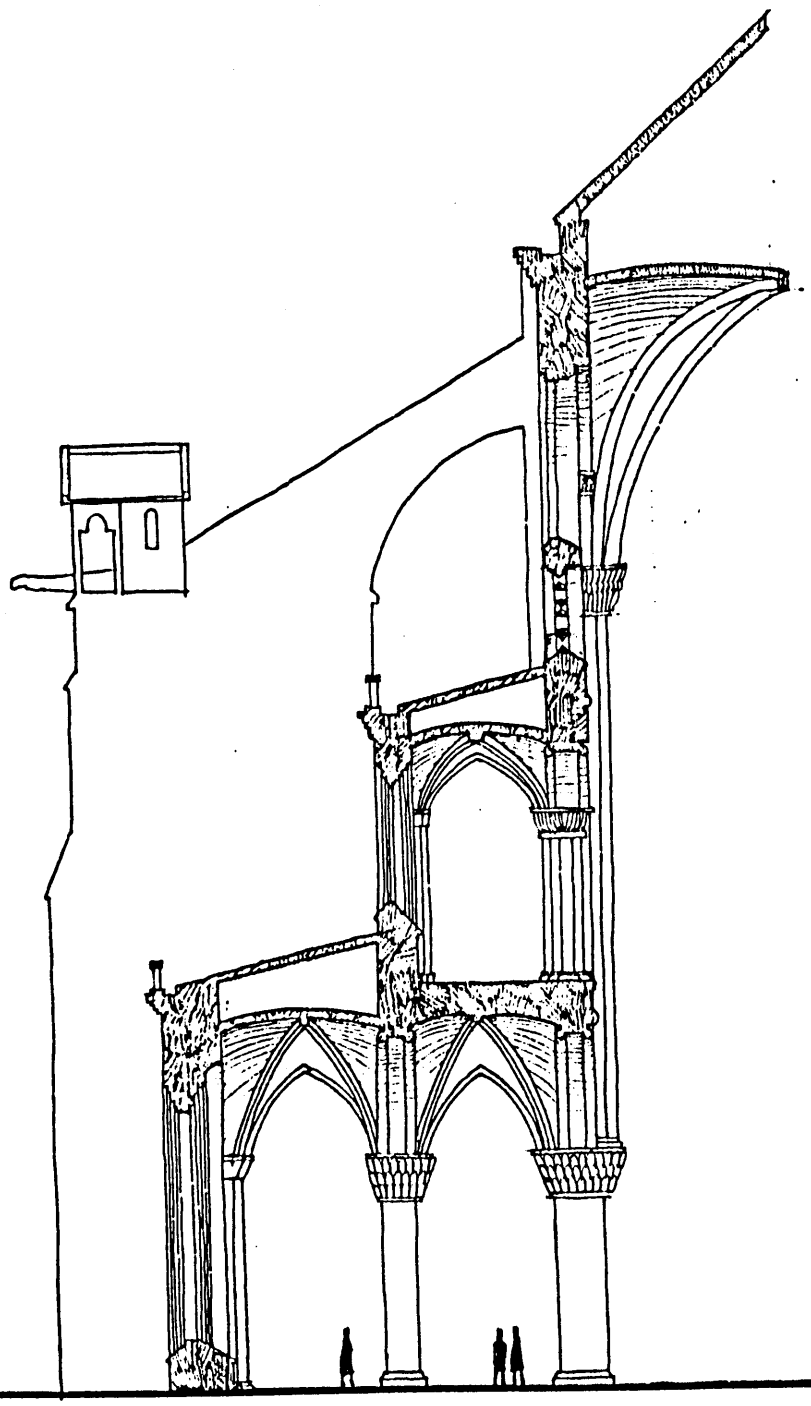
NOTRE DAME de PARIS

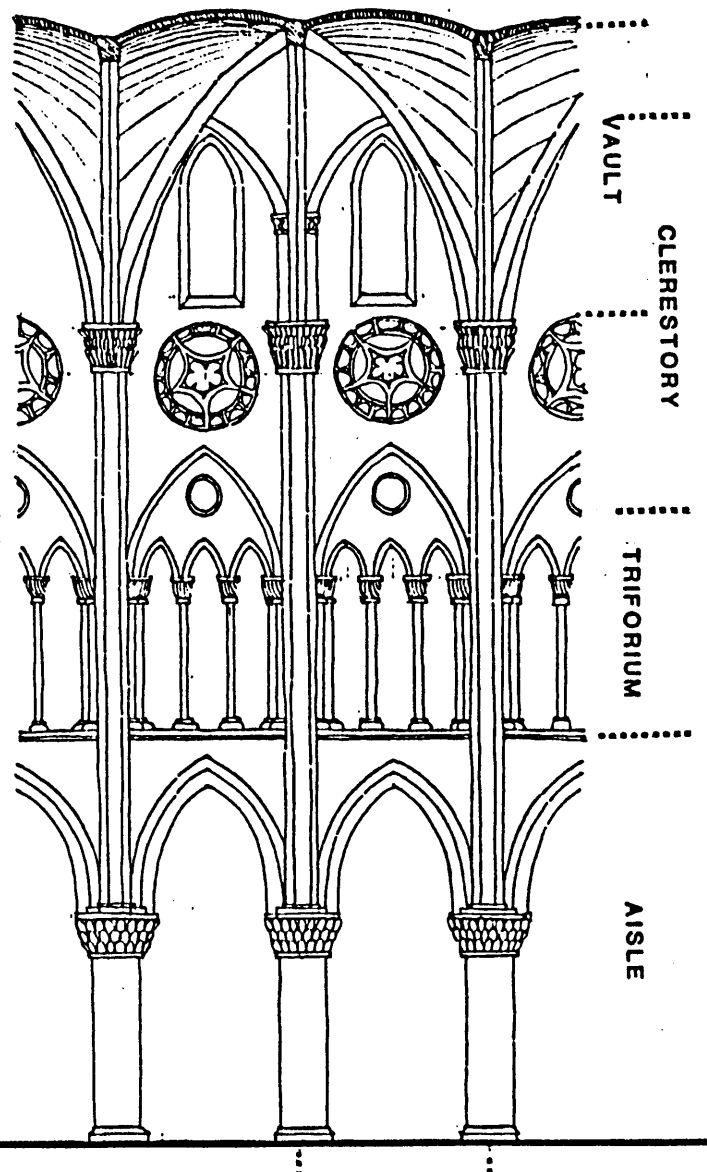
Notre Dame, in Paris, has the added feature of a second aisle in the nave.

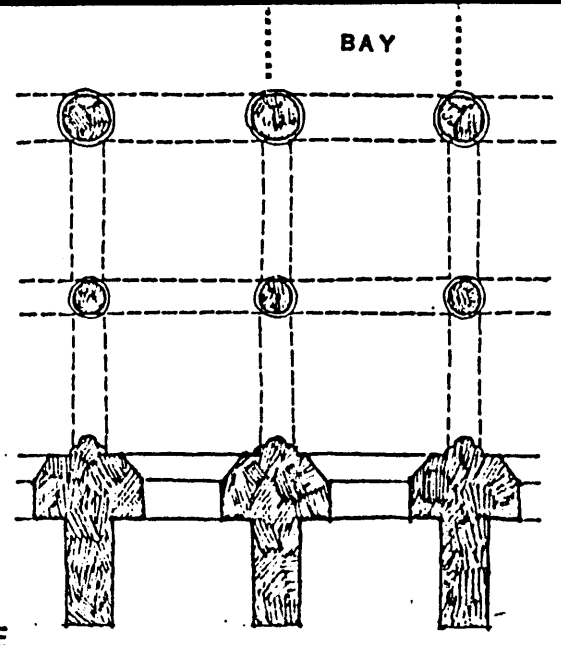
While it was fairly common for the choirs of the cathedrals to have double aisles, double nave aisles were less common. To provide reinforcement for the nave vault, the great buttresses had first to bridge over the outer aisle.

At Paris this condition was accomplished with a deep masonry section. In more advanced work, however, the reinforcement was provided with double pairs of flying buttresses and an intermediate pier.

In conjunction with these changes, the nave wall has risen to almost 30 meters, while at the same time the bay has widened to 10 meters. This increase in height has been principally absorbed in the clerestory portion of the wall. The net effect is to increase the area available for glass in the clerestory. The triforium, though subordinated, has reached its fullest development with some of the most evident use of repetitive elements in its colonade.







Repetitive Elements:	Arch patterns Pointed arches Horizontal bands Vertical elements
Varying Solutions:	Windows Major/minor ribs Penetration aspect ratios
Technology:	Gothic vault absorbs thrust Flying buttresses resist thrust at haunch Aisle vaults resist thrust at springing

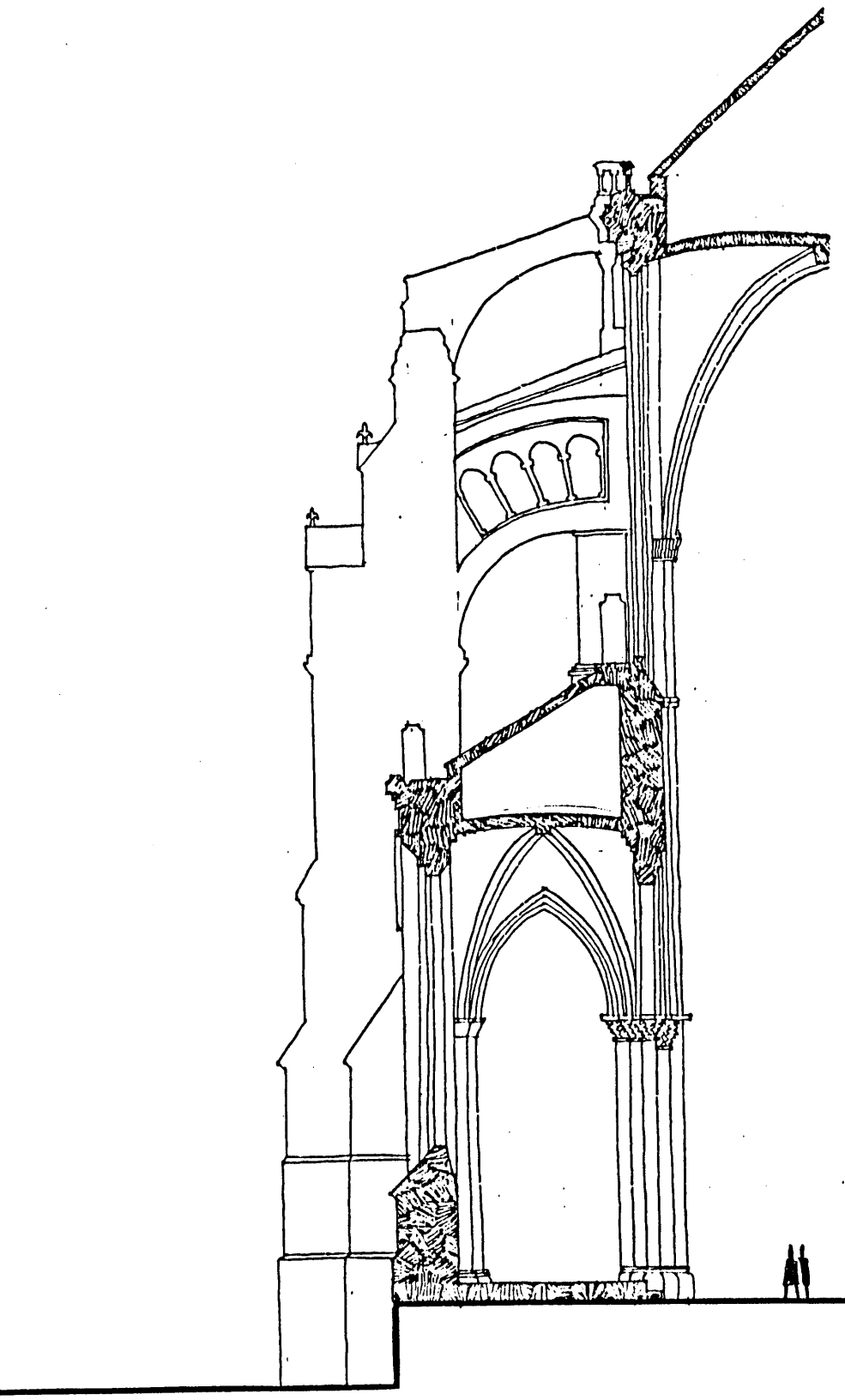
NOTRE DAME

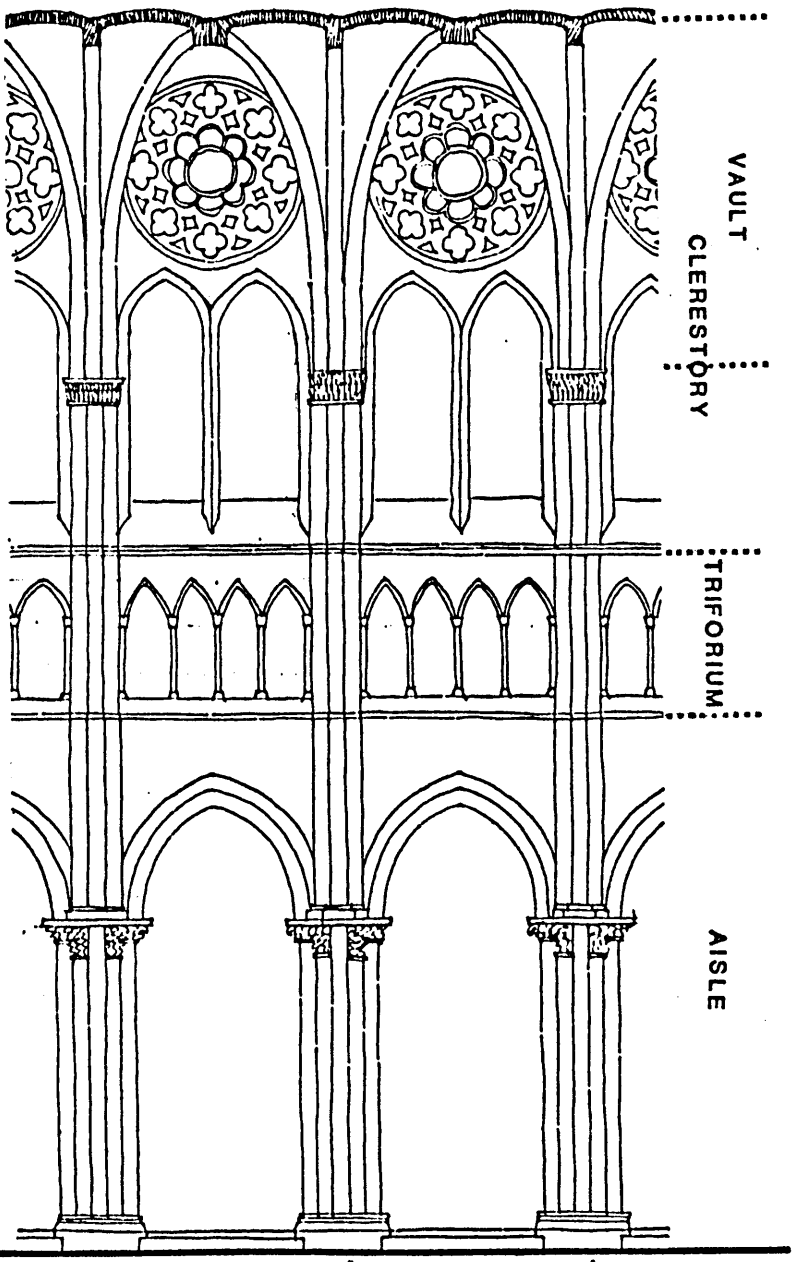
St.PIERRE de CHARTRES

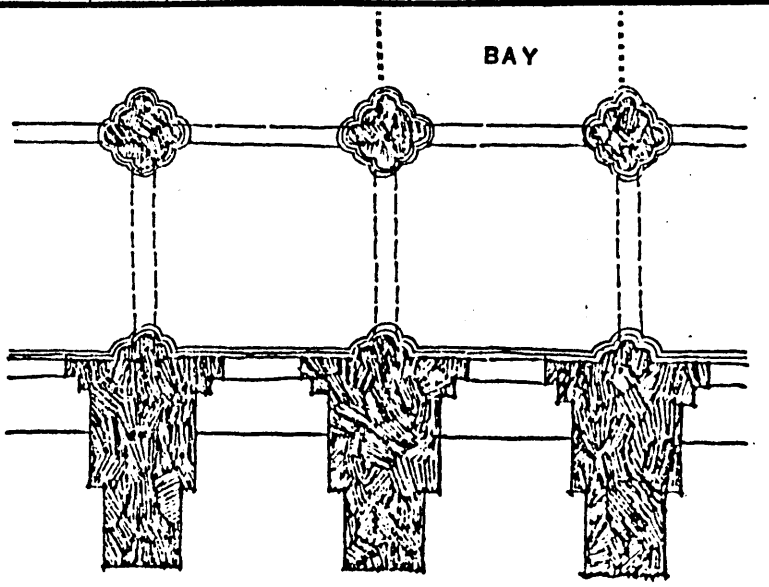
The flying buttresses at Chartres have taken on a partially developed form of the double buttress. This structural advancement gave the architect the freedom to undertake a major modification of the wall. The new buttress profile, with its heightened structural efficiency, resulted in a diminished need for the structural contribution of the wall. As a result, the clerestory, which has grown to the largest component of the wall, has a diminished function as a structural member and greater visual impact.

The nave wall has fewer repetitive elements than Paris, but there is a more defined hierarchy of elements. In addition, the architect has introduced the rose window, which becomes a focal repetitive element.

The triforium has dwindled in size as a consequence of the increase in the clerestory and the growth in the aisle vault. The increased height of the aisle vault has consumed the space formerly occupied by the triforium vault and the gallery has returned to surface detailing rather than actual penetrations.







Repetitive Elements:
- Arch patterns
- Pointed arches
- Rose windows
- Horizontal bands
- Vertical elements

Varying Solutions:
- Windows
- Penetrations aspect ratios
- Arch Detailing

Technology:
- Gothic vault absorbs thrust
- Double flying buttress resists thrust along entire pier
- Wall no longer functions as structure

CHARTRES

NOTRE DAME de REIMS

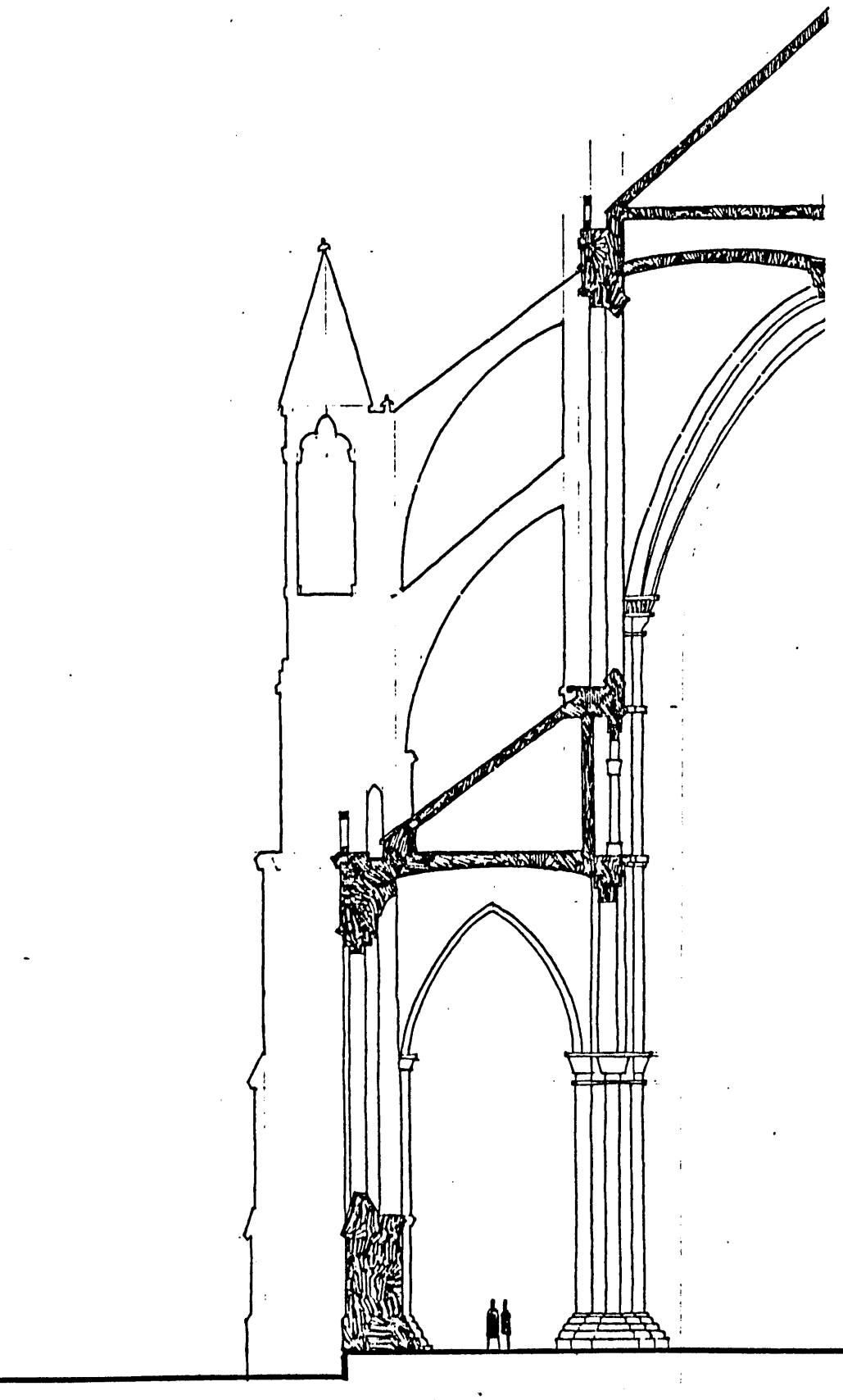
The cathedral at Reims and the cathedral at Amiens, which is documented in the next drawing, are considered to be the preeminent examples of Gothic architecture.

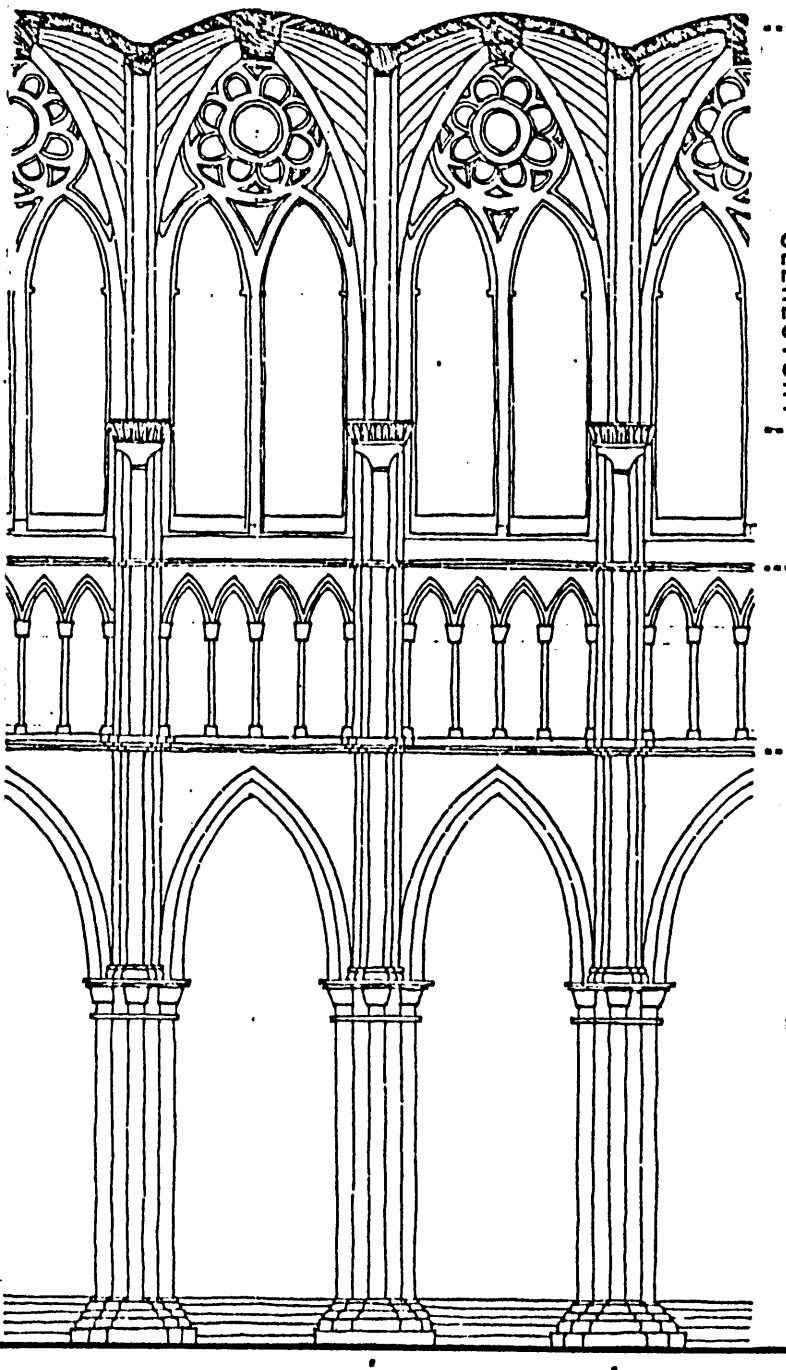
The nave at Reims is similar in many ways to that at Chartres. The principle changes are, first, the increased penetrations of the clerestory, which has become almost totally glass; second, the increased height of the nave vault; third, the increased aspect ratio of the piers--1.6 at Chartres, 1:7 at Reims--and finally the fully developed double flying buttress.

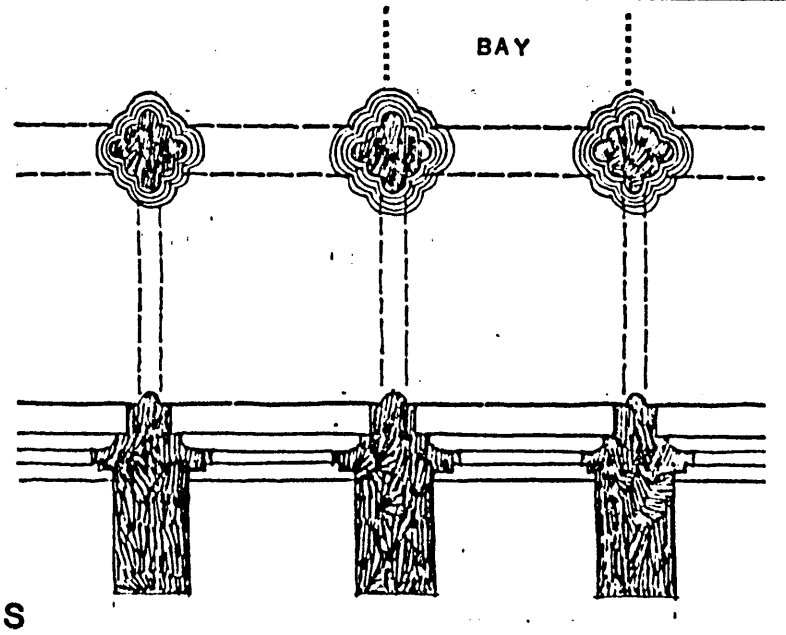
The repetitive elements at Reims are present in fewer varieties than in some of the earlier structures, but the repetition is still evident. The elements have been lengthened with narrowed intervening spaces, which creates a strong vertical component.

Divergent solutions have also been restrained in an apparent attempt to achieve a subtle interior.

At Reims the full impact of refined technology is evident. It can be noted in the overall height of the structure, the calculated concentration of structure into discrete elements, and the total elimination of the clerestory wall except as support for the glass panes.







Repetitive Elements:	Arches Col patterns Windows Horizontal bands Vertical elements
Varying solutions:	Windows Penetration aspect ratios
Technology:	Gothic vault resists thrust Buttresses support vault

REIMS

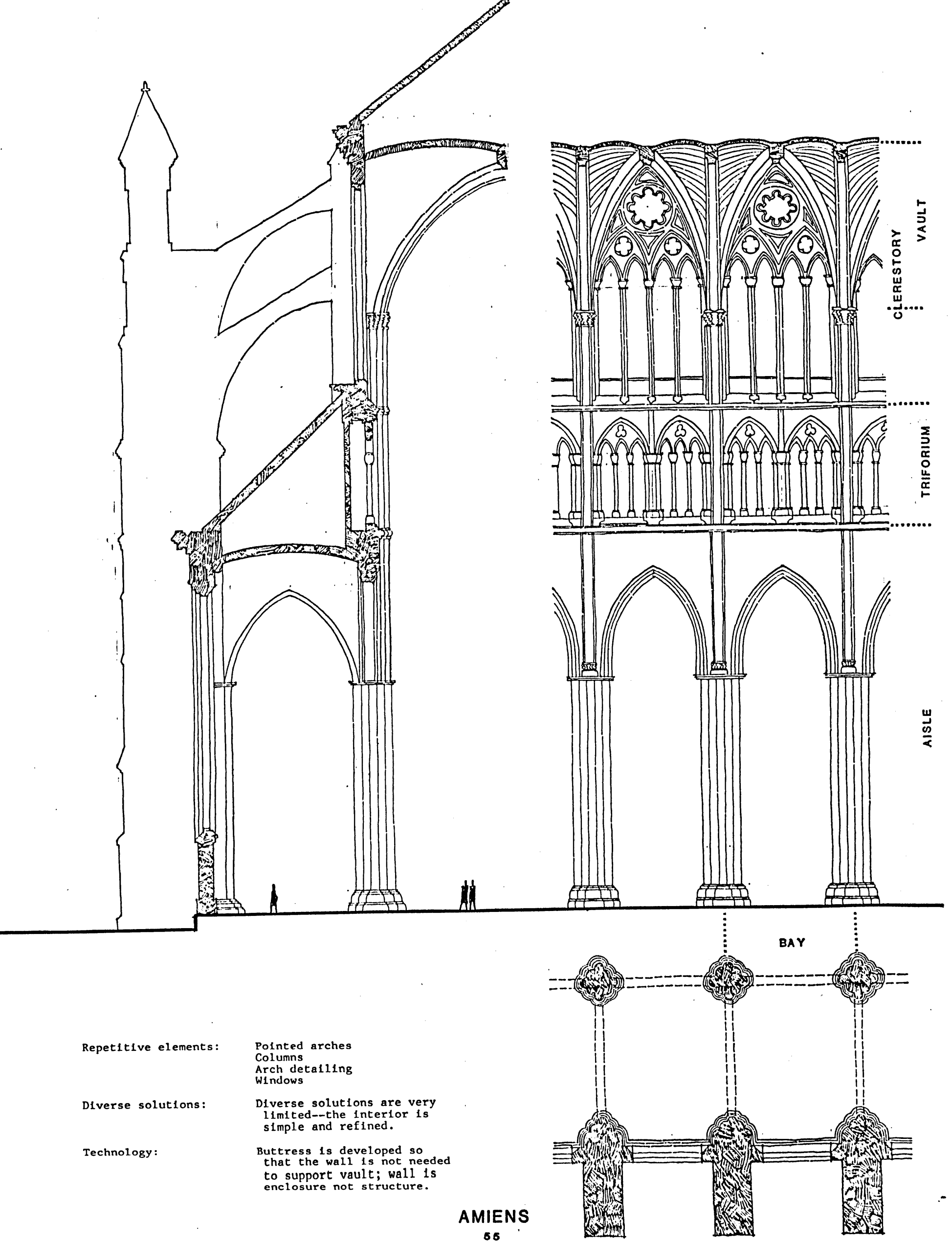
NOTRE DAME d' AMIENS

Amiens Cathedral, along with Reims, represents the culmination of the development of the Gothic style.

Repetitive elements are evident in the interior in the aisle piers, the vault ribbing, the triforium gallery, and the clerestory framing. Interestingly, these elements, while all essentially columns, have three quite different or divergent functions. The piers and the vault ribs are structural elements. The clerestory members are designed to frame visually and define the glass areas. The triforium columns are only partially structural, with their primary function being to minimize the surface area of the wall, but all the elements contribute to the vertical focus.

The solution of problems by divergent menas is evident at two levels in Amiens and Reims. The visual level relates primarily to the manner in which the master subdivided space, detailed openings and established the hierarchies of the wall. The net visual impact relates to the religious philosophy of the period, which saw the cathedral as a gift to God and as such the detailing and quality of finishes increase as the eye moves upward, carried by the line of the structure. On the non-visual level, the action of divergent solutions is more active. The Gothic cathedral is rather like a 150-foot house of cards. The entire structure is a balancing act. The diversity of solutions finds its most obvious expression in the ways in which the forces inherent in the structure are collected, directed, balanced, and channeled to the ground.

This successful balancing act is evidence that the refinement of the structure has been completed. From the modest beginnings of Chateau Gontier, where the vault, a mere 11 meters in height, relied exclusively on distributed masonry for its structural support, the architect at Amiens has completely replaced that mass by transforming the structural elements. This transformation, which replaces mass with carefully directed and counter-balanced forces, is both a product of the development of the Gothic as well as one of the reasons for that development.

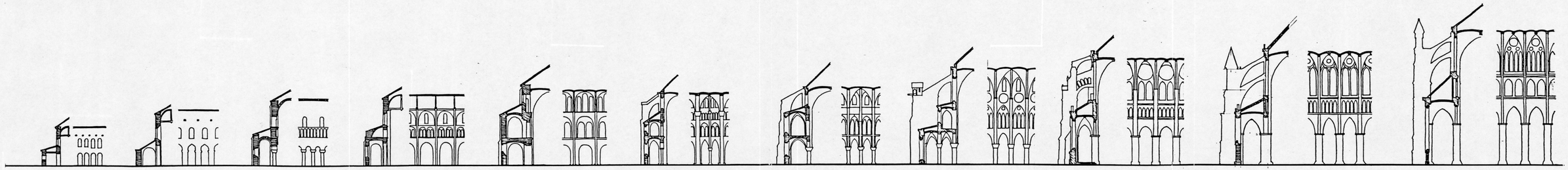


Repetitive elements: Pointed arches
Columns
Arch detailing
Windows

Diverse solutions: Diverse solutions are very limited--the interior is simple and refined.

Technology: Buttress is developed so that the wall is not needed to support vault; wall is enclosure not structure.

AMIENS



ENCLOSURE

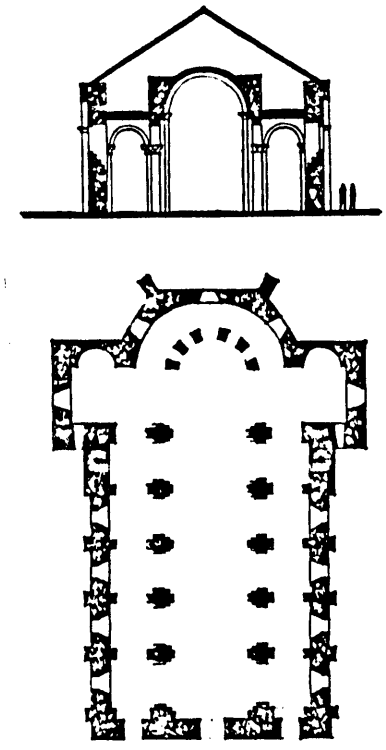
The next four pages contain drawings which are something of an overview.

These drawings show buildings which vary greatly in scale. The intent is to help solidify the magnitude of the change in scale as well as to provide an additional human focus.

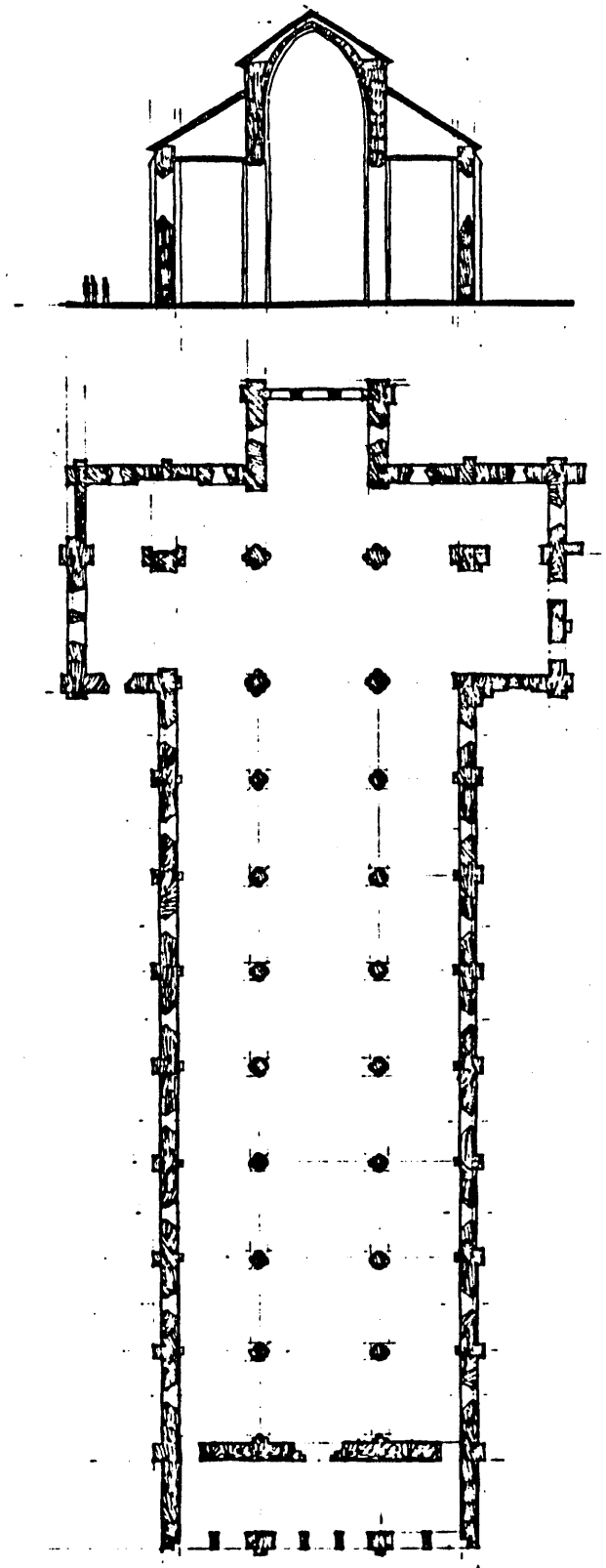
The emphasis is directed toward enclosure rather than structure or materials. The information has been limited so that the space is brought into better focus.

Three of the buildings are totally dependent upon stone for their structural support.

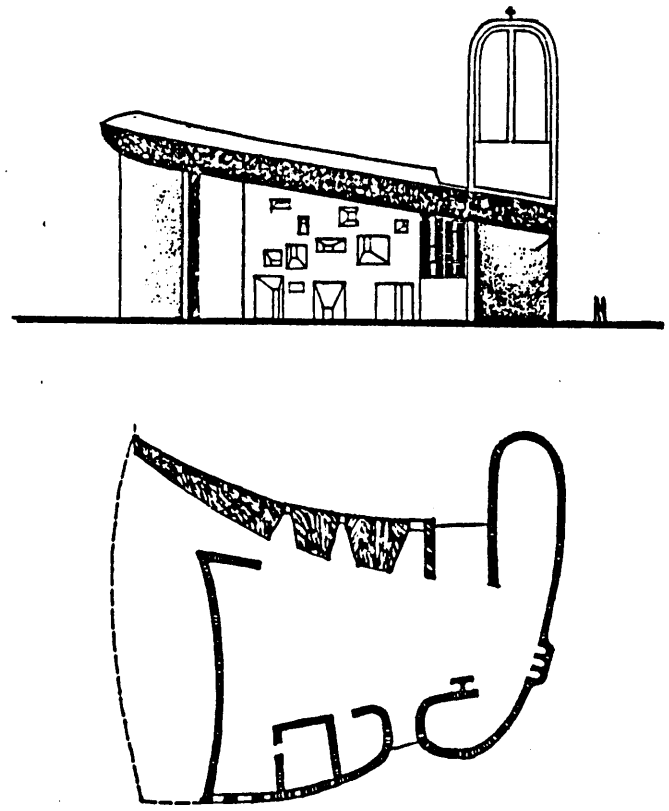
The fourth building, which is placed in the sequence by size rather than chronology, is a modern structure that was selected because of its readily identifiable nature and its ability to provide a reference point.



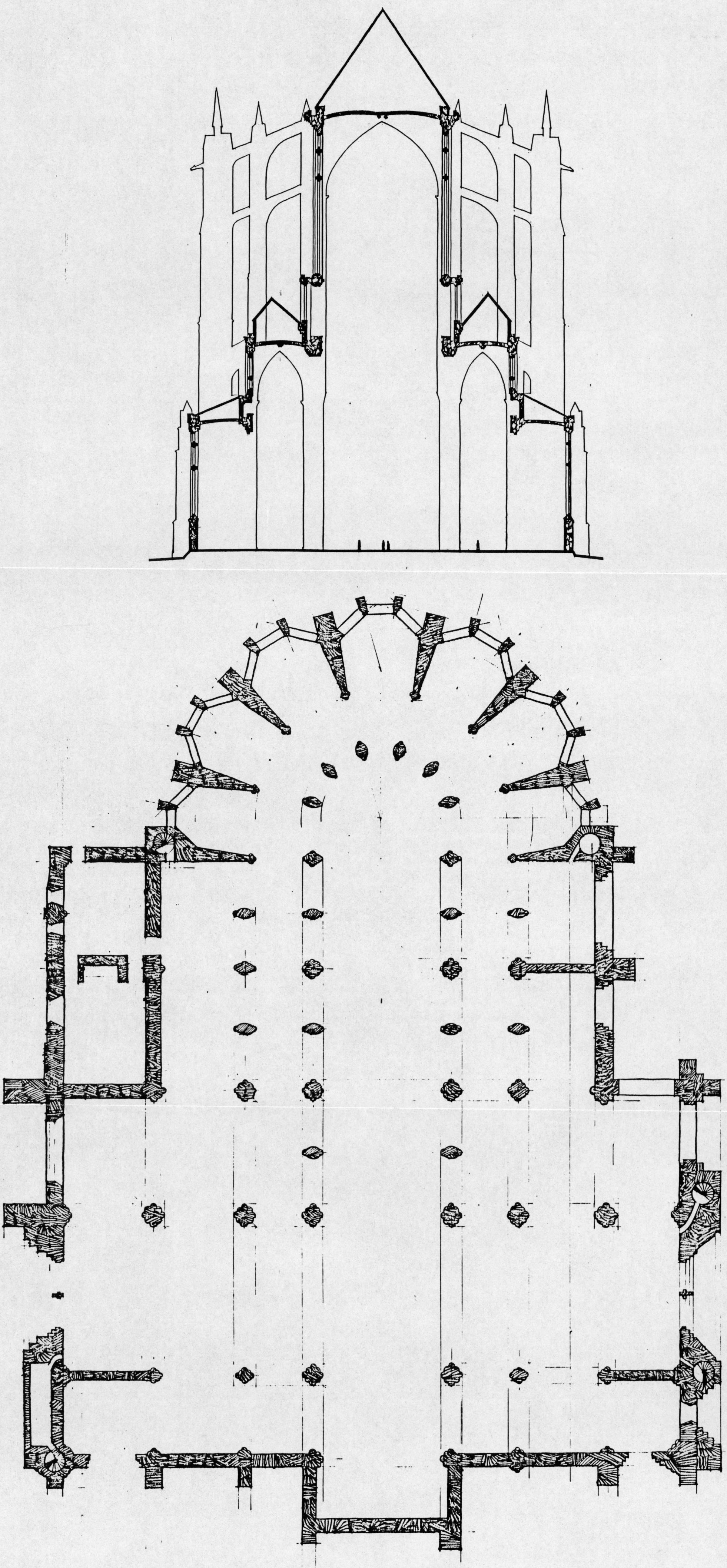
ABBAYE CHAMPAGNE



ABBAYE FONTENAY



LA CHAPELLE de RONCHAMP



St. ETIENNE de BEAUVAIS

STRUCTURE

The final series of drawings chronicles the development of the flying buttress. This element, which is so readily identified with Gothic architecture, is one of the strongest examples of how technology can affect a building.

This impact occurs on two levels. The first and most apparent is visual. The second, less obvious but more significant, is structural. While the visual aspect of the flying buttress cannot be ignored, it is the structural component which prevents the buttress from being mere decoration and gives it validity in the structure as a whole.

On the visual level the transformation is from simple to complex. The structural transformation deals with the manner in which roof thrusts are resisted. In the simple case, the force is resisted solely by mass; in the complex case, it is resisted with articulated structure.

The development of articulated structure is the heart of Gothic architecture. The ability of the buttress system to counteract the forces within the structure is what permitted architects to transform walls of inert mass into flowing tracery.

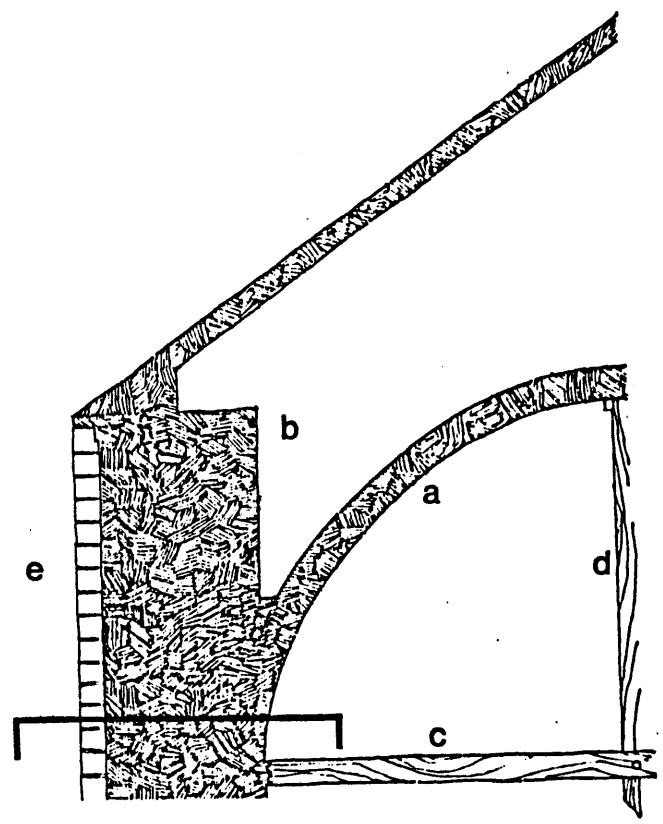
BARREL VAULT

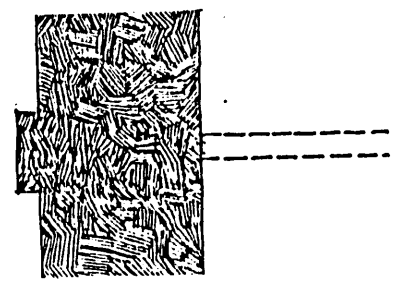
CHATEAU GRONTIER

The first case is the least complex. These early vaults were usually wood with the thrust resisted by the mass of the walls and tie beams acting in tension.

The tie beams were typically made of wood and supported vertical wooden posts. These posts acted as supports for the center of the vault, which was prone to saddle failure.

The earliest ancestor to the flying buttress can be noted in the pialaster strip. This strip was little more than a thickening of the wall, but it marked one of the earliest attempts to bolster the stone structure.[9]





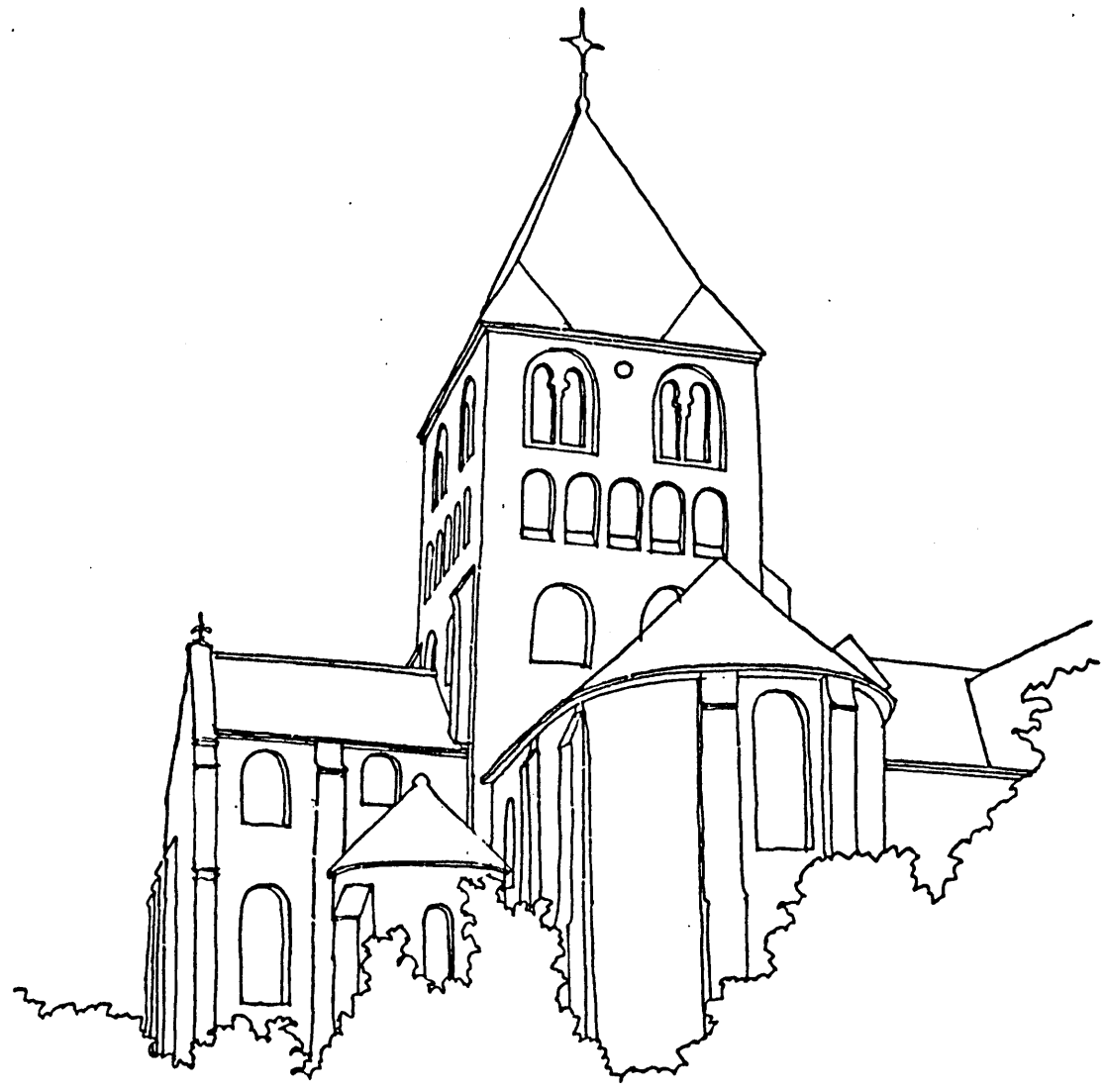
Round vault--wood

Vault reinforced with the beams and crutches

Wall reinforced with pialaster strips

Thrust resisted by mass

St. JEAN



St. JEAN

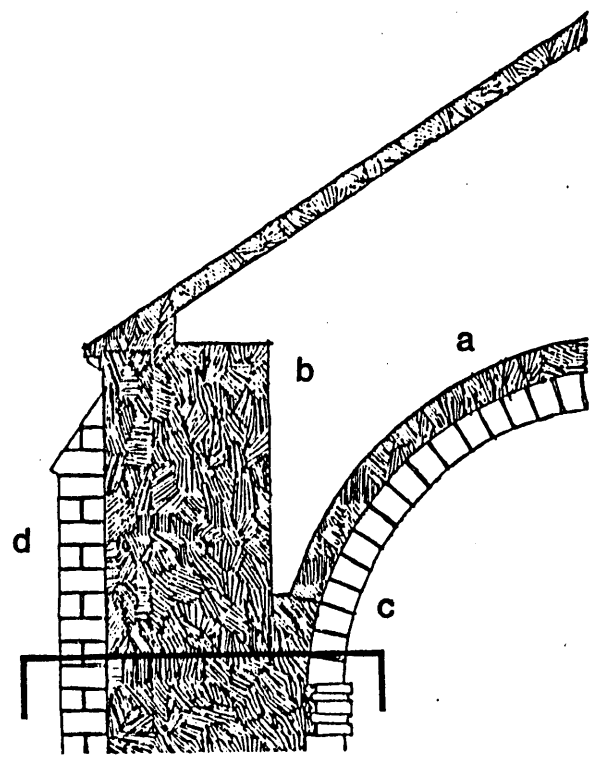
REINFORCED BARREL VAULT

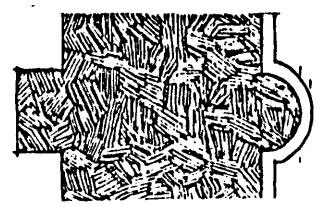
CERISY LA FORET

With the advent of heavier stone barrel vaults (a), there was increased need to strengthen the system and augment the wall mass (b).

This was accomplished by adding dual elements. On the inner surface of the wall, ribs (c) were added at a constant spacing. At corresponding locations on the exterior, fully developed pialasters (d) completed the reinforcing.

These pialasters were significantly deeper than the earlier strips and were normally detailed at the top in order to more effectively shed rain. [10]





Round vault--stone

Vault reinforced with piers and arches

Wall reinforced with pialasters

Thrust resisted by mass

CERISY LA FORET

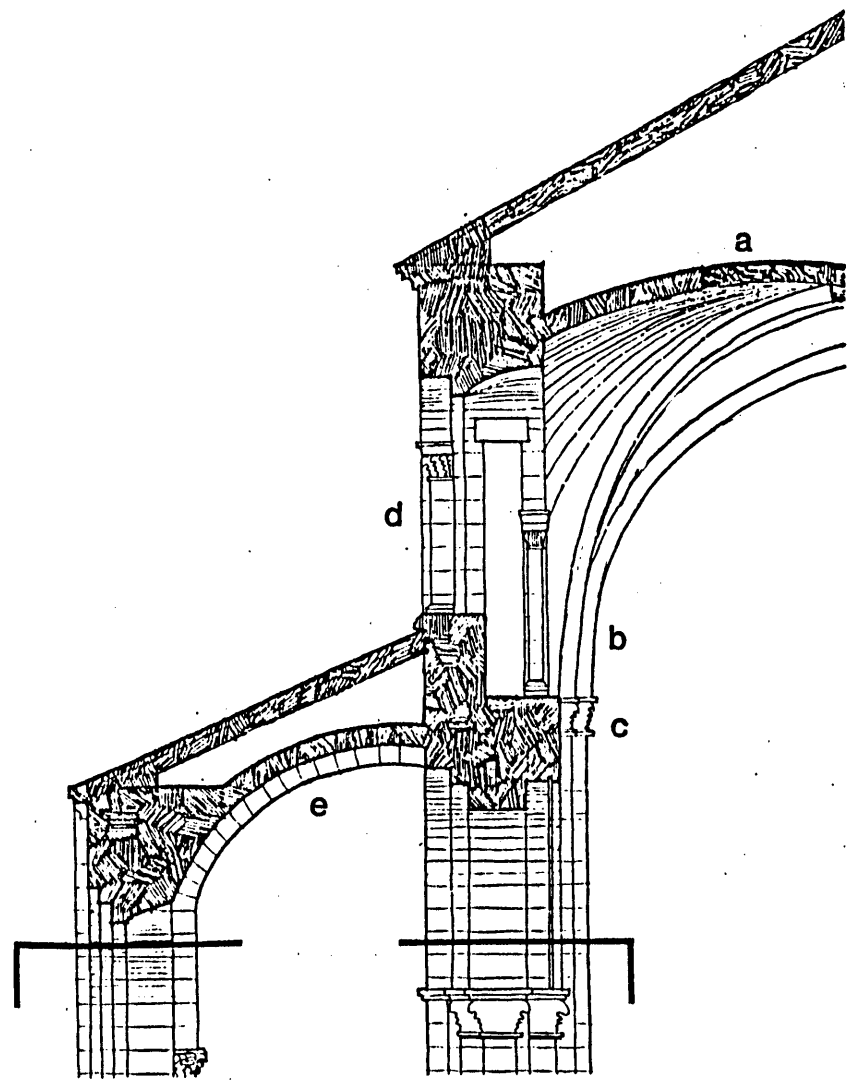
CERISY LA FORET

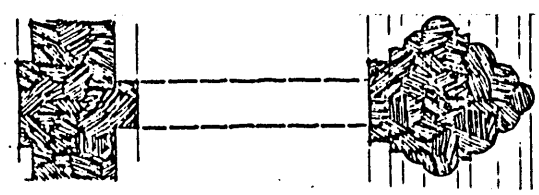
REINFORCED GROIN VAULT

ABBAYE AUX HOMMES

The continued developments in construction and architectural techniques went hand in hand with increases in the size and complexity of the structures.

In the Abbaye-aux Hommes, several distinct improvements were brought together. The main vault (a) is composed of repetitive intersecting barrel vaults with ribs (b) springing (c) from the interior piers, which greatly reduced the tendency toward saddle failure. The clerestory wall (d) has been lightened with more of the mass concentrated in conjunction with the piers, which allowed the wall penetrations to increase in size. Finally, in order to resist the thrust at the point of the vault springing, a continuous half barrel vault (e) was constructed over the aisle. This half vault does act to restrain the main vault, but it is excessively heavy and is not sensitive to the specific need of the structure. It is rather like killing flies with a baseball bat.[11]





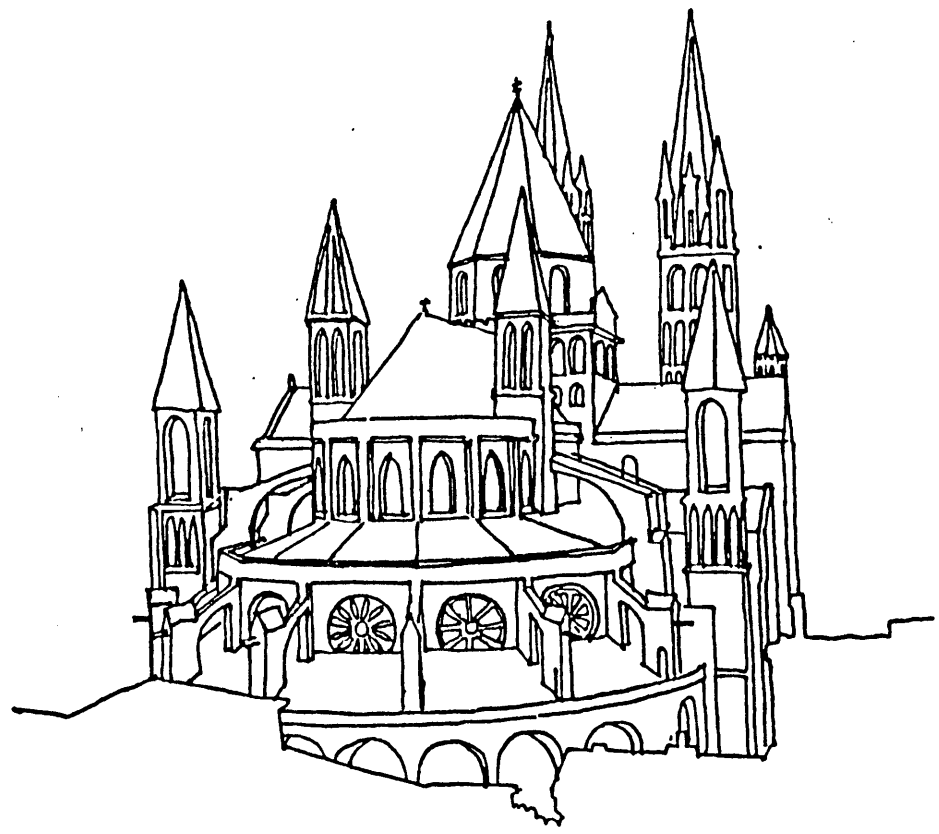
Groin barrel vault--stone

Vault reinforced with piers and arches

Wall reinforced with continuous half arch

Thrust resisted by local mass and remote mass

ABBAYE AUX HOMMES



ABBAYE AUX HOMMES

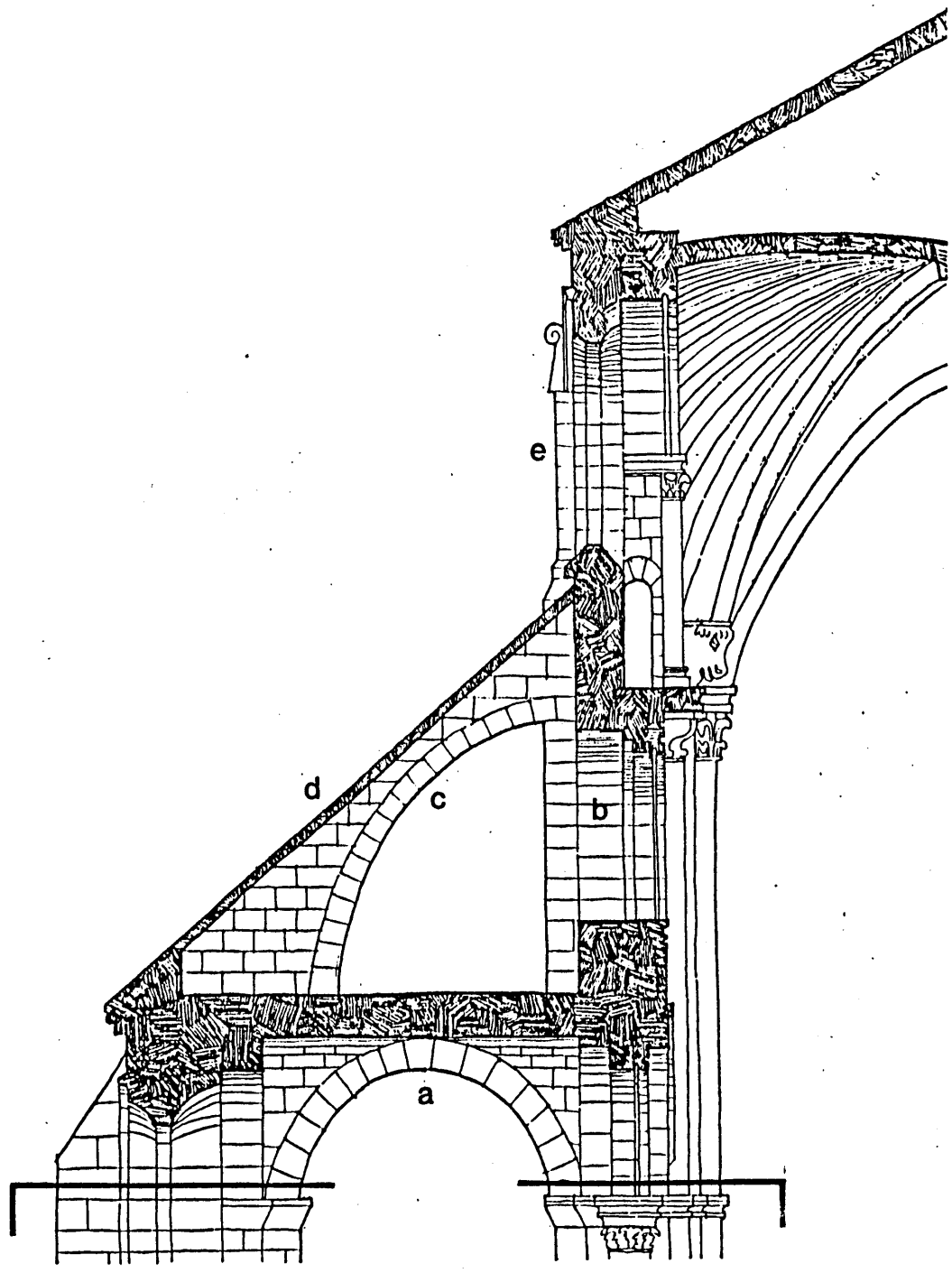
GROINED VAULT WITH CONCEALED BUTRESS

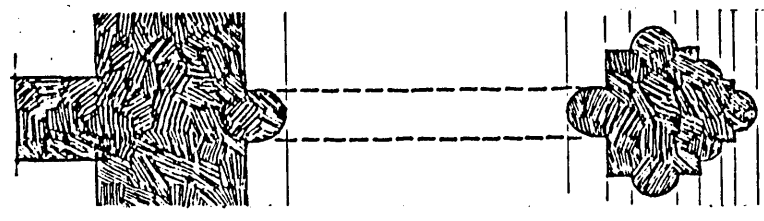
St. GERMER de FLY

St. Germer-de-Fly expands upon the improvements of the Abbaye-aux-Hommes.

The improved functioning of the intersecting barrel vault is retained, but instead of a heavy half barrel vault over the aisle, a fully developed barrel vault (a) is employed over the aisle. The architect also introduced a new element to counteract vault thrust. Placed against the nave piers (b), over the aisle, is a buttress (c). This buttress is completely enclosed by the aisle roof (d) and hence cannot be considered a flying buttress. In addition, due to its low point of contact with the pier, it does not do a particularly efficient job of resisting the thrust.

Another interesting feature is the appearance of a pialaster strip (e) at the clerestory level. This addition is evidence of the need to further reinforce the upper portion of the wall.[12]





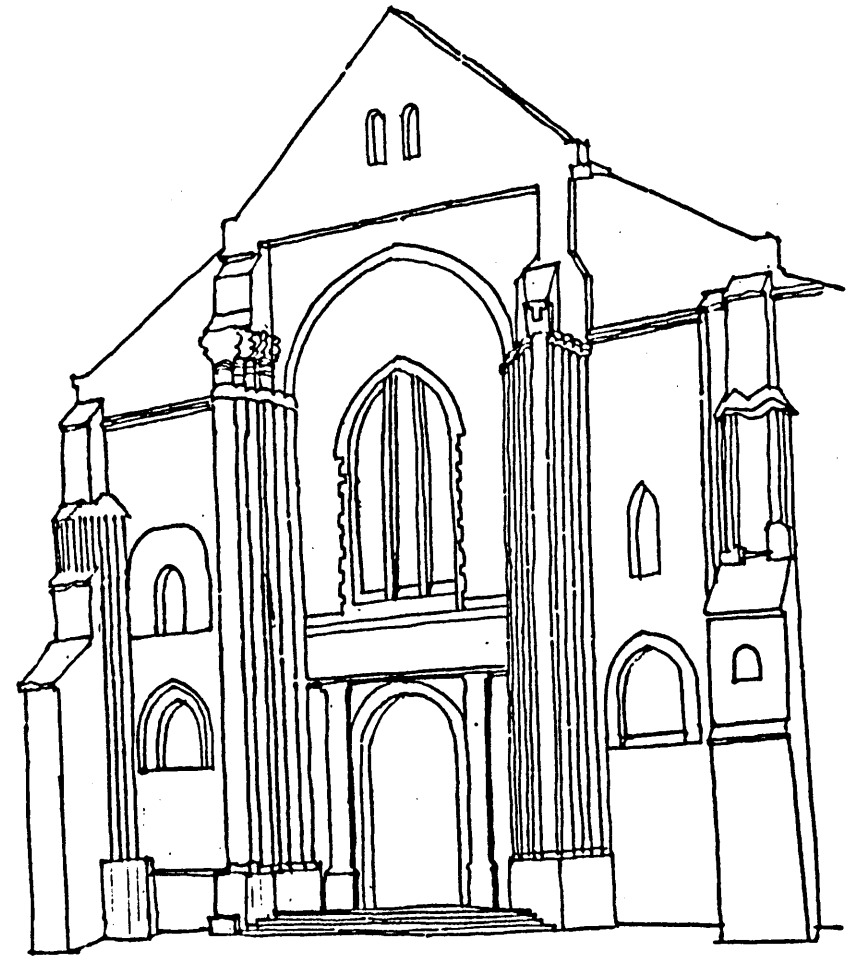
Groin and vault--stone

Vault reinforced with piers and arches

Wall reinforced with half arches at pier locations

Thrust resisted by local mass and remote mass

St. GERMER



St. GERMER de FLY

GOTHIC VAULT WITH FLYING BUTRESS

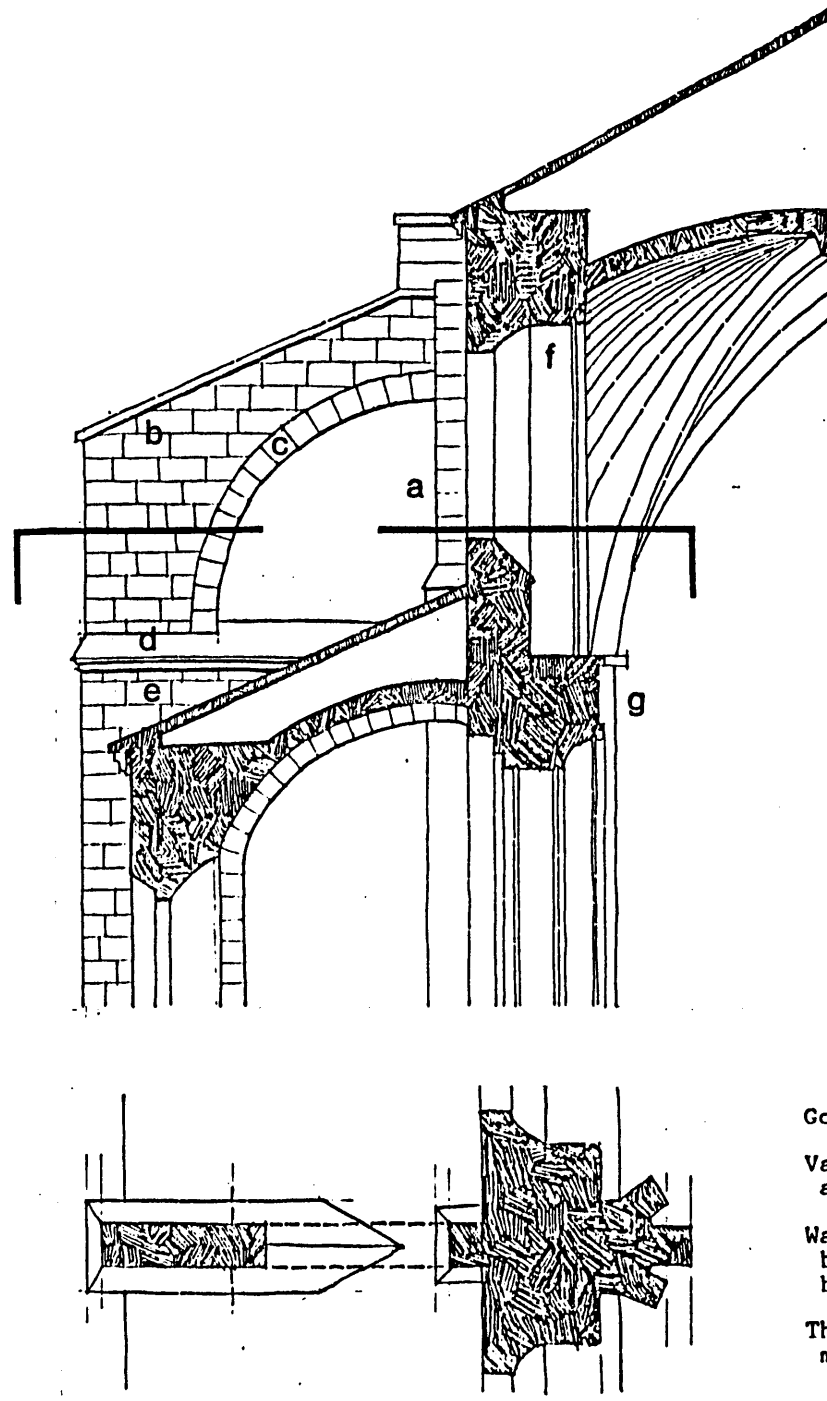
St. MARTIN de LOAN

The next marked improvement is the appearance of the true flying buttress.

In the cathedral of St. Martin Laon, the buttress has finally emerged from the aisle roof. This separation is combined with the several other features to provide an example of all the constituent parts of a flying buttress. The pier buttress (a), the flying buttress (b), the arch voisseurs (c), the offset (d), the great buttress (e).

This new feature retains the heavy masonry construction of its predecessors, but it is situated to provide a much more effective resistance pressure against the vault, by meeting the vault at the haunches (f) and the springing of the arch (g).

This is one of the first examples of a rather basic articulated structure replacing mass as the means to resist the vault thrust. It is also the first case in which the structural element has become a significant visual element.[14]



Gothic vault--stone

Vault reinforced with piers and arches

Walls reinforced with pier buttresses and flying buttresses

Thrust resisted by remote mass and counter thrust

LAON

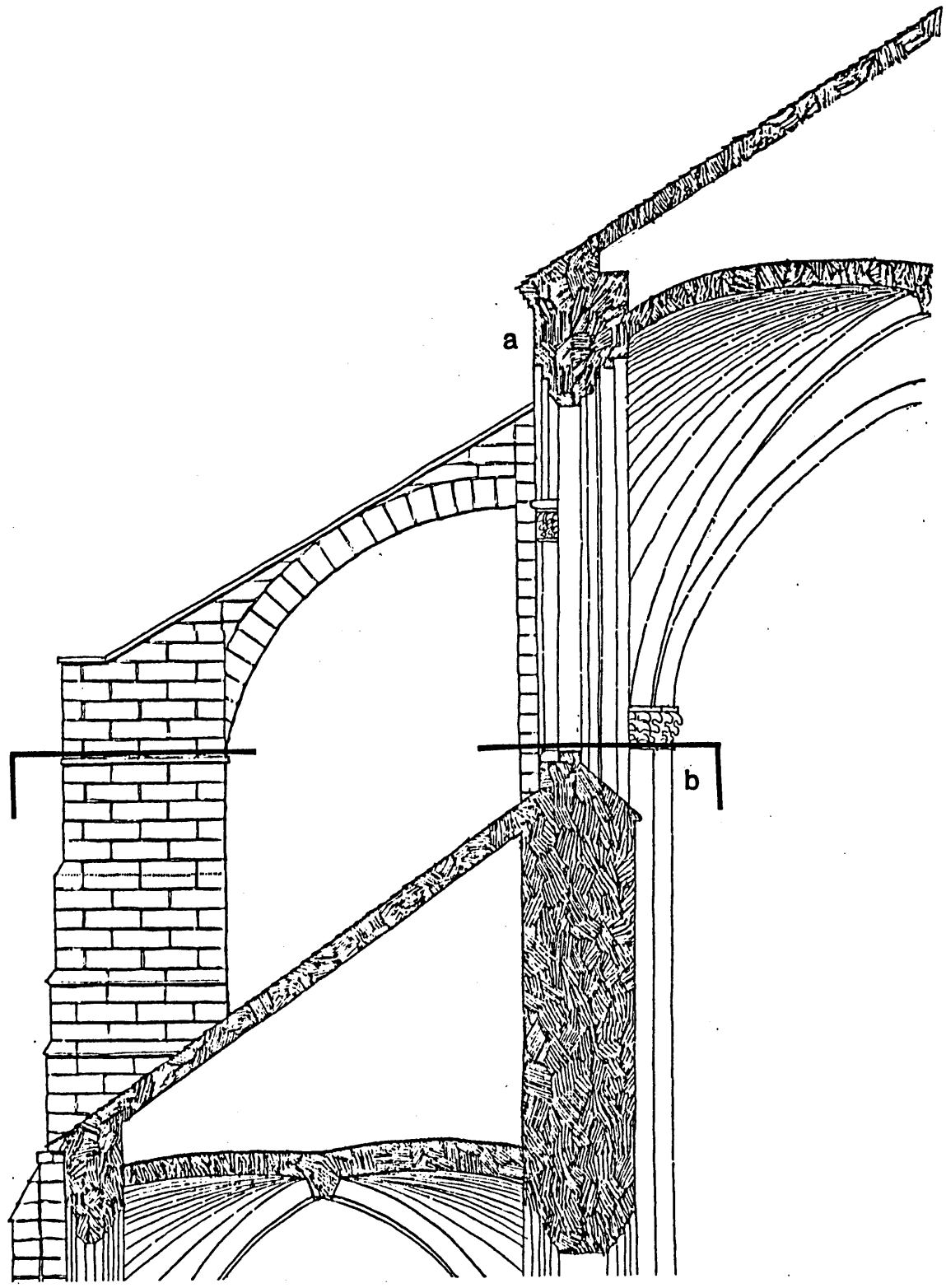
St. MARTIN LAON

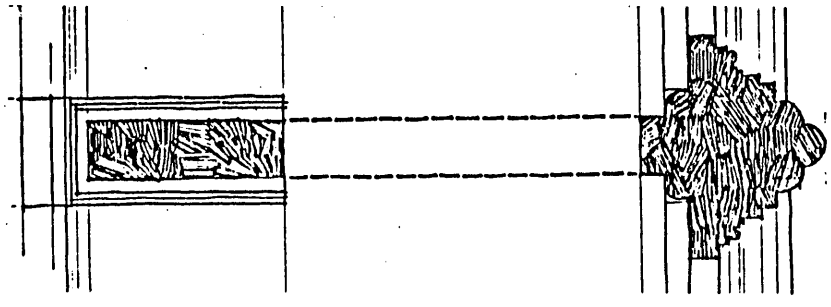
GOTHIC VAULT WITH FLYING BUTRESS

St. LEU d'ESSERENT

The next two drawings are from the cathedral St. Leu D'Esserent. What makes them especially noteworthy is the development evidenced between the two examples.

The flying buttresses over the apse at St. Leu are significantly lighter and higher than those at Laon. The point of intersection with the main wall is more effectively placed in order to restrain the vault (a). In addition, the structure under the aisle roof acts against the wall near the point of springing of the vault (b). The great buttress (c) has been detailed with small offsets which lighten its profile and add interest.[15]





Gothic vault--stone

Vault reinforced with piers and arches

Walls reinforced with pier buttresses, flying buttresses

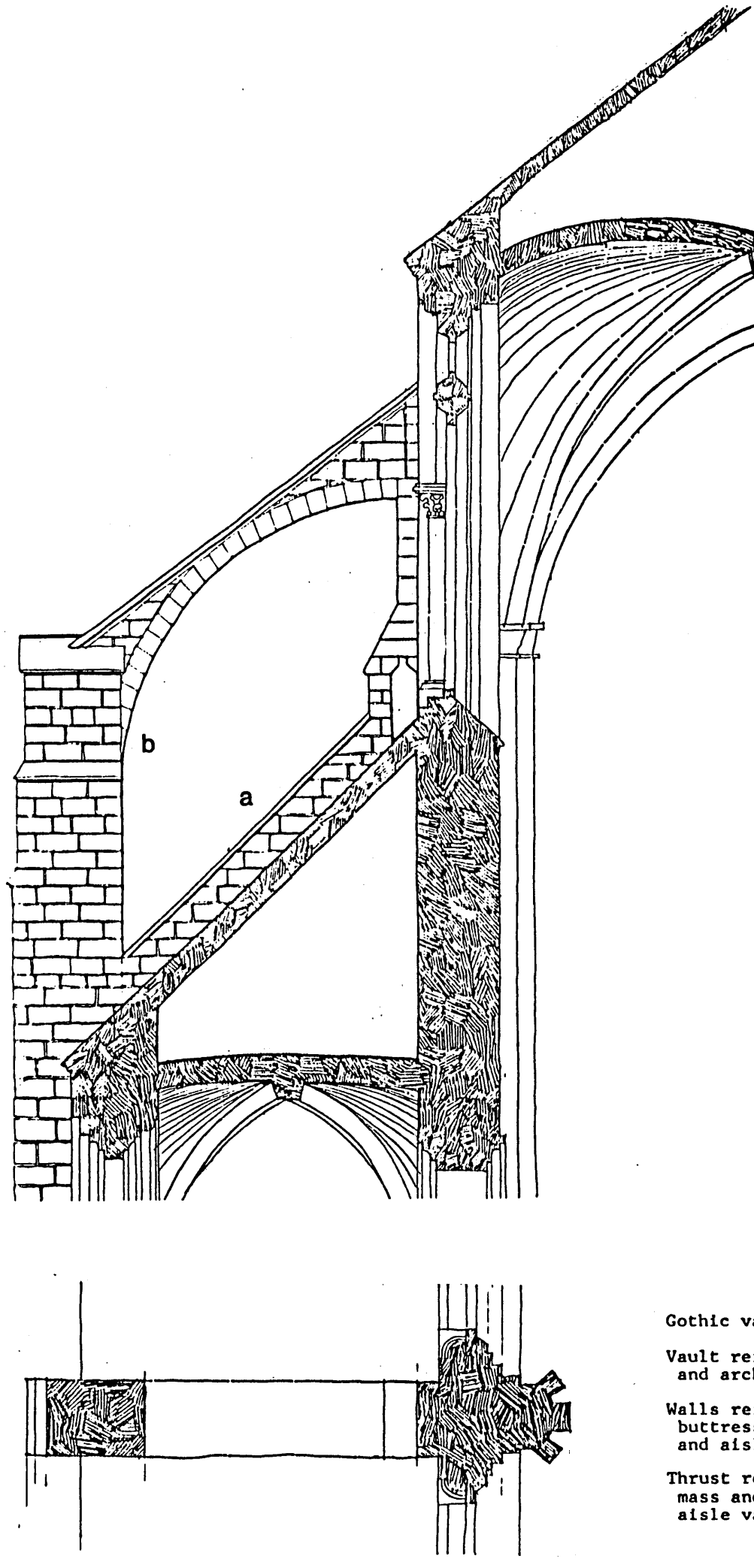
Thrusts resisted by remote mass and counter thrust

St. LEU D'ESSERENT

St. LEU d'ESSERENT

The flying buttresses over the nave at St. Leu D'Esserent are technically more advanced than those over the apse, a fact which can be attributed to the custom of building the nave after the apse, allowing outside influences time to impact the construction.

First, the structure at the aisle roof (a) has been raised above the roof itself in order to meet the spring thrust more equally. The flying and great buttresses have been differentiated (d), which allows for a gable over the great buttress in order to shed the elements. Finally, the great buttress has been constructed as a unit from top to bottom with no major offset at the roof line.[16]



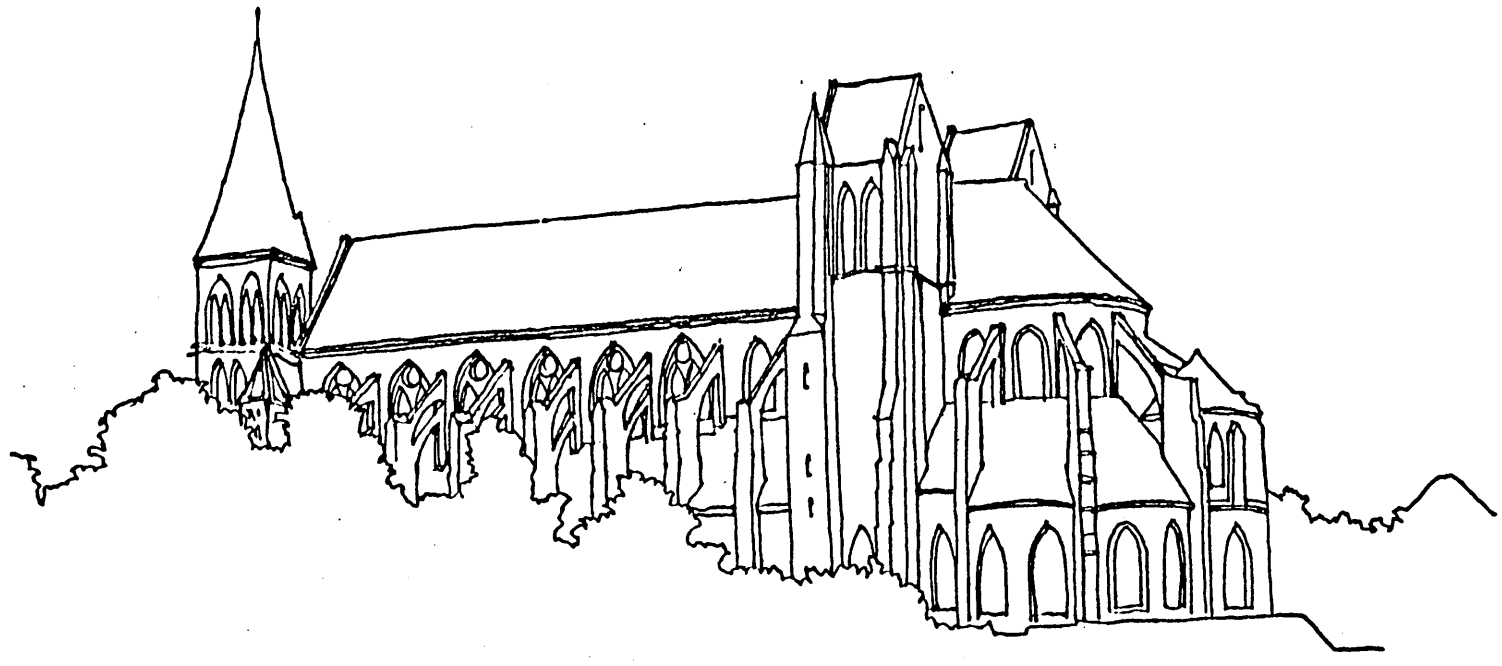
Gothic vault--stone

Vault reinforced with piers and arches

Walls reinforced with pier buttress, flying buttress and aisle buttress

Thrust resisted by remote mass and counter thrust of aisle vault

St. LEU D'ESSERENT



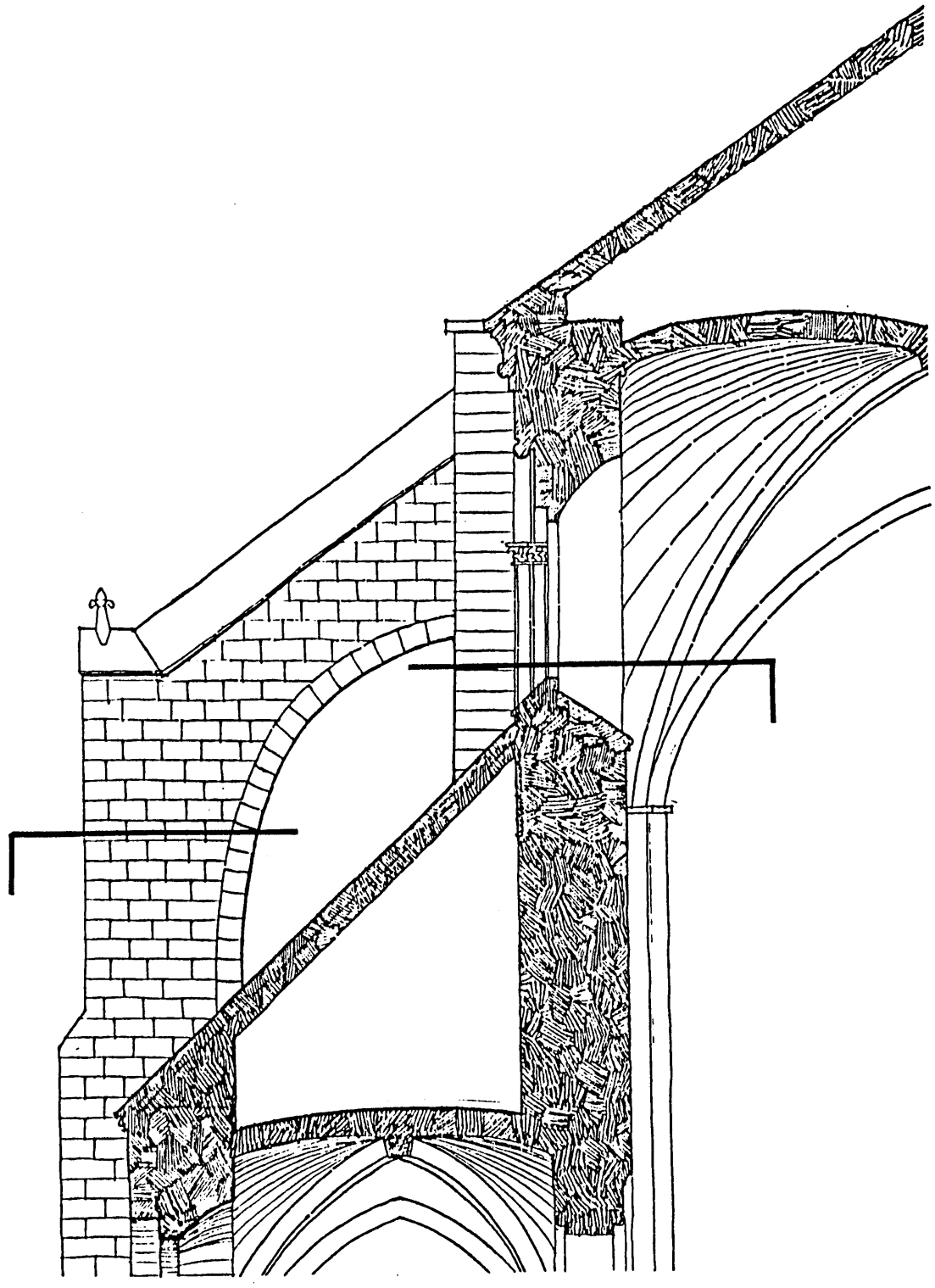
St. LEU

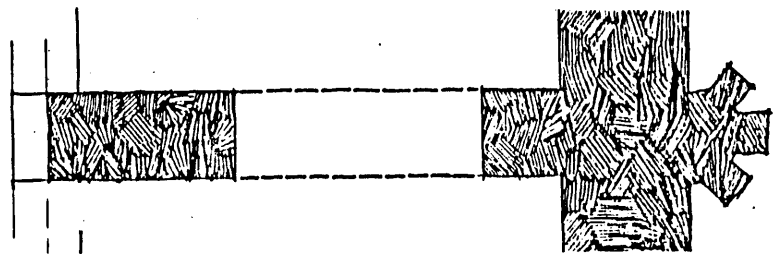
GOTHIC VAULT WITH FLYING BUTTRESS

NOTRE DAME de NOYON

The flying buttresses at the cathedral at Noyon would at first glance seem to be a step backward. Closer investigation, however, indicates the opposite. Gothic architects were, at this time, still struggling to find the most effective point at which to abut the thrusts of the vault. The use of the continuous vault over the aisle had proven impractical due to its tendency to cause inward collapse of the piers. In addition, light high buttresses tended to provide insufficient resistance and hence were prone to outward buckling.

At Noyon, the architect overcame these two problems by using a larger, more massive flying buttress and pier buttress. The significance, however, is in the point of contact with the wall, which has been deepened. This increase in section, while less elegant than its predecessors, is structurally more efficient.[17]





Gothic vault--stone

Vault reinforced with piers and arches

Walls reinforced with pier buttresses, flying buttresses

Thrust resisted by remote mass and counter thrust

NOYON

NOYON

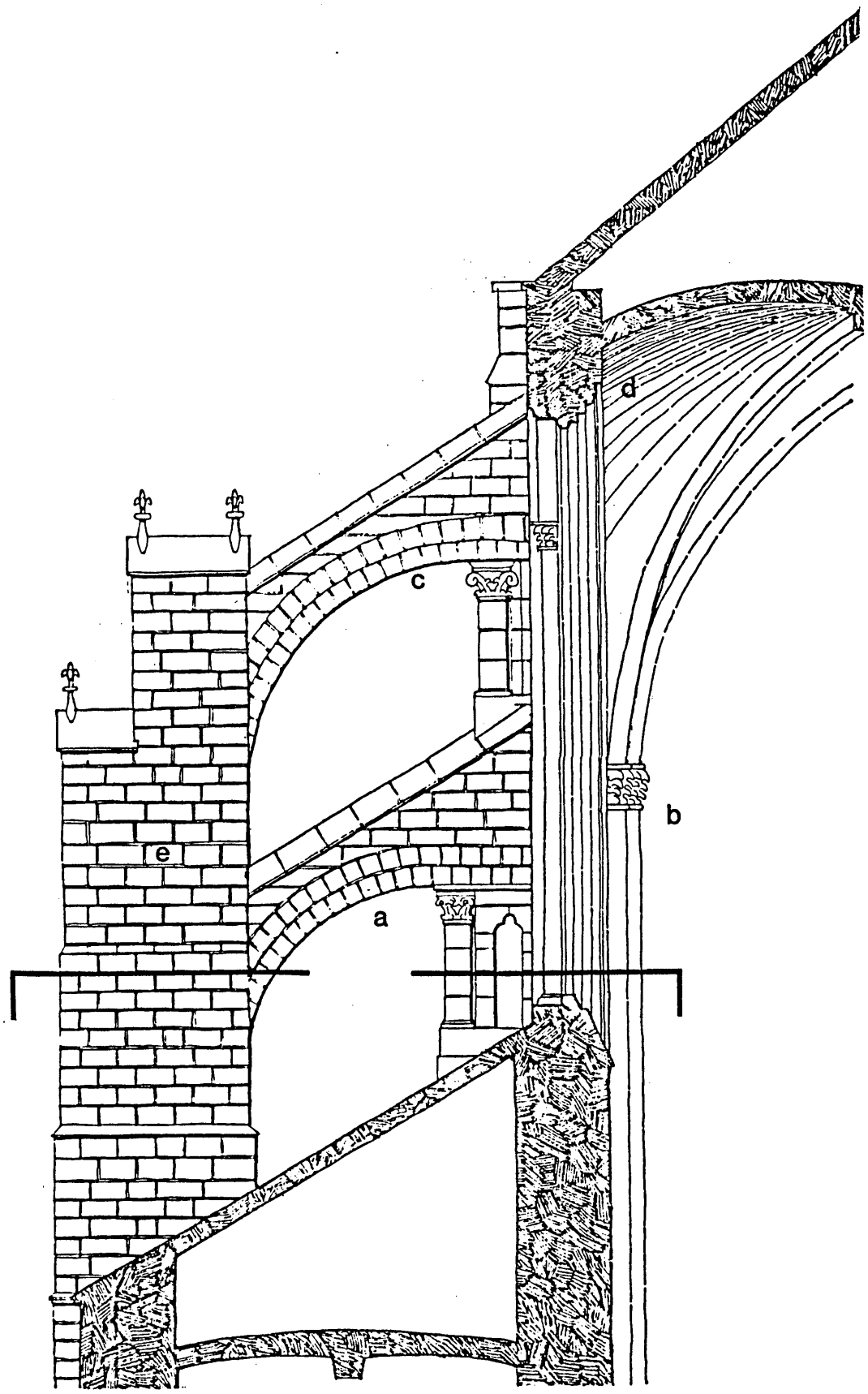
GOTHIC VAULT WITH DOUBLE FLYING BUTTRESS

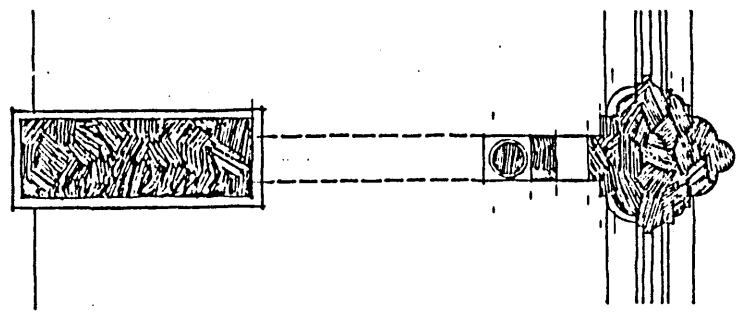
St. GERVAIS de SOISSONS

The construction of the flying buttresses at Soissons continue to show advancement. The structure, while still massive, has been highly refined to stabilize the structure.

As previously noted, one of the identifying factors in the development of the Gothic cathedral is the transformation, from mass to articulated structure. By the time the apse at Soissons was constructed, Gothic architects had gained sufficient skill to have made an almost complete transformation from mass to articulated structure. For while the constituent parts of the system are still excessively massive, the vault thrusts are resisted less by the mass than by the structure.

The double flying buttresses have been developed to meet the vault at the points of greatest thrust. The lower arch (a) abuts the vaults at the springing (b). The upper arch (c) abuts the vault at the haunches (d). The thrusts are relieved by the half arches and transmitted to the great buttresses (c) and hence to the foundations.[18]





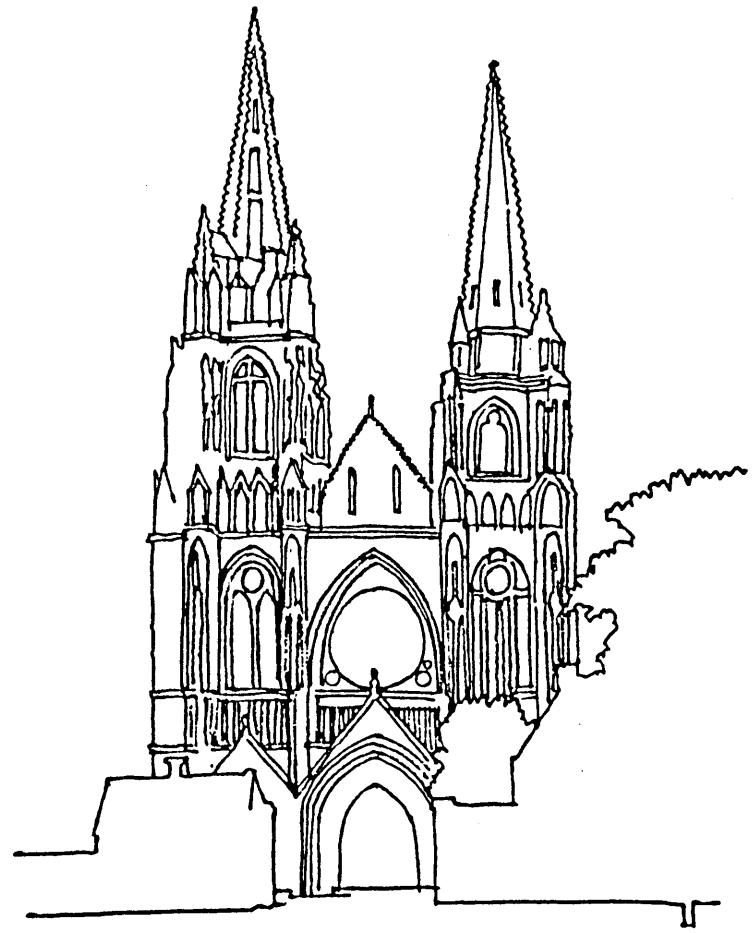
Gothic vault--stone

Vault--reinforced with piers and arches

Walls reinforced with pier buttresses and flying buttresses

Thrust resisted by remote mass and counter thrust

SOISSONS



St. GERVAIS de SOISSONS

GOTHIC VAULT WITH DOUBLE FLYING BUTTRESS

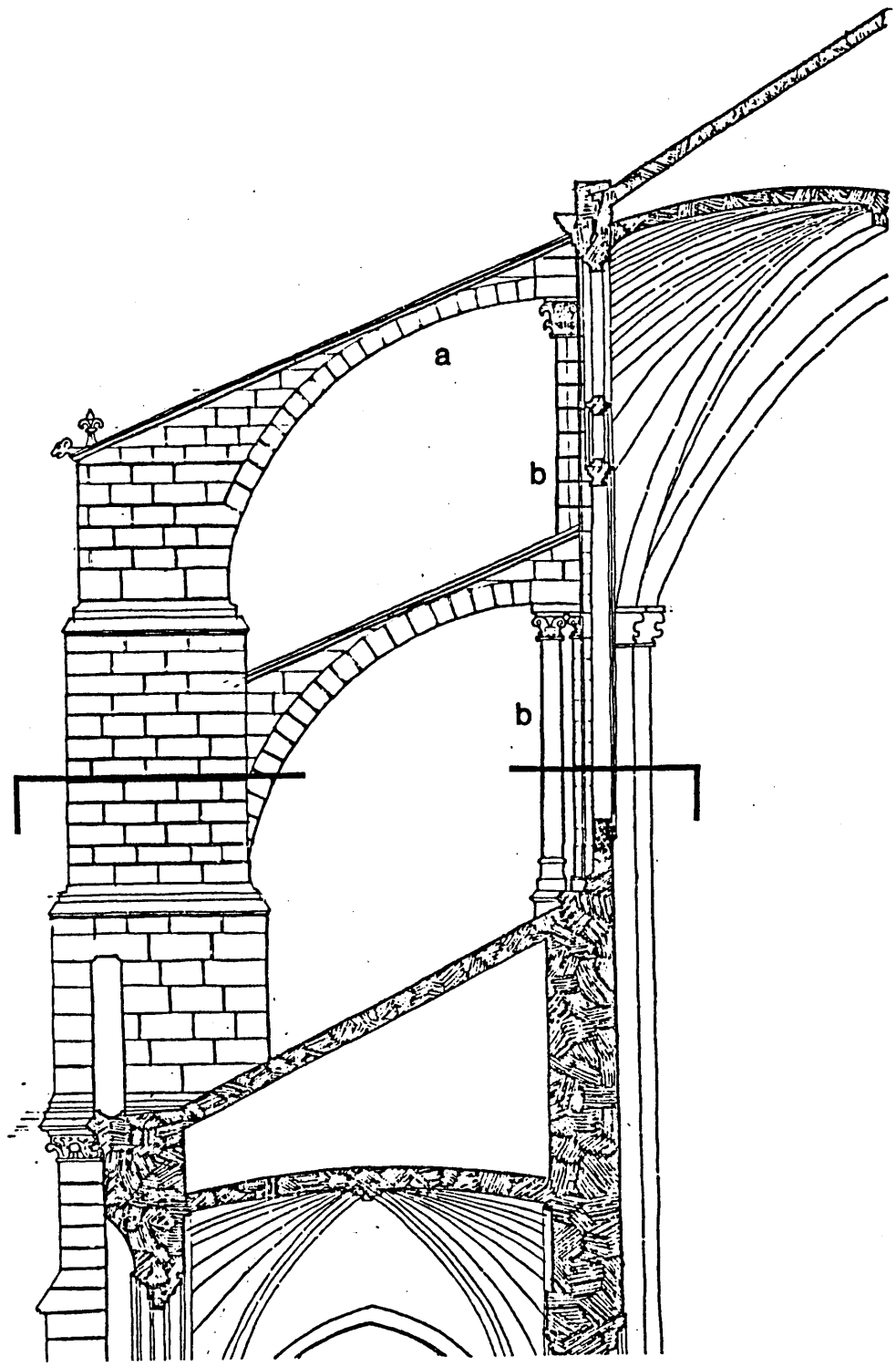
St. PIERRE de CHARTRES

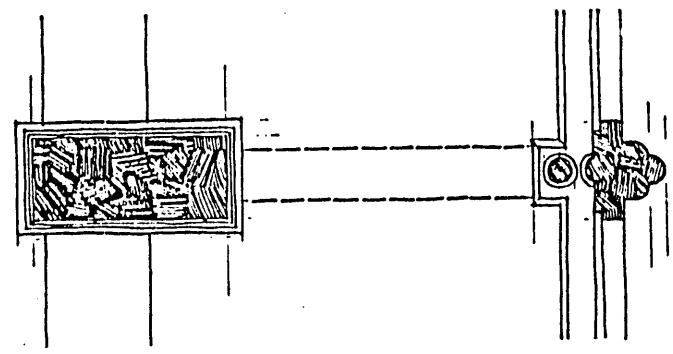
The church of St. Pierre at Chartes is more refined than the massive structure of Soissons.

The flying buttresses are light, almost delicate. This change is possible because the point of contact between the buttress and the nave are exactly coincident with the forces in the wall.

The pier buttresses have been lightened and are more highly adorned than before. This has been made possible by the increased ability of the flying buttress to support the wall. The pier buttresses serve to help resist shear at the upper end of the arch.

Chartes also has examples of the penchant of the Gothic architect for diverse solutions. The pier buttresses and the related pialasters are all treated in subtly different ways. This is also the case with the multiple offsets in the great buttress.[19]





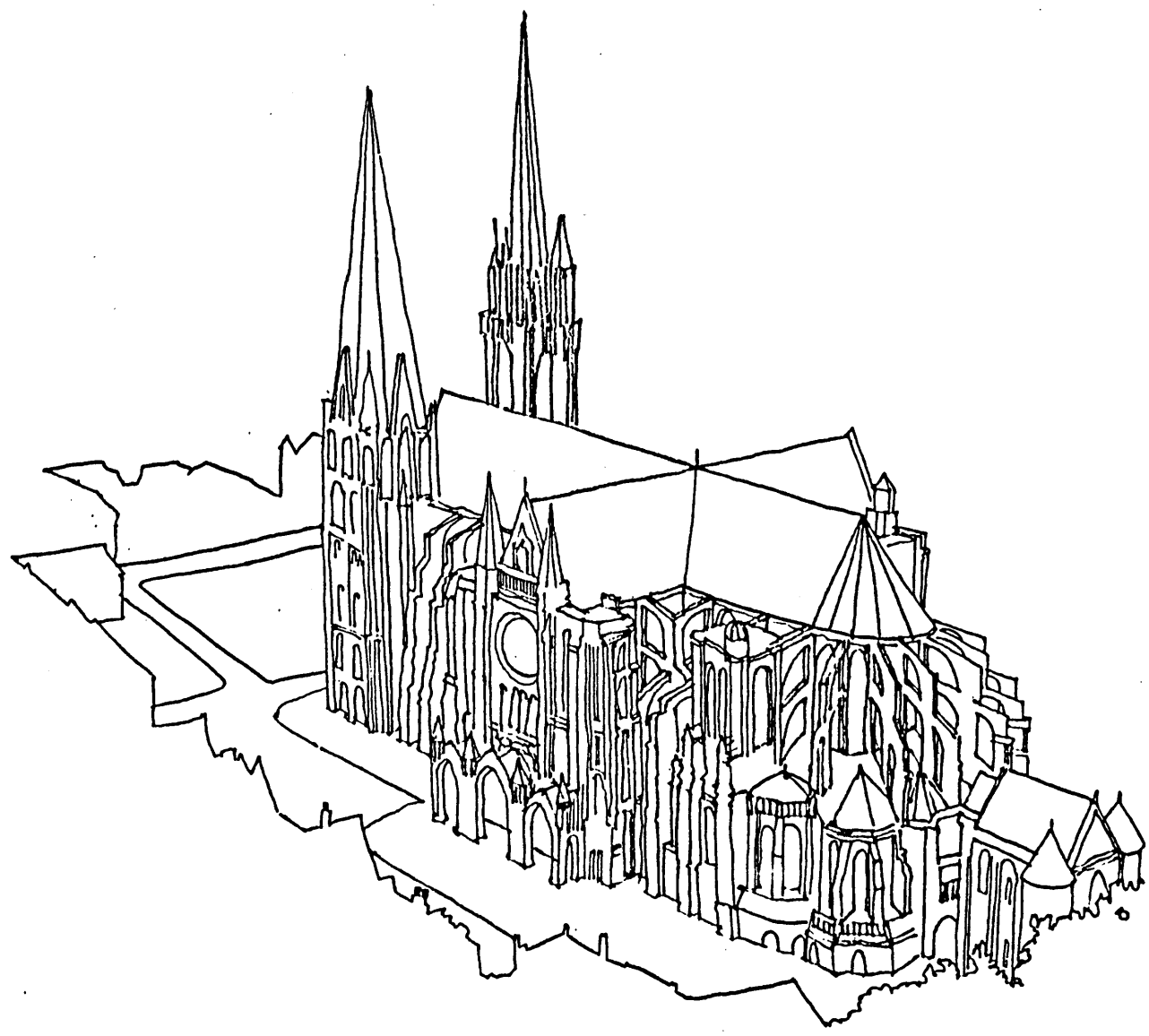
Gothic vault--stone

Vault--reinforced with piers and arches

Walls reinforced with pier buttresses and flying buttresses

Thrust resisted by remote mass and counter thrust

CHARTRES



CHARTRES

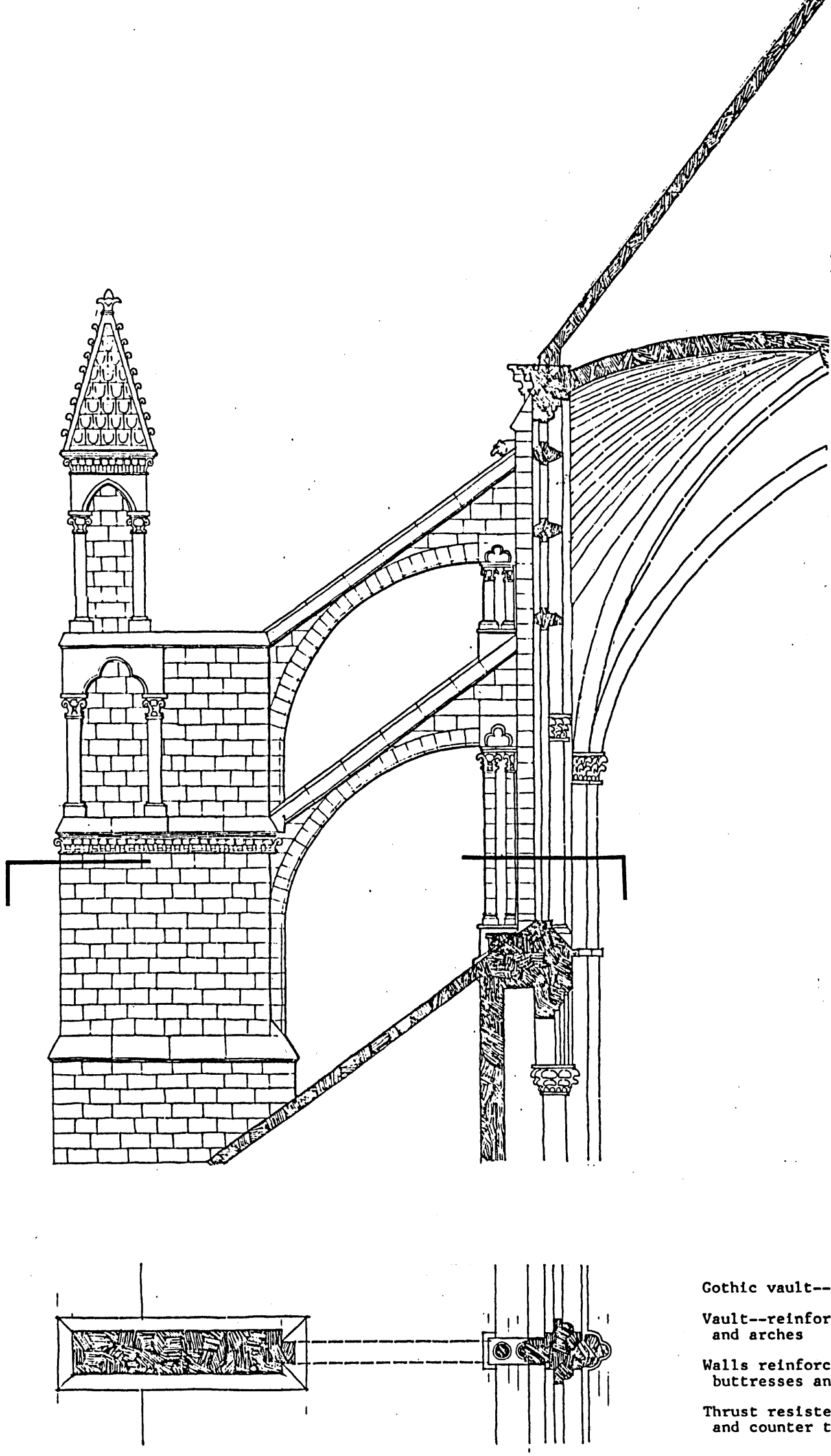
GOTHIC VAULT WITH DOUBLE FLYING BUTTRESS

NOTRE DAME d'AMIENS

This drawing and the next are the conclusion of the series on the flying buttress. The two cathedrals, Amiens and Reims, represent the highest achievement of the Gothic architect.

In these two structures, the structural system has been refined to its maximum potential. The respective elements have been judiciously modified in both form and finish until even a slight reduction in any member would mean collapse.

The arrangement of the elements and then highly refined shapes are the result of the masters' quest for ways to achieve the maximum height and minimum wall in their structures. The transformation is now complete. The stone vaulting in Amiens, almost 42 meters above the pavement, is resisted not by heavy masonry walls but by skillfully constructed structure. The basic materials have not changed, but the approach and solution to the problem are totally different.[20]



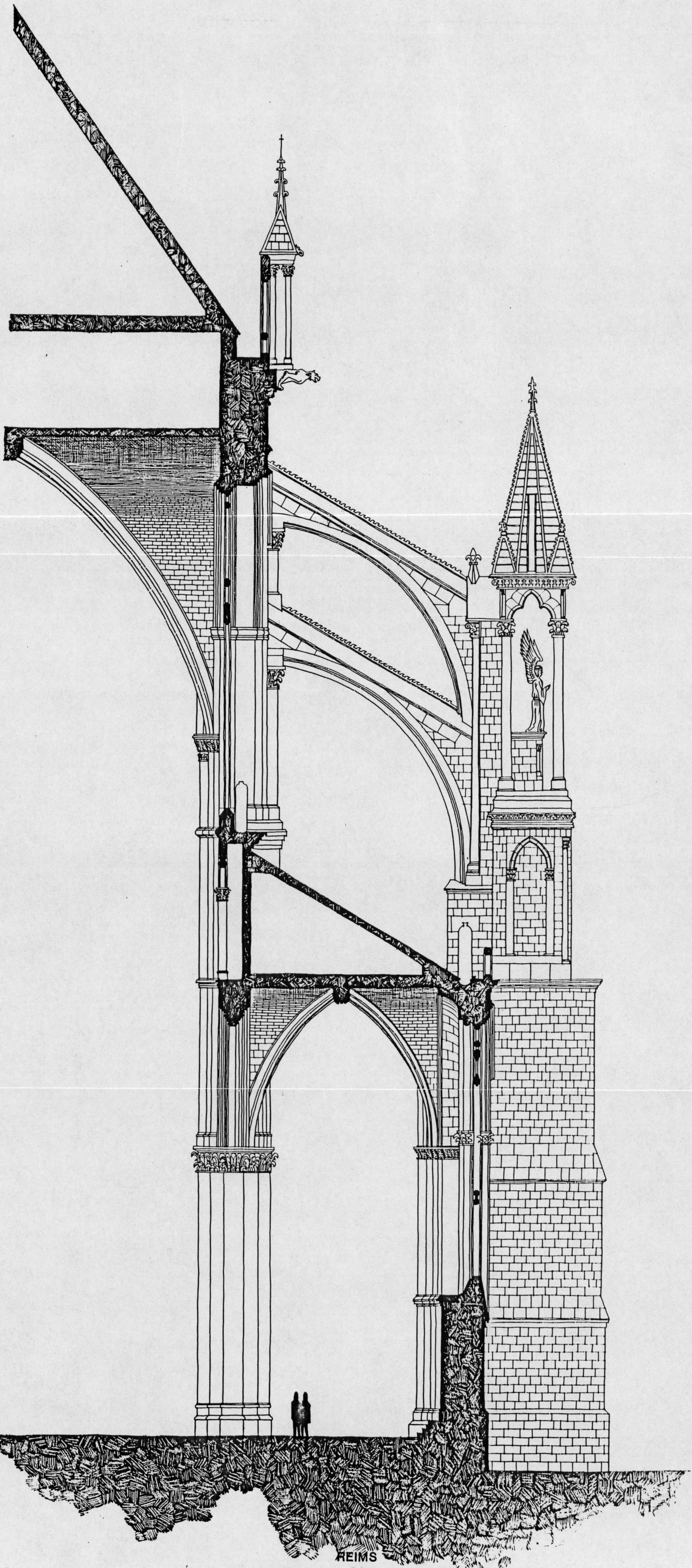
Gothic vault--stone

Vault--reinforced with piers and arches

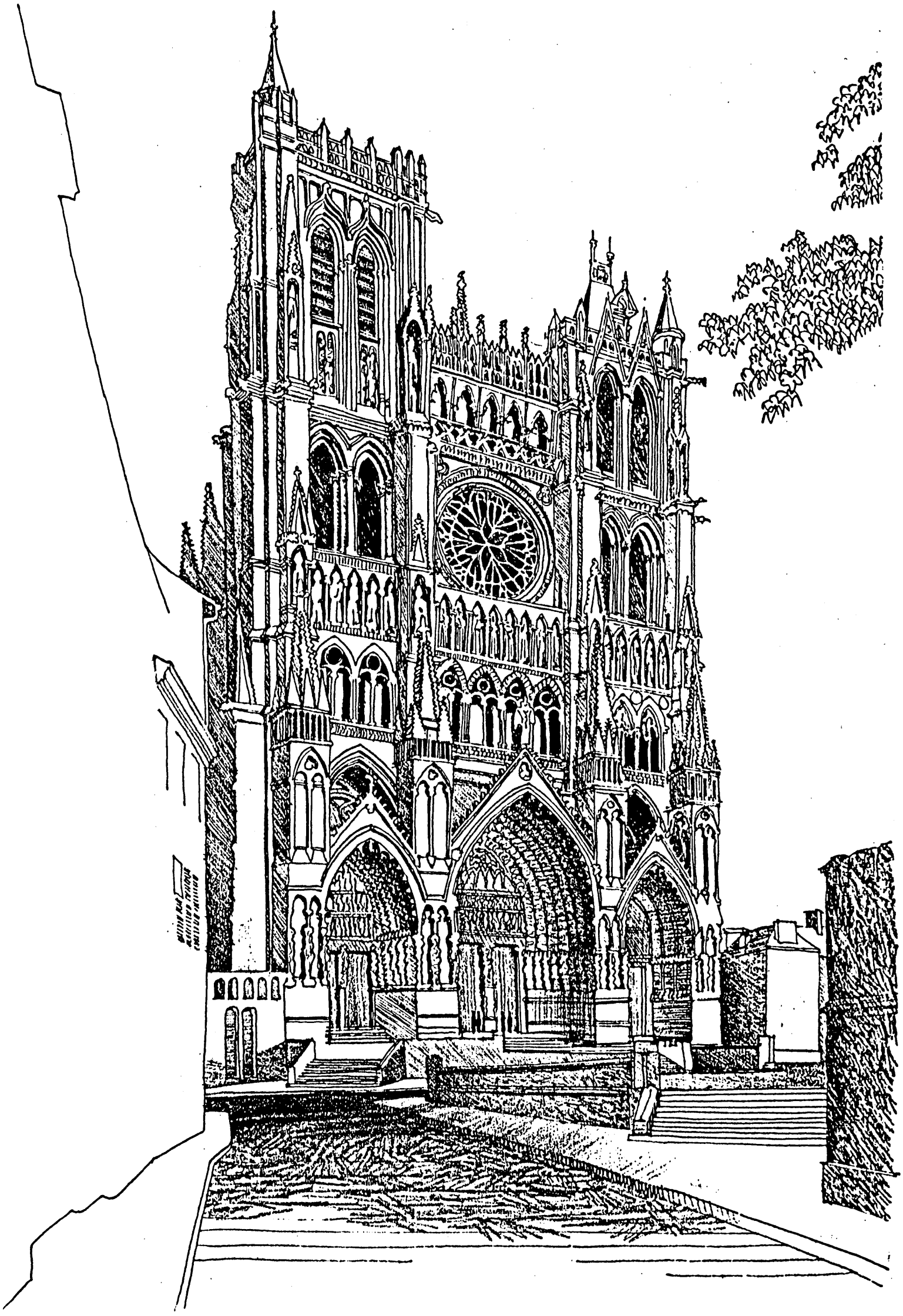
Walls reinforced with pier buttresses and flying buttresses

Thrust resisted by remote mass and counter thrust

AMIENS



REIMS



AMIENS

CONCLUSION

This study does not pretend to be an exhaustive survey of gothic architecture.

It is a presentation of a number of drawings. These drawings are the vehicle by which gothic architecture is explored and various aspects are compared.

There are many design principles which are evident in gothic architecture. The three which were selected are noteworthy because of their major impact and because they have continuing validity today.

The study of design principles has validity today as a means to coherent design, design which has a sense of purpose and which is founded on intent not accident.

It is not possible to extract design principles from gothic or any other epoch directly. These principles must be studied in terms of their impact on a space and how that impact changes as the application varies.

This study seeks to explore

1. The use of repetitive elements
2. The use of varying solutions to a common problem
3. The refinement and application of technology to enrich space

in such a way.

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FOOTNOTES

1. Charles Moore, Development & Character of Gothic Architecture (London: Macmillan Company, 1899), p. 6.
2. Ibid.
3. James H. Acland, Medieval Structure: The Gothic Vault (Buffalo: University of Toronto Press, 1972), p. 28.
4. Ibid., p. 27.
5. Ibid., p. 39.
6. Ibid., p. 40.
7. Ibid., p. 72.
8. Violet-Le-Duc, Dictionnaire Raisonne De L'Architecture Francaise, 1967.
9. Moore, op. cit., p. 12.
10. Ibid.
11. Ibid., p. 12.
12. Ibid., p. 80.
13. Ibid., p. 139.
14. Ibid., p. 145.
15. Ibid., p. 146.
16. Ibid., p. 147.
17. Ibid., p. 149.
18. Ibid., p. 150.
19. Ibid., p. 139.
20. Ibid., p. 151.

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