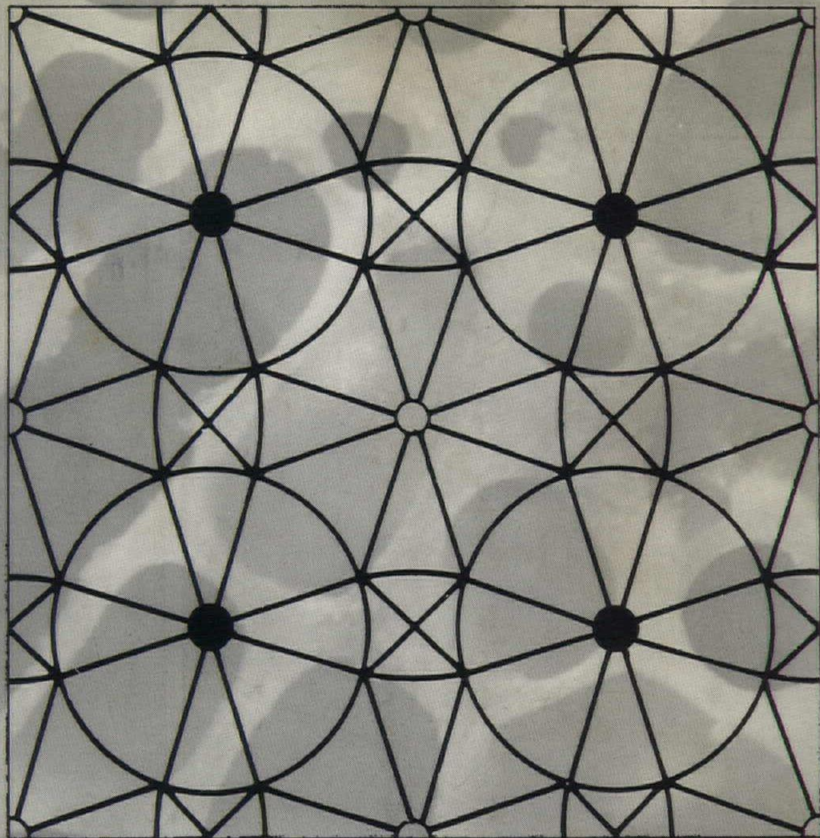

THE STUDENT PUBLICATIONS OF THE SCHOOL OF DESIGN

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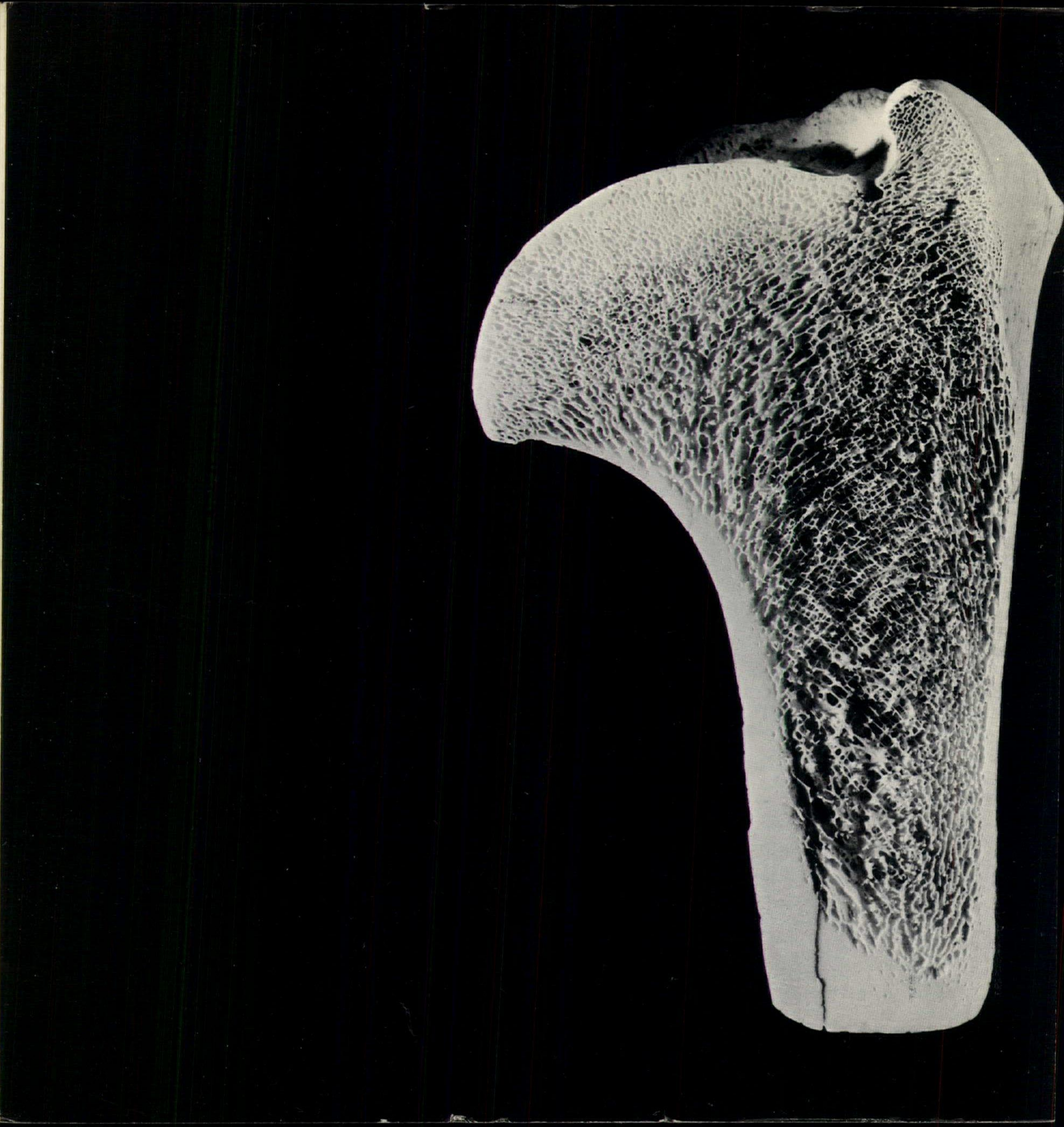
RALEIGH, N. C. VOLUME 11 NO. 2

"— in our own bones, and in all weight-carrying bones in general, the hollow space is filled with marrow, blood-vessels and other tissues; and amidst these living tissues lies a fine lattice-work of little interlaced 'trabeculae' of bone, forming the so called 'cancellous tissue'. —and we have no difficulty in seeing that the anatomical arrangement of the trabeculae follows precisely the mechanical distribution of compressive and tensile stress. —. The lines of stress are bundled close together along the sides of the shaft, and lost or concealed there in the substance of the solid wall of bone; but in and near the head of the bone, a peripheral shell of bone does not suffice to contain them, and they spread out through the central mass in the actual concrete form of bony trabeculae." *

* D'Arcy Wentworth Thompson, On Growth and Form, Volume II, (Cambridge, 1952) P. 975, P. 978-79.



Volume 11 Number 2

STUDENT PUBLICATIONS OF THE SCHOOL OF DESIGN

Augusto Cavallari-Murat

STATIC INTUITION AND FORMAL IMAGINATION IN THE SPACE LATTICES OF RIBBED GOTHIC VAULTS

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Pier Luigi Nervi

SOME CONSIDERATIONS ABOUT STRUCTURAL ARCHITECTURE

Pier Luigi Nervi, celebrated designer, engineer, builder, and Professor of Engineering at the University of Rome. Principal and consultant on numerous buildings in Italy and abroad. Author of the Books, SCIENZA O ARTE DEL CONSTRUIRE ? and CONSTRUIRE CORRETTAMENTE

Augusto Cavallari- Murat

Static Intuition And Formal Imagination In The Space Lattices Of Ribbed Gothic Vaults

AUGUSTO CAVALLARI—MURAT reimposes the classification of the gothic ribbed vaulting to the ogive, star, reticulated, sail, and cellular vaults with emphasis on the ease of interpretation of their geometrical generation and of their static behavior. He is critical of the unfavorable prejudices regarding the mechanics of such vaults, especially the examples of the much later period. Also, he revises the critical guides on the aesthics of such structures as works of art. He signals interest for this thesis as a source of inspiration and productive meditation for the exponents of thin shells and for contemporary architects.

This paper in slightly altered form first appeared in the July 1958 issue of *Atti E Rassegna Technica,* the Journal of the Society of Engineers and Architects Turin, Italy. It is reprinted with the permission of the author. Translation for this publication was by CHARLES H. KAHN Associate Professor, School of Design, N. C. State College.

There are many reasons for examining closely the complex ribbed vaults that gothic builders executed in stone and brick. Two, however, are of particular importance.

First, there is the laboriously acquired conviction that in the resistance of buildings great emphasis should be placed on questions of form. In the scarcely surpassed attitude of the science of construction, however, which cautiously confined itself to the study of the most elementary ideal solid bodies, the stress was laid upon the elastic quality of the materials.

Second, there is the impression which has helped theoretical aesthetics to establish, even though only empirically in the field of criticism, the bonds in the centuries of Gothic art between the formal ideation of structures from the mechanical-geometrical standpoint and the architectonic language expressing itself in style.

(Left), Interpenetrating star vaults from 1431 in the left nave of St. Thiebaut at Thann (Haut-Rhin)

We have already found an anticipation of both problems in Viollet-le-Duc who introduces one to the study of ribbed vaults built between the twelfth and fourteenth centuries in a well-formulated manner worth recalling.[1] Which mental attitudes, Viollet-le-Duc asks, must twelfth century French architects have assumed in starting "one of the more thorough and most justified revolutions that has ever been made in the architectural field". What did architects of the transition period say of this revolution? Perhaps they thought that the Romans in building their barrel vaults and hemispheric cupolas, appearing as compact and homogeneous geometric solid bodies to the observer inexperienced in building technique, would in fact have executed them by constructively distinguishing the elementary parts hidden behind the smooth surfaces. They would have organized an active structure in masonry and a neutral conglomerate filling, the former being a supporting structural element and the latter inert matter—two elements, then, one essential and supporting and the other less necessary with regard to static purpose because it is merely borne. These two fuse with each other in one apparent form, 'une concretion'.

However excellent and satisfying the theoretical intent had been (and it may be noticed that Viollet-le-Duc also perceived remarkable qualities of economy in its realization which would be envied by the smartest contractors of today and even by the so-called scientific organizers of labor), the outcome of Roman architecture as an art would have appeared defective to Gothic architects in deference to a longed-for aesthetic program according to which the real function of each member must be exposed by a form which is in rapport with its function. If the vaulted structure can be made self-supporting by means of the sole or prevailing ribbing reticle, such reticle should not be hidden by the decoration. On the contrary it ought to be conspicuous, and the more useful it is, the more clearly discernable it should be.

Such was the essential thought and the program attributed by Viollet-le-Duc to the Gothic innovators of the twelfth century.[2] Consequently, there they are at work making the ribs emerge from the simple homogeneous geometric solid body of the vaults and cupolas. From then on these ribs will run in relief under the surface of the intrados; and since the vaulted structure would rely on their network, both to form the vault and to effectively carry the loads, it is logical to think of such nets as independent frames on which are laid small secondary vaults sometimes of double curvature. The vault would have been conceived and realized as composed of many secondary vaults—that is of many small vaults covering the spaces left empty in the ribwork.

This whole assembly comprises a spatial system which Viollet-le-Duc

[1] E. Viollet-Le-Duc, *Dictionnaire raisonne de l'architecture francaise du XI au XVI siecle*, Morel, Paris, 1875 (vol. IX, p. 465-550).

[2] "That western architects had made this reasoning full in the twelfth century, we will not assert; but their monuments made it for them, and that is sufficient for us", says Viollet-le-Due in his exquisite and picturesque prose, with highest taste. What a shame that the historians of literature understand nothing technical and have not, therefore, been able to discover in Viollet-le-Duc a classic of French writing, always alive and splendidly illuminating.

Figure 1. The ribwork at the top is continuous in Notre Dame d'Alencon.

already dared to call an elastic system[3] because he must have perceived by intuition, with the newborn notions of the science of construction, that the static behavior of secondary ribs could become similar by analogy to that of the collection of the fluxes of static forces.

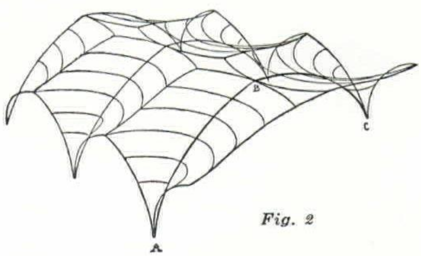


Figure 2. Fan vaults without ribwork.

It is to be noted that in the period between the third and the fourth quarter of the past century, when Viollet-le-Duc was printing his texts, there arose the theory of arches and vaults as a result of the propounding of the fundamental theories of elastic potential and of the work of deformation (Castigliano, Menabrea, Clapeyron) and of the equally numerous fundamental principles of reciprocal behavior (Maxwell, Land, Betti).[4] It is to be noted also that in the same epoch the philosopher Schopenhauer gave to architectural aesthetics the interpretation of the concept of the state of tension; that is to say, of the struggle between load and support, between "Stutzen" and "Lasten."[5]

The active mechanical behavior of the Gothic ribs was sometimes placed in doubt. In fact, it is very doubtful that in the cross vault generated by the intersection of two orthogonal homogeneous barrel vaults, the diagonal arches or intersections, which form an angle and which the French called "ogives", alter noticeably with their presence the static behavior of the original barrel vault formed bare of ribwork in relief.[6] Nevertheless, as soon as the vault becomes broken up with more numerous secondary ribs, upon which are placed the secondary smaller vaults, no doubt can any longer be held of the supporting function of the ribs. At times it could be easier to doubt the rationality of the distribution and the equal static carrying capacity.

We have no direct mention of contemporary Gothic opinion on this question. The French writers of the seventeenth century, however, remember with their most expressive locution that "les nerfs d'ogives portent et soutiennent les pendentifs."[7]

"Pendentifs" would be the secondary small vaults; "nerfs d'ogives"[8] would be the ribwork which would take the significant sense of the latin "nervus." This is an anticipated application of the 18th century theory of the Einfuhlung, that is sympathetic understanding (or rather "symbolic sympathy") by which man attributes anthropomorphic attitudes to the things which surround him.[9] The state of internal tension is defined through our sensorial and muscular

[3] "From the Roman concrete system—in spite of the different members which made up the Roman vault—the masters of the twelfth century, in separating these members, in giving to each their real function, arrived at an elastic system."

[4] A. Cavallari—Murat, *Considerations and Diversions Around the Hundredth Anniversary of the Theorem of Menabrea*, "Atti E Rassegna Tecnica", Torino, 1957.

[5] A. Cavallari-Murat, *Metal Skeletal Architecture*, in "Construction in Steel", January 1949; Id., *The Bearing Structure as Architecture*, "Atti E Rassegna Tecnica", August 1954.

[6] H. Focillion, *The Problem of the Ogive*, "Periodic Bulletin of the Office of the Institutes of Archeology and of History of Art", March 1935; P. Abraham—*The Problem of the Ogive*, ibidem, November 1935.

[7] Francois Derand, *The Architecture of Vaults or the Art of Plans and Section of Vaults: tract*, at Paris, at the home of S. Chamoisy, MDCXLIII
Guarino Guarini, *Civil Architecture*, posthumous edition at Turin, 1737; A. E. Brinckmann, *The Greatness of Guarino Guarini and his Influence on Architecture in Germany in 1700*, Acts of the Congress of Cavallermaggiore of the S.P.A.B.A., 1932.

[8] "Ogive" derived from the latin augeo = increase; because it stood out underneath from the vault as an increase of material.

[9] A. Cavallari-Murat, *The Theory of Pure Visibility and Architecture*, "Atti E Rassegna Tecnica", February 1957.

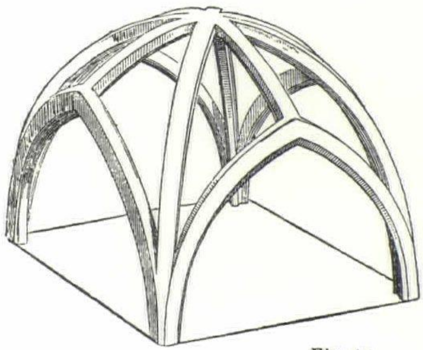


Fig. 2a

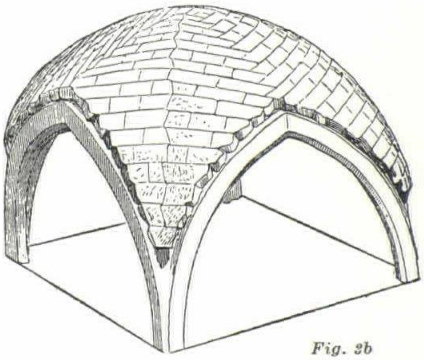


Fig. 2b

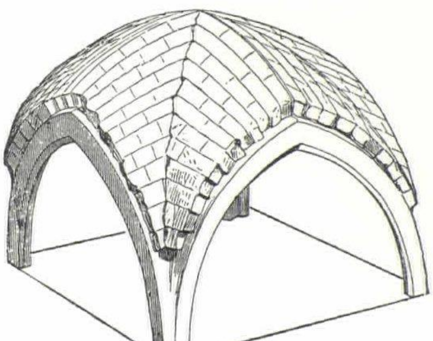


Fig. 3c

Figure 3. The "Dictionnaire Raissonne de l'Architecture Francaise" of Viollet-le Duc distinguished in Gothic vaults between those of English-Norman construction and those in the French manner, according to the prevailing arrangement of the courses. The illustration shows the differences in the placing of the masonry work, even if the plastered surface will show two structures of apparent identical geometrical form.

experience. Through the contraction of tendons one succeeds in making the mechanical life of vaults understood: "ces voutes, ayant beaucoup de poussee, ont aussi besoin des bons arcs-boutants pour les contrebuter et maintenir en état." *

In the constructive reality these barrel vaults, which are made to cross and to intersect in order to make the concept of cross-vaulting understandable, are never homogeneous in their internal structure.

Vaults even of modest dimension from which the plaster has been removed (for which then the visible ribwork should not be necessary) appear composed of hidden ribs, one next to the other. It is a question of the courses of stone elements or of the brick courses.

Such courses are generally provided with curvature and can be considered to act like arches.

The arrangement of the courses distinguishes between them the antique building techniques. In the French tradition the arches of the pieces have horizontal projections, for the most part normal to the arches of the perimetal supports.

In the Anglo-Saxon tradition, on the other hand, such horizontal projections have been arranged such that they tend to be normal to the diagonals (the projections of the ogives or crossings.) *(Fig. 3)*.

The method of loading the perimetal arches and the diagonal arches is different. This procedure explains the possibility of eliminating, with the Anglo-Saxon technique, the same ogives arrived at by constructing English fan vaults with very small bricks. The resulting vaults have smooth intrados surfaces but are capable of being thought of as ruled surfaces of rotation. In *(Fig. 4)* two fan vaults are represented; one with summit almost flat and the other with the lines of the roof intersection quite

* These vaults having a large amount of thrust have need also of good flying buttresses in order to counter balance them and maintain equilibrium.

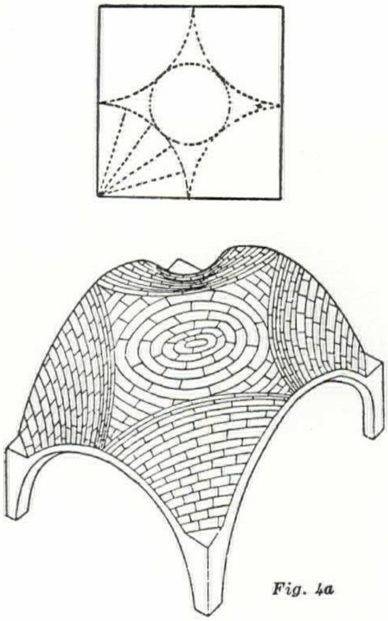


Fig. 4a

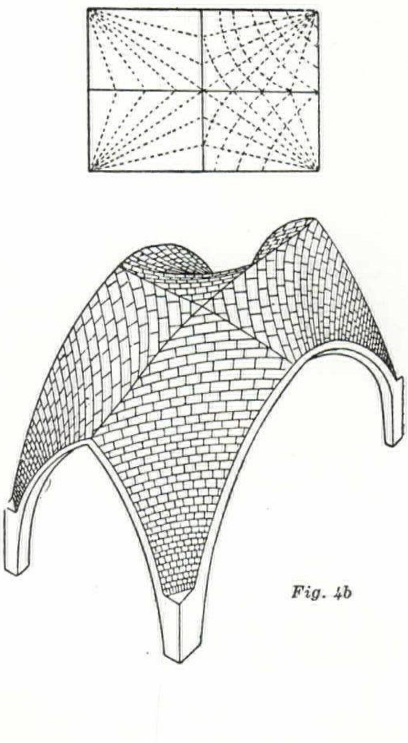


Fig. 4b

inclined. Illustrated above them are the schemes of the eventual ribwork which could have been traced to fans departing from the capitals of the columns. In a topographic representation, the courses of the bricks could have constituted contours with a circular or pseudo-circular progression. The ribwork instead would have established lines of maximum inclination.

Passing from the covering of spaces of modest dimension to the covering of spaces much more vast, it is necessary to abandon the system of hidden courses and to operate with visible ribs. That explains, for example in England, the consistency between the work of the modest mason and the daring technique of the architect-organizer of the most audacious reticulated bearing spaces. One needs, therefore, to accustom oneself to see mentally the generation of such reticulated bearing spaces, but it is necessary in addition to know their elements. Besides the ogives mentioned before, which run diagonally in the square or rectangular mesh, the French of the Gothic period distinguished between the "tiercerons" and the "liernes". The first are ribs which project themselves from the capitals and have a rapidly rising path culminating in the keystone of a secondary vault into which is decomposed the large vault covering the basic mesh. The second are ribs which join the keystones of the secondary vaults with the keystone of the total vault.

A very rare design of the XIII century, by the architect Villard de Honnecourt *(Fig. 5)*, shows us the scheme of the tiercerons and of the liernes necessary to form a cover on a large mesh. As can be seen, the ogive loses importance, transforming itself in the higher part into liernes and in the lower part into pairs of tiercerons which dispose themselves not to the vertices of the basic square, but on intermediate capitals ideally placed on an octagonal perimeter.

The design of Villard de Honne-

Figure 4. The fan vaults, if we consider their method of execution, are derived from the English-Norman vaults of the preceding figure. Otherwise, both the vaults of English ogive and the fan vaults are derived from the generation (a:∞). The fan or mushroom is born at the limit making the ribwork disappear from a surface of rotation with vertical axis coinciding with the axis of the loaded pillar.

court has the faculty of clearly showing the ribs rising to bear the weight of the vault and its imposed loads.

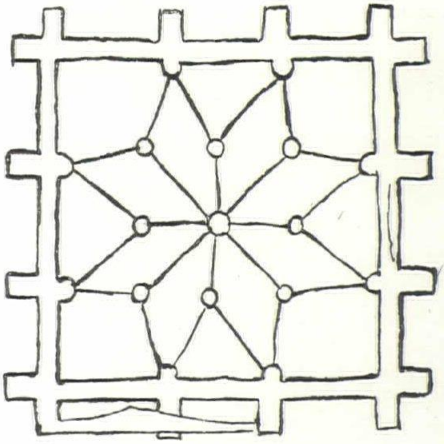


Fig. 5

Within the intent of acquiring as much facility of ideation as possible, it is well to abandon the traditional confused and non-productive descriptive layouts. We, therefore, proposed a method of describing the vault departing always from the columns, observing the number of sections into which the vertices of the total pattern of the tiercerons is broken up. If a visible or hidden ogive is not present, evidently we are to consider sail vaults, which now and then necessitate pendentives to found themselves, as in byzantine architecture.

When the vault consists only of ogives without tiercerons, one has the classical cross vault, with or without ribs, with inclined ridges or flat ridges. In the classification table of *(Fig. 9)* there are therefore listed in columns all the vaults distinguished one from the other by the symbol (α:2), signifying that ribs which are imposed on the capital divide the angle at the vertex in two sections. Shown in the upper section are the vaults which are distinguished by having the principal keystone of the vault raised above the keystones of the perimetral arches. Listed below are the vaults with the keystones level, these being the principal keystones or the secondary keystones. In the

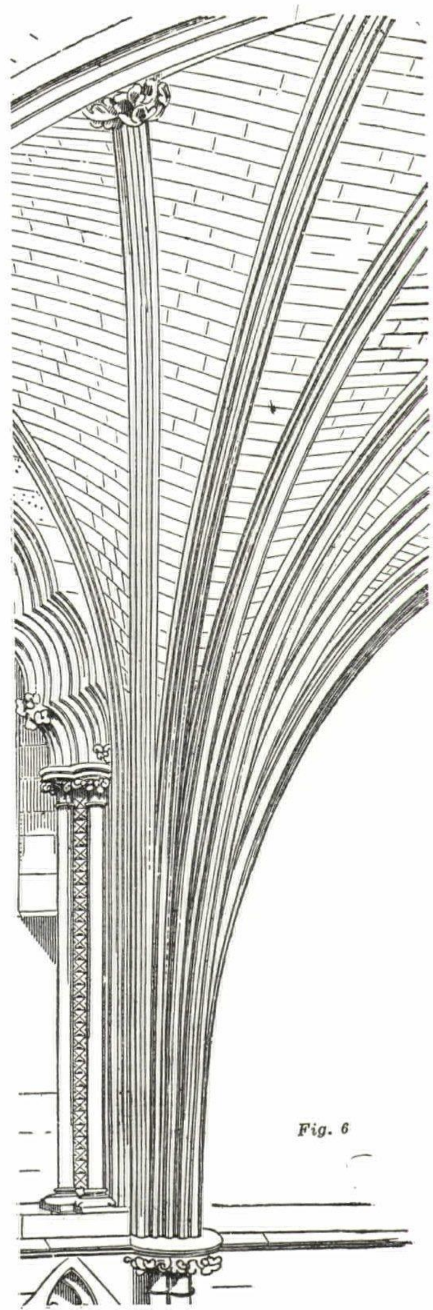
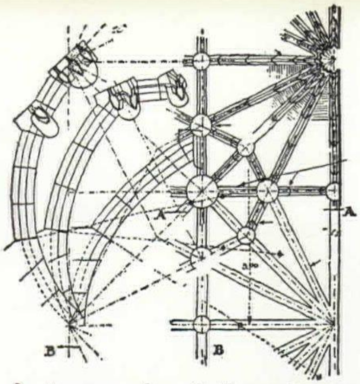


Fig. 6

Figure 5. Design of Villard de Honnecourt, architect of the XIIIth century, resolving the ribbed structure with a vault composed of "liernes" and "tiercerons." From manuscript No. 19093 in the National Library of Paris.

Figure 6. Characteristic method of loading of the secondary vaults on the ribs springing from the capitals (tiercerons).



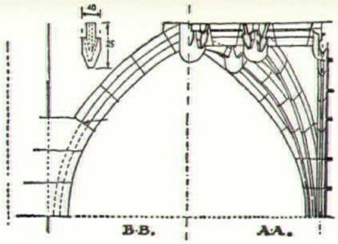


Figure 7. Geometrical generation and appearance of the star vault (a:4); furnished, that is to say, at every support with two "tiercerons" in addition to the ogive. The prolongations of the "tiercerons" which form the sides of the octagon take the name of "false-liernes." While "ridge-liernes" are the arches following the centers.

last example of the column (α:2) there is shown the principal phenomenon of a cross vault with horizontal ridges. In such a vault a ridge has been underlined decoratively by a ribwork which involves with continuity all the principal nave of the cathedral and which is connected by other ribs to the capitals, but only in the surface of the intrados of the principal jointed barrel vault. Sometimes these secondary ribs run along in both the orthogonal barrels, as in the suggested pattern of Notre Dame d'Alencon. *(Fig. 1)*

When (α:3), it is a sign that the ogive has disappeared to make room for two tiercerons which have, therefore, really the etymological function of breaking the angle of the vertex into three parts.

If the tiercerons had to meet with more or less numerous liernes they would so generate the examples shown in columns in the lower part of the table. If instead the principal keystone itself also has disappeared, it is easy to know intuitively the true mechanical behavior of such a vault. It will be as if to say that for a slender ogive there is substituted a flat ogive, or spindle-shaped form with the maximum section in the central area and with minimum section at the two imposts functioning as a hinge. The vault arises from the crossing of two arches and two spindle-shaped hinges of U-section (a thin stem, a flat horizontal region and another thin stem). Also the last example could be brought back to the following schematization of the vault: essentially on the crossing of two three-hinged arches, the highest being included in the principal keystone.

The vaults of the type (α:4) which are the most diffuse in France and take the name of "star vault," are composed of ogives, tiercerons and liernes and other secondary ribs.

The ribs can even have in plan projections of curvilinear path and complicated design figures. These

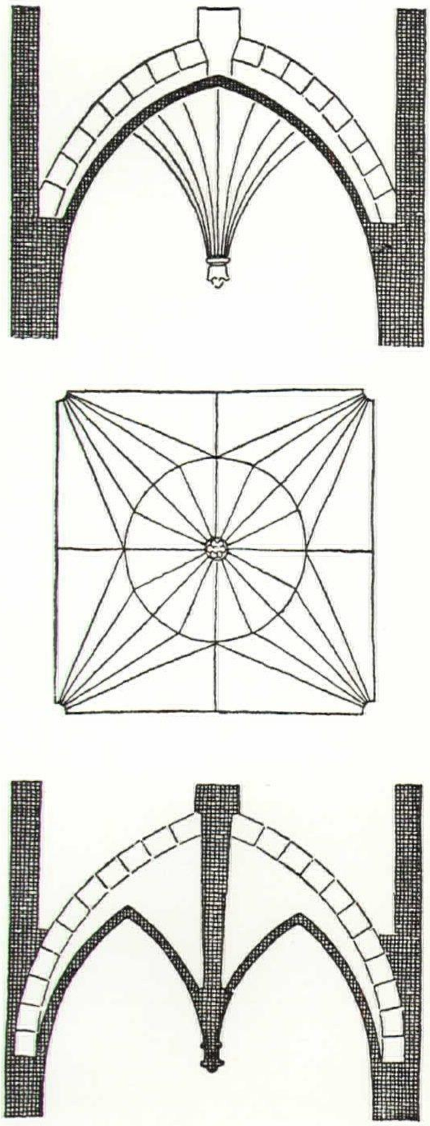


Figure 8. English vault (a:6) with hanging keystone resisting tension to retransmit the loads to the real vault.

TABULATED CLASSIFICATION OF RIBBED VAULTING

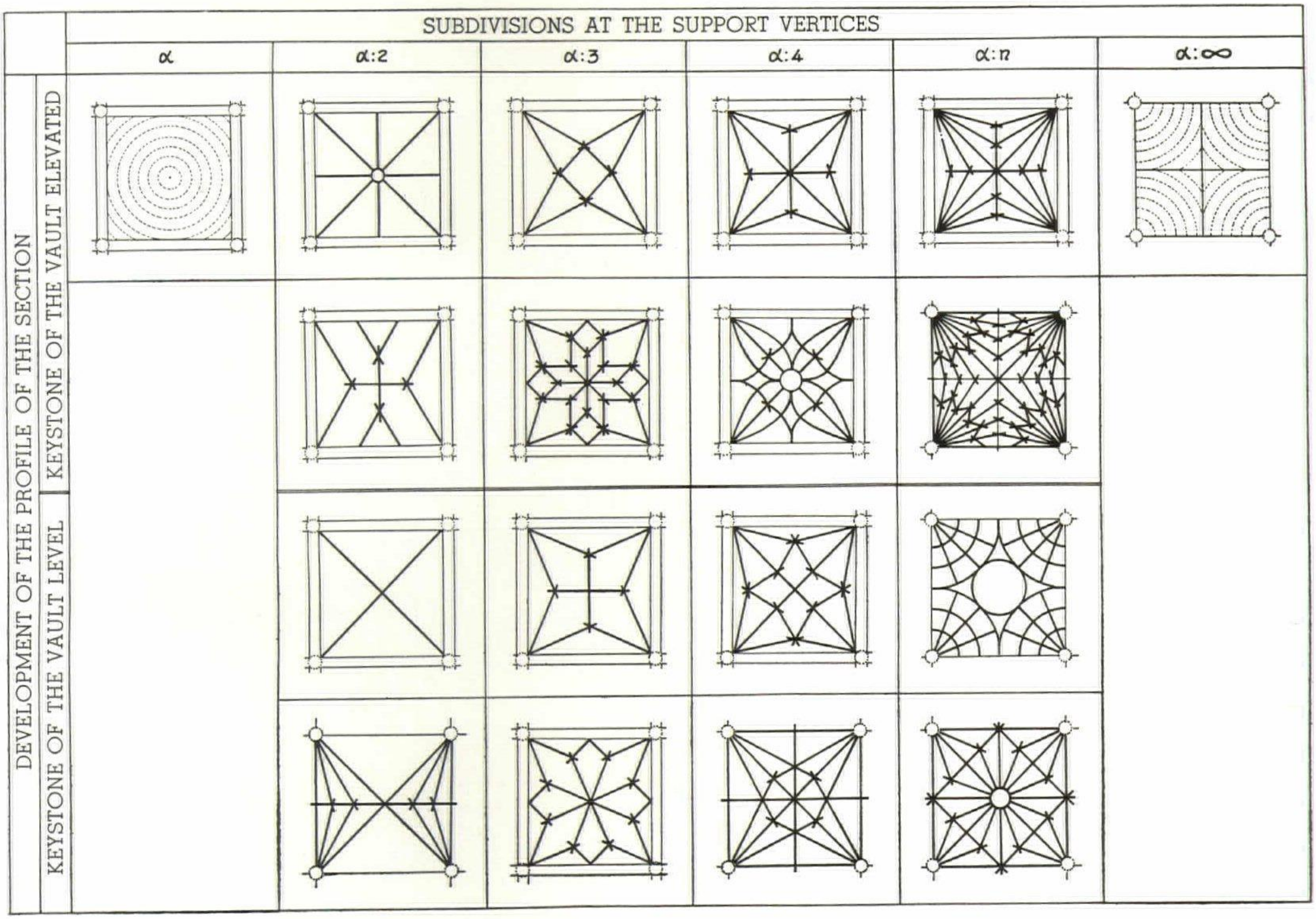


Figure 9. The columns (vertical) of the table consider vaults with an equal number of divisions at the support forming angles at the vertex of the plan which assume respectively the value (a); (a:2); (a:3) (a:4); (a:n); (a:∞). The lines (horizontal) differentiate the progress of the profile of the section; the resulting divisions made depending on whether the keystone is or is not at the same level as the keystone of the peripheral arches.

patterns bring to mind the star but also flowers with multiple lobes which resemble capricious decoration but which have in pretense of

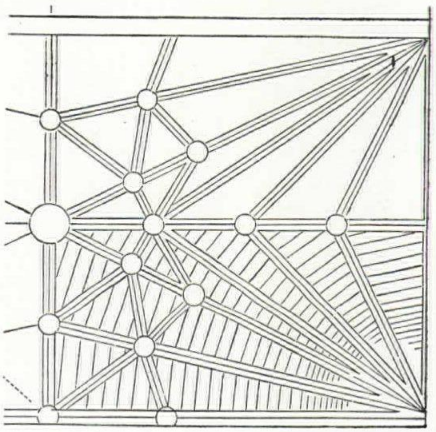


Fig. 10

the architectonic form much more profound exigency of static organization, as one will see later. (It is possible to contain in the table only a few examples. The column (α:4), therefore, has demanded a special documentation in another table.)

The last (α:4) vault, initially, is frequently called a vault with five keystones in the previously rejected classification of Bosc.[10]

The vaults of the type (α:n) are more widely used in Anglo-Saxon countries, where we frequently find that n tends toward ∞, recovering the smooth continuous surface of the fans or mushrooms.

Now and then the secondary vaults raise their profiles arching themselves acutely or organizing themselves in their turn as small cross vaults with very inclined ridges.

These then are the cellular or diamond-shaped vaults that have stimulated the curiosity and the delight of present-day criticism.[11]

The table of the geometric-mechanic generations of the ribbed vaults is discontinued in the lower part where it would have been necessary to represent the vaults with a path of the profile composed of inclined and contra-inclined section with

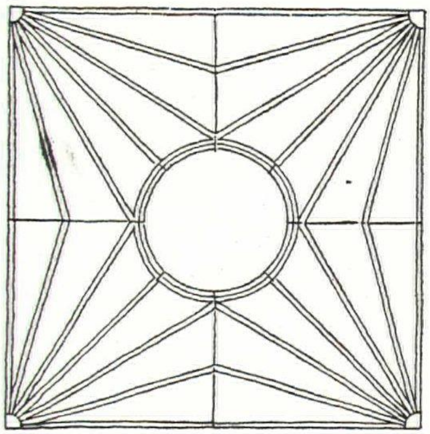


Fig. 11a

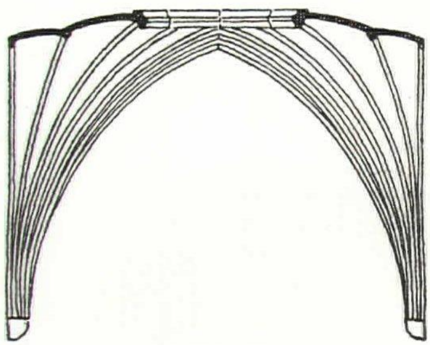


Fig. 11b

[10] E. Bosc, *Descriptive Dictionary of Architecture*, Paris, 1879. The "Ribbed Vault with 4 hanging keys" would be for such classification the prototype (α:3) a short time ago examined under more productive formal or mechanical aspect.

[11] Review in *Sele Arte*, number 35 of the volume of Vaclan Medcl, *Eleven Hundred Years of Architecture in Czechoslovakia*, Prague, 1957.

Figure 10. Rib fan vaults of the generation (α:6) in the Cathedrals of Ely and Lincoln.

Figure 11. Vault of the order (α:6) which leaves the center part open having substituted for the keystone a ring framing the hole.

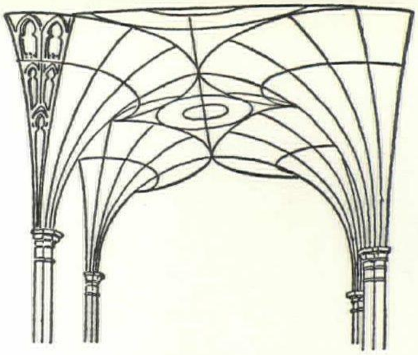


Figure 12. Generative scheme (a:∞) of the vaults of Kings College.

dropped principal keystones of the vault. These are unpleasant forms in which the English of the time of the middle part of the Gothic era, but more often the neo-Gothic 18th century and the romantic period, took delight.

The suspended keystone is a temptation which arises if one has at one's disposal a material resistant in tension, either timber or metal.

For the most part such vaults are related to the unfinished vaults with open cupolas, used in crypts and in towers to relate lower openings with those above. Therefore, one considers vaults (α:n) where n is 6 and 8, in which a stone ring has the function of the real keystone.

The vault (α:n) with "n" a large number opens the way to the idea of the mushroom ceilings, much overworked today in industrial construction, but—alas—with significantly less decorum and aesthetic prestige than the old fan vaults.

A refined old example, not modifiable without brutalization, is expressly shown in *(Fig. 13)*. The rib is a marvelous linguistic sign in pure hands, convincing one that, as it has been well said, "Poetry is a dream which one makes in the presence of the reason."

The linear design in the hands of the Gothic artist of maturity has infinite possibilities. He invents even the aforementioned reticulated nets ("a reseaux" for the French, "Netzgewölben" for the Germans).

We will give a tabulated classification of these in a subsequent section of this article.

Gathering in tabular form the many families of Gothic rib vaults requires that they be classified. At the same time it is necessary to suggest a method which serves not only for the descriptive interpretation, but also for the invention and for the rediscovery of historical forms[12] in the same way as the

[12] A. Cavallari-Murat, *Classifications of Materials and of Works under the Concept of Constructive Individuality,* Atti E Rassegna Tecnica", Turin, October 1952; Id., *Problems Belonging to the Classifications of Materials of Construction.* "Atti del Congresso di Metodologia", Turin, December 1952.

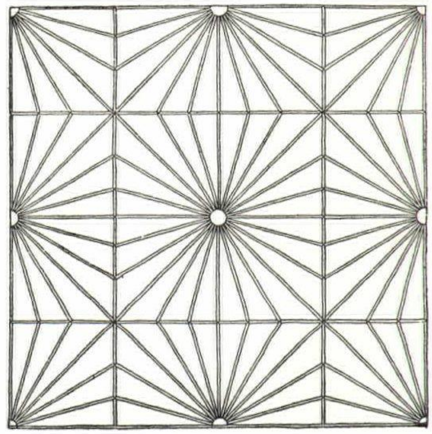


Fig. 13a

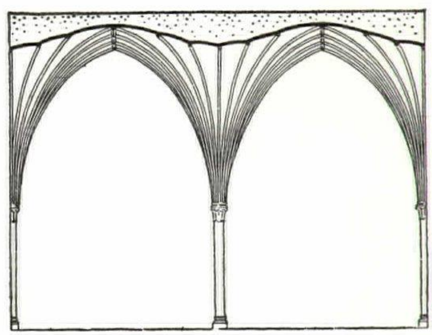
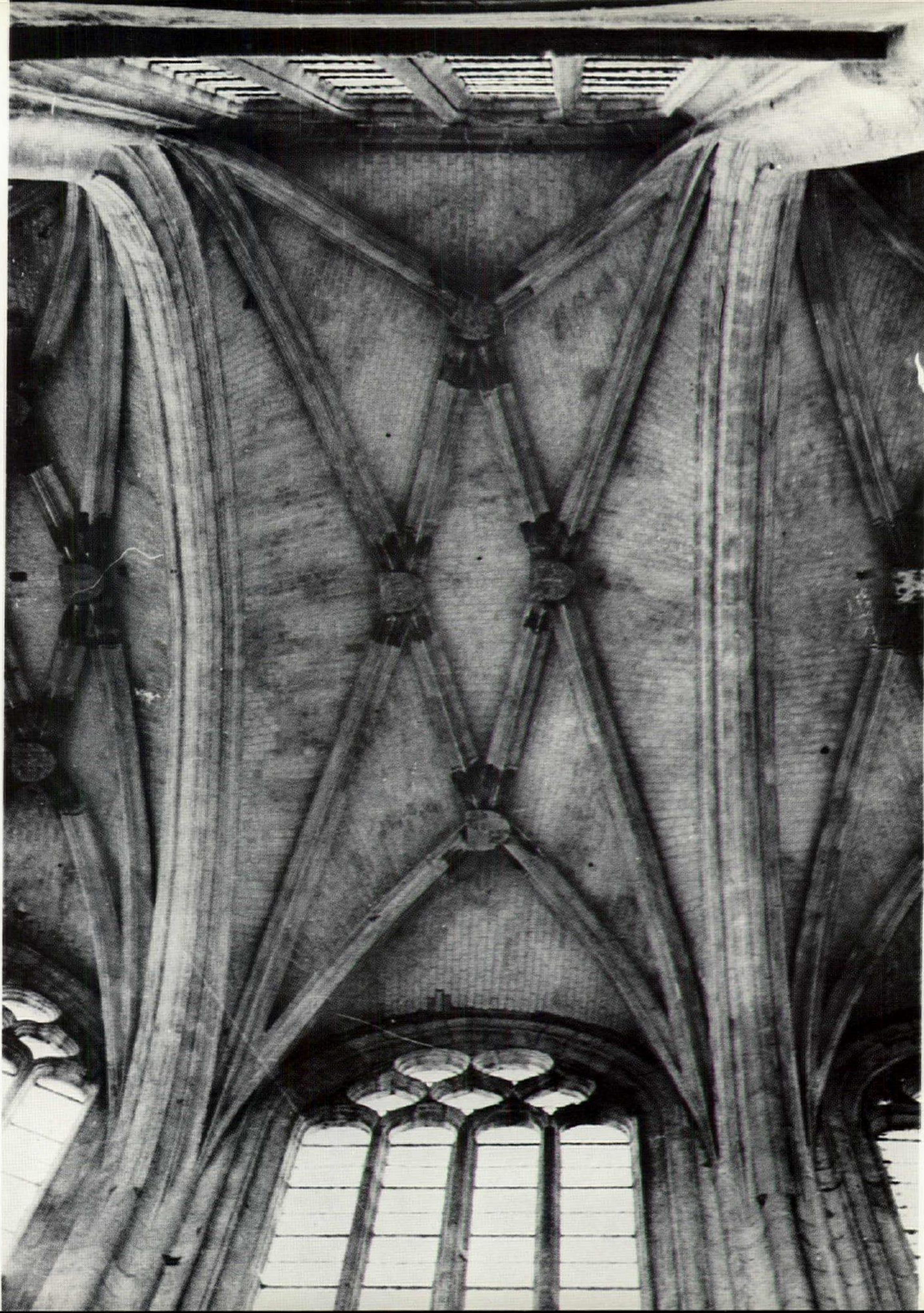


Fig. 13b

Figure 13. Ribbed vault (a:6) of the type called by the Germans "Fächergewölbe," realizing a refined unmodifiable plan of ribwork statically equipotential.



celebrated classification of Mendeleyev permitted predicting the physical-chemical characteristics of elements formerly unknown having determined atomic weight and valence.

The ease in selection allows a geometric scheme to be validly changed into a form of art if the talent assists. Vice-versa, the fatiguing research of the scheme adopted to express that which urges one from within, involving the reinvention of the schemes anew one after another, indubitably cuts the wings of fantasy and of sentiment.

When the designer of the Cathedral of Bourges adopted the scheme of the ogive involving two nets instead of only one *(Fig. 15)* he performed a prodigious act of courage. It is the courage of the artist conscious of the technical possibility of the constructive realization but much more certain of the effect realizable in opposition to the traditional impost solution of the cross vault, as one sees for example in Santa Croce in Florence. It has been well said that in the example of Bourges one has a singular effect of apparent lightening of the architectonic volumes.[13]

In a certain sense, he would have been right who said, contrary to Lodoli, that "architecture is constructed ornament."[14] In architecture the forms must be not only the tactile manifestations or the plastic representations of the constructive forces but essential agents of their determining themselves and of their organizing themselves in equilibrated systems.[15] As for the most recent structurally-oriented architects operating with reinforced concrete or with metallic constructions, as for the Gothic builders, technical research would not be other than formal research.

In such an aesthetic conception, there cannot exist contradictions against construction and architecture, as Argan has justly said.[16]

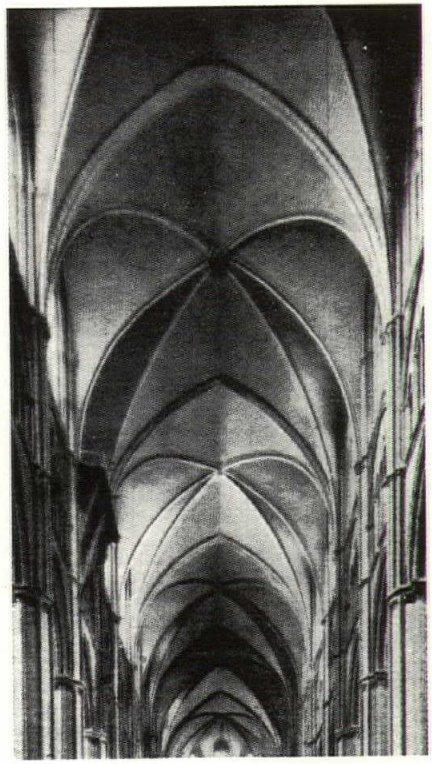


Fig. 15

[13] A. E. Brinckmann, *Giotto bis Juvarra, ewige Werte italienischer Kunst,* Hamburg, 1940.
[14] It seems that Auguste Perret, the early builder of reinforced concrete churches, said this.

[15] Recollected concerning the Lodoli polemic: A. Cavallari-Murat, *The Rigorist Polemic of Father Lodoli for the Functional Finality of the Architechtonic Form* "Atti E Rassegna Tecnica", January 1957.
[16] Argan, *Pier Luigi Nervi,* Edizione il Balcone, Milano, 1955.

Figure 14 (Left). Star Vaults in the Cathedral of St. Wulfran in Abbeville.

Figure 15. In the Cathedral of Bourges the ogive relates to two networks, producing a singular and troubling effect of apparent lightening (from a photograph of Brinckmann).

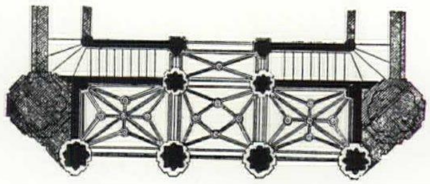


Figure 16. Small star vaults at the rood screen of the Cathedral of Rodez (1468-78).

The forms of the star vaults are signs of an abstract language of superb possibility. They are signs of highest specialization and ideogrammatical magic, for which the artist makes eclectic use of apparently diverse techniques in the same instant of the poetic discourse. In the rood screen of the Cathedral of Rodez (1468-78) *(Fig. 16)* over four vaults one is of the type (α:2), a second of the type (α:3) and the other two of the type (α:4). Thus, as in a symphonic composition the techniques of the pick and of the bow, of the harpsichord and of the brass are employed.

In the Cathedral of Amiens, begun in 1220 by the "master of work" Robert de Luzarches using monotonously all cross vaults, an anonymous artist inserted in 1529 a star vault at the crossing of the central nave and of the transept *(Fig. 18)*. This gem revived with measured polyphonic accent the initial Gregorian chant. On the contrary in the Cathedral of Condom *(Fig. 19)* the polyphonic key is dominant and exclusive.

Truly the variations of the theme of the star vault are infinite. Let us observe the vaults (α:4) in *(Fig. 9)* already seen and those other variations of the theme (α:4) in *(Fig. 20)* which collected together seem more to be schemes for decorations of gates and windows than schemes for effectively and rationally carried structure.

The first column (vertical) in *(Fig. 20)* develops predominantly a theme which in plan is brought back to rectilinear geometry. The last pattern is found in its most elaborate form in the city hall of Breslavia *(Fig. 26)*. The second column, on the contrary, cherishes themes which in plan are resolved with curvilinear geometry. These curvilinear solutions must be seen in the space. The forked ogives are really run by the flow of forces divided in pairs of small arches which arrive then at the keystones

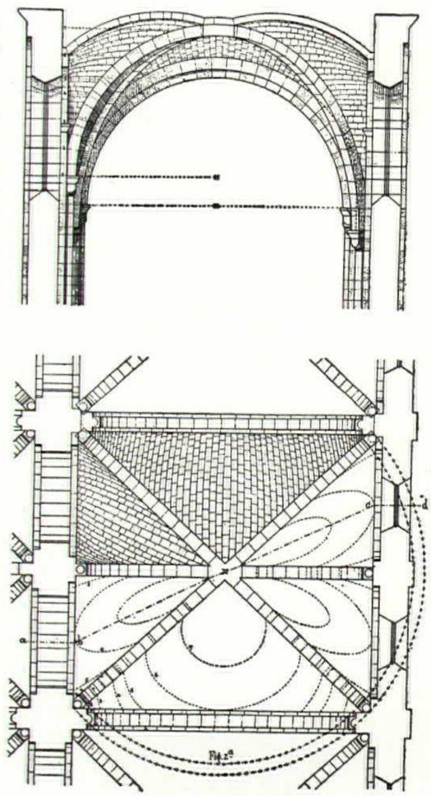


Fig. 17

Figure 17. In the style of transition between Romanesque and Gothic there was frequently used the ogive thrown across two nets in such a way that the keystone of the vault coincides with the keystone of the arch of the intermediate typanum. Particular care necessitates the apparatus of the secondary vaults and the relative curvature, below which are developed the curves of equal level shown with dotted lines.

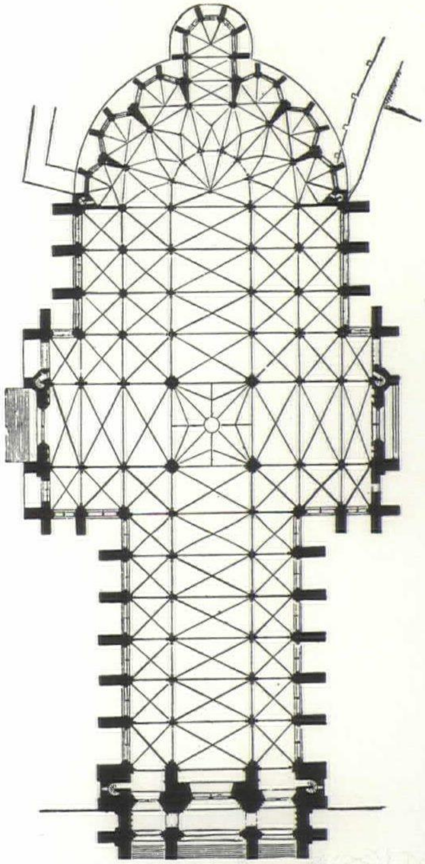


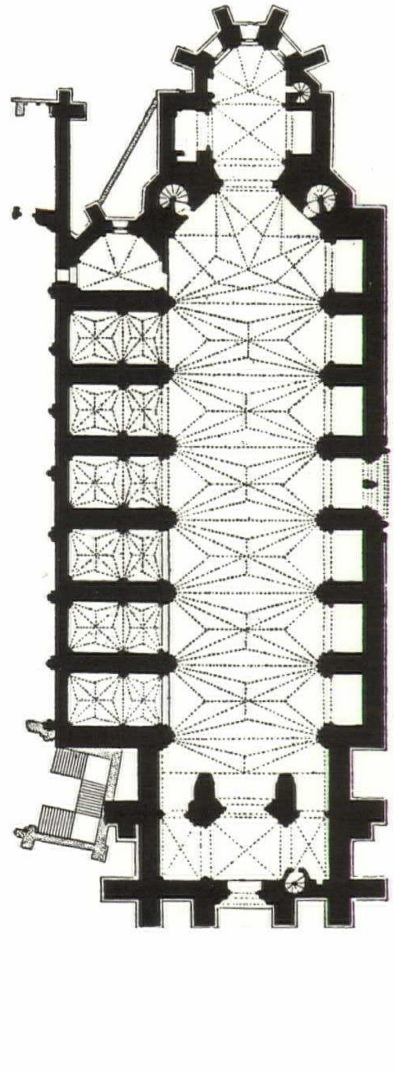
Figure 18. Plan of the Cathedral of Amiens begun in 1220 by "Master of the Work" Robert de Luzarches, but continued and rebuilt in large part since 1529. At the crossing between the transcript and the central nave is the lone star vault, ornate gem which announces a late work and a taste sumptuous but measured.

of the peripheral arches of the impost, while the tiercerons develop hooked trajectories to nestle themselves, without or through liernes, at the principal keystones. They seem floreal clover-leafed motives, but in reality they are projections on a horizontal plane of isostatic lines similar in function to the trabeculae of our bones.

Even in the strange vault used in the celebrated Borsa of Saragossa the motive most revealing in decorative inspiration (notwithstanding the gratification for floral themes) can be reconducted to a drawing of ribs mechanically fulfilling their ordered work of support if ideally we prolong the tangents at the points of inflection also to reach the capitals.

The dotted lines in *(Fig. 20)* (*h*) show that it resembles a pseudo vault (α:4) while in reality it derives from an (α:6) in which two tiercerons have been omitted and their action committed for short portions to the lamella structure of

Figure 19. Plan of the Cathedral of Condom, where, through the absence of the transcript, the six star vaults constitute the predominant decorative key.



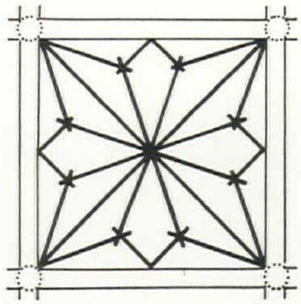


Fig. 20a

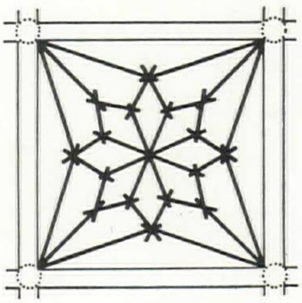


Fig. 20b

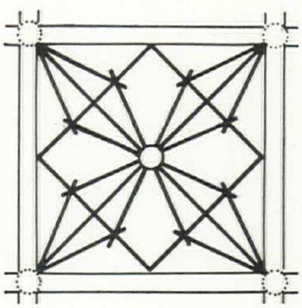


Fig. 20c

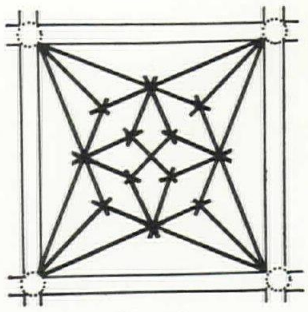


Fig. 20d

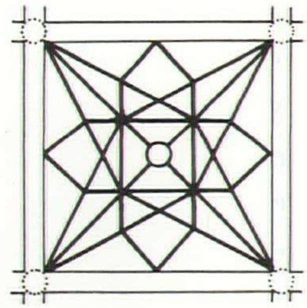


Fig. 20e

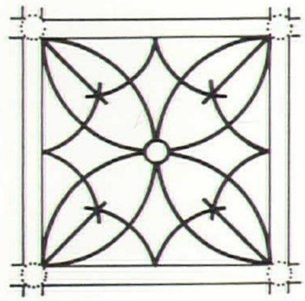


Fig. 20f

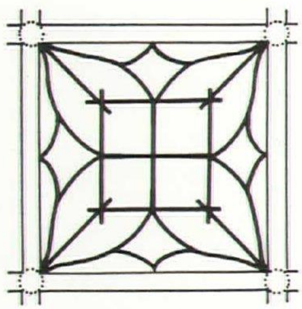


Fig. 20g

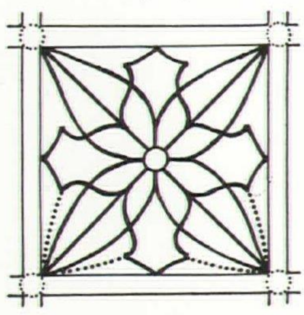


Fig. 20h

the secondary vault in the portion where they are more screened and free from the danger of the phenomena of lateral instability.

Certainly the next to the last scheme, that of the vault of the lateral naves of the Church of Anneberg in Sassonia *(Fig. 31)*, is more convincing and the branches of the ribwork develop themselves in logically controlled trajectories, even in the forking, although they are no more matter of technique but pregnant substances of poetry and music.

The constructive technique necessitated a notable expertness in the tracery work. The small model did not always suffice to resolve the problem of aiding the fantasy of the architect and of transmitting the idea to the builders, although it is remembered that the architects had loved to use it. It was necessary to make sections along with plans, to project on the surfaces, in order to compose the most spe-

Figure 20. Some variations on the theme of the star vault (a:4).

Figure 21. The star vault serves well to disguise the impossibility of enlargements following planimetric basilican or symmetrical schemes. Free expansion in all directions, but organic arrangement of space in the choir of St. Jean au Marche at Troyes.

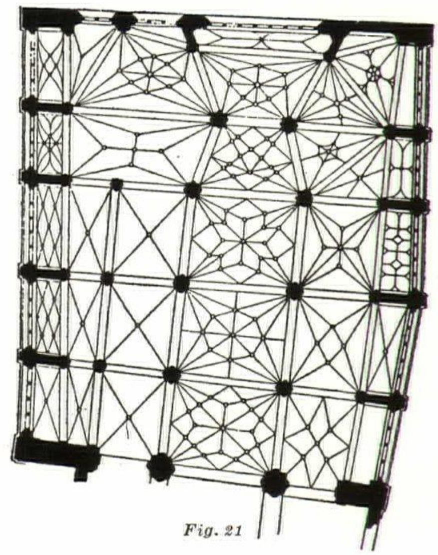


Fig. 21

cial intersecting solids. Perhaps it is not wrong to suspect that the extraordinary charge of the geometric problems faced in practical applications towards the end of the fifteenth century had created the atmosphere propitious for the imminent analytic, descriptive and projective geometry.

It was a marvelously figurative world—projection on the matter of a civilization of highest quality—a civilization with so much enthusiasm that even today, for us who discover it again, helps to make us understand better the difficulties met and the numerous five year periods and decades needed to prevent the Renaissance of the Classic style from canceling it completely.

It is said that the humanistic blast carried it along because henceforth a decadent world enveloped in mannerisms existed.

But are they truly mannerisms and academic virtuosity, these profusions of dreams and perpetually new heavens which each important building was pleased to recall? Is it a mannerism the fervid orchestral fantasy in the Castle of Meissen? *(Fig. 27)* In the jube of the Cathedral of Albi? *(Fig. 25)* In the church of Maria at Danzig, *(Fig. 28)* already dating from the beginning of the fifteenth century? In the transformation of the vaults in the Church of the Holy Cross of Gnund? *(Fig. 33)* In Saint Stephens of Vienna? *(Fig. 34)*. In large and in small, the delight for abstract music expressed by stone resolves the problems connected with the technique and the spirit. How could organic growth have been able to be resolved in the time without symmetrical programs of St. Jean au Marche at Troyes? *(Fig. 21)* How could the monotonous plan of the collegiate church of Moulins *(Fig. 24)* have been able to find such energetic unity if not through a maturity of style not yet demonstrated? While in other vaults, in other historical cycles, the parabola

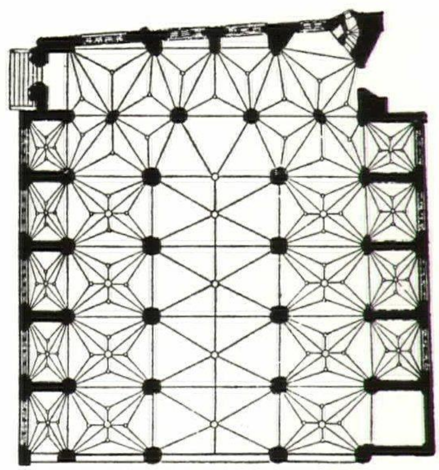


Fig. 24

Figure 22. (Left) Moldings of an arch which passes over the moldings of another arch.

Figure 23. (Right) Spiral column of the Gothic period (XVth century) in the Cathedral of St. Biagio at Brunswick.

Figure 24. Unified composition, arranged on the theme of the star vault in 1468 by the architects of the Dukes of Bourbon, in the collegiate church of Moulins (Allier).

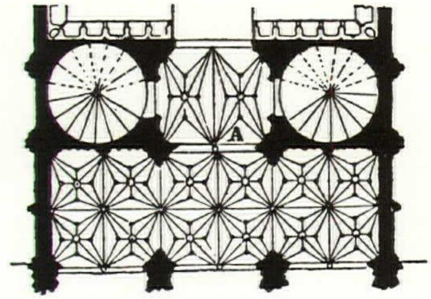
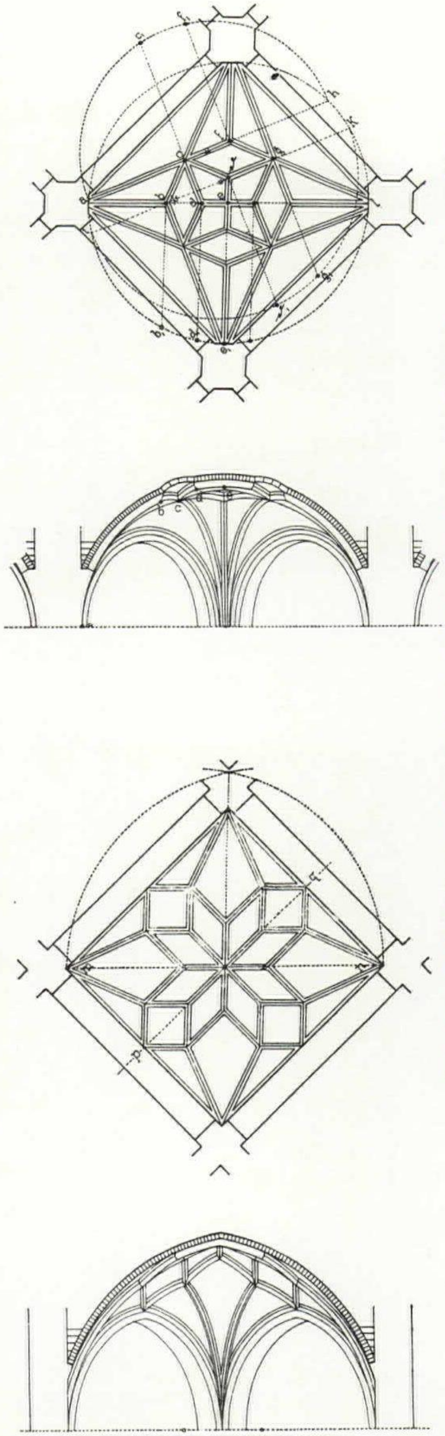


Figure 25. (Right) Rood screen in the Cathedral of Albi (from around 1500) with decorative star vaults arranged in superb composition.



is complete with its ascending and descending paths, here the second part of the parabola, the descending one, had not developed, because taste changed the main way before reaching the decadence.

Slovenliness, which is the first symptom of stylistic relaxation, has not nearly enough time to be developed because new problems always arise and call urgently for solutions.

Here is one of such problems that certainly could not have presented itself at Meissen *(Fig. 27)* in the tortuous and fragmentary general plan. The approach of most nets, running longitudinally through the naves and transversely passing from one nave to the other, poses the problem of the static collaboration of the confined vaults and the consequent integrated geometrical foundation. The problem is felt much more when less is applied to massive walls of separation between bays reducing "arcs doublaux" and "arcs formeret" to the minimum thickness. Let us look at the plan of the Sanctuary of St. Nicolas du Port at Meurthe and Moselle *(Fig. 29)*, the plan of the Cathedral of Schneeberg in Sassonia, *(Fig. 30)*, the plan of the church of Saint Anne at Anneburg *(Fig. 31)*. In these examples, the sight of the ensemble of the tracery of the ribs straddling the nets is necessary for the comprehension of the artistic and compositive theme and even for the evaluation of the statics of these most daring structures.

Some ribwork goes out from one net in a path which would seem explorative into neighboring nets.

Some mouldings, born in the arches of the perimeter, cross the boundaries interlacing themselves with those of impost arches orthogonal to those of the origin *(Fig. 22)*.

Some twisted columns, used again

Figure 26. Star vault of the places of the Town Council at Breslavia, above with the section "a-1" and a pseudo-stellar reticulated vault, below, with its section "m-n".

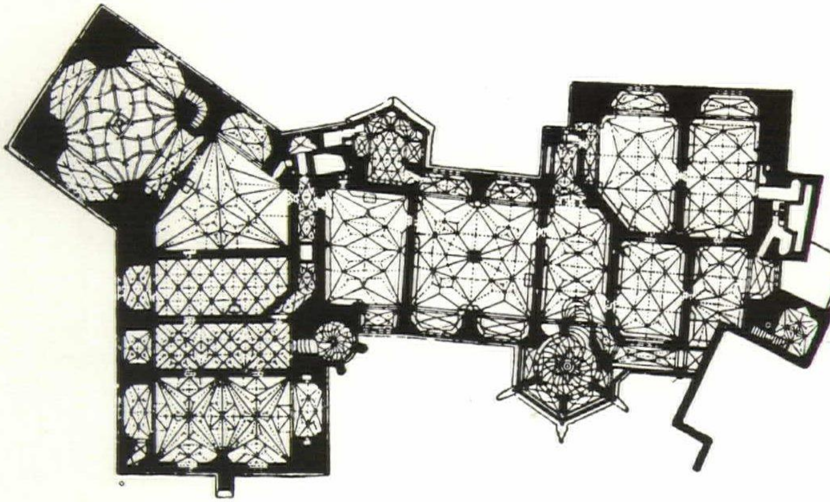


Figure 27. The most fervid fantasy and the most refined architectonic arrangement in the vaults of the Castle of Meissen.

after a long abandonment, assume other meanings, for example that of the impressed torsion from an incomplete equilibrium in the summit between the ribs of the vault. *(Fig. 23)*

If we remember the experience concerning the states of tension induced from a hole punched in a plate, in the figure Krüger for example *(Fig. 50)*, which do not have a behavior radial to the origins at the sides of the punched hole, perhaps the mechanical institutions are reborn which had to inspire the most mature works of Gothic architecture. The isostatics are developed in the reality on plane and curved surfaces, in massive solids and in thin membranes, in different ways roughly schematized in the usual calculations. The isostatic lines, even in a beam, do not proceed directly from the point of application of a load to the points of support. They arrive again at such points after being themselves pushed apart in a sinu-

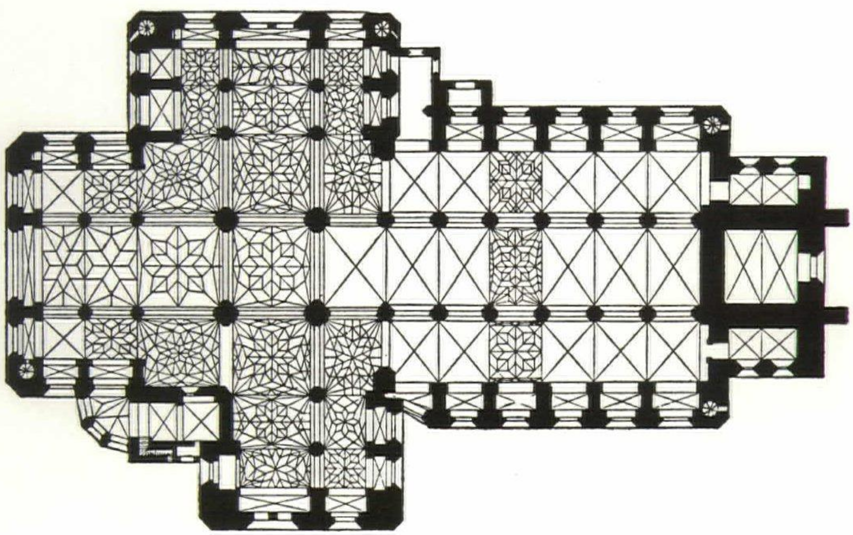


Figure 28. Plan section of the Church of Maria at Danzig with the projection of the ribworks of the most complicated vaults dating from the beginning of the 15th century.

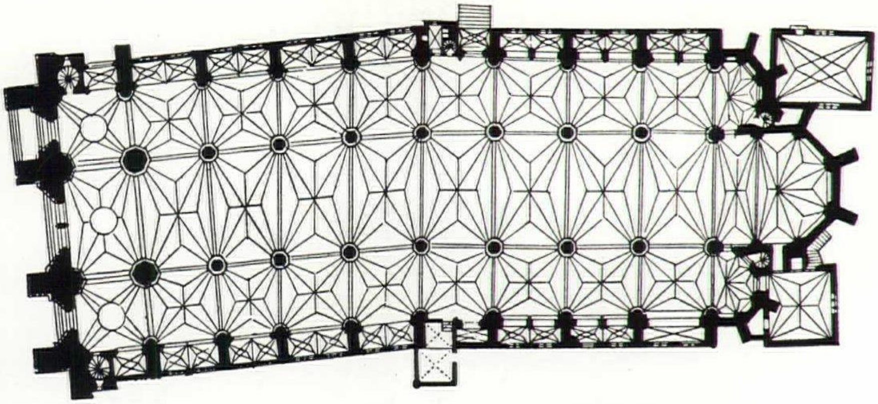


Figure 29. The sanctuary of St. Nicholas-de-Port (Meurthe and Moselle) with the strange curvature of the longitudinal axis. Architecture singularly unified in the general composition over the period from 1494 to 1530.

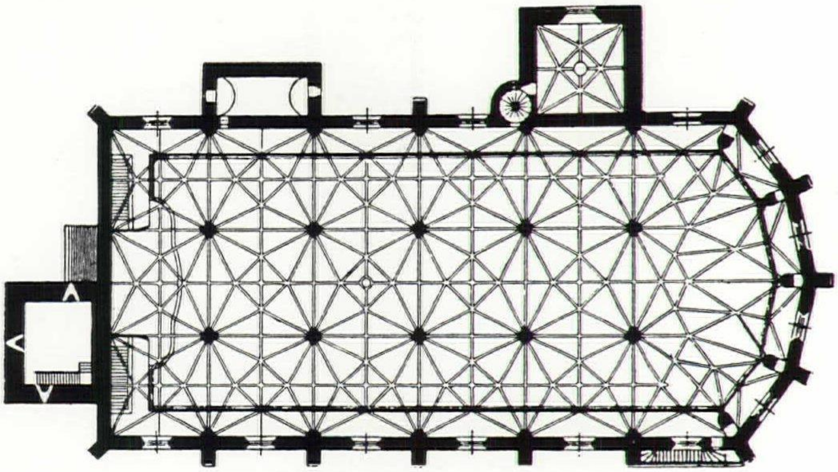


Figure 30. Plan of the church of Schneeberg in Sassonia, where the three naves are founded in a unified atmosphere and the vaults collaborate in a unified static behavior.

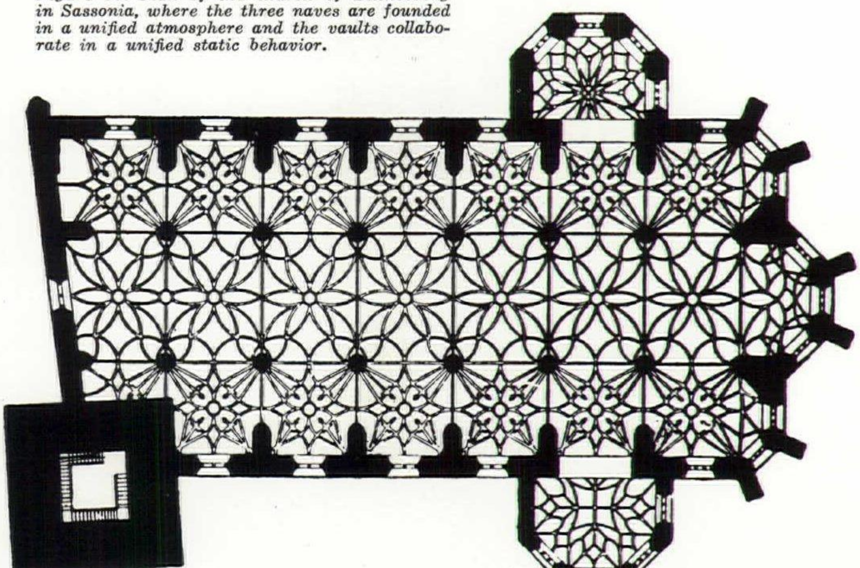


Figure 31. The Church of St. Anna at Annaburg built between 1499 and 1520 by Bartol von Durbach and Konrad von Buttigen. The vision of the whole of the tracery of the ribwork is necessary for the comprehension of the architectonic composition and of the statics of the boldest structure.

ous bundle in a manner to involve more matter than is possible in the phenomenon of resistance *(Figs. 36c and 36d)*. Consequently, some lines pass over the sections where forces and reactions are placed in order then to cross them again.

Some diagrams of the isostatics in a beam, which have the supports at varying distances, treated in the books by Nadai and by Akiri Muira,[17] present to us problems analogous to those suspected in membranal vaults supported with point supports and loaded in the zone of the principal keystone.

Observe the scheme of the vault of the Church of Jeronimous at Belem near Lisbon *(Fig. 32)*. The histories of art become enthusiastic because these schemes have called to mind gigantic palm trees. Technical historians are fascinated by the fact that the arches of the divisions between nets are not of constant section, but are truly of small fusiform vaults, as are the pairs of

[17] Nadai, *Der Bildsame Zustand der Werkstoffe*, Berlin, 1927; Akirimiura.

Figure 32. Star vaults in the central nave of the Church of Jeronimous at Belem near Lisbon, interpenetrating with those of the lateral naves. From the joining disappear the arches of the peripheral supports, substituted by fusiform vaults. This is a celebrated major work of Portugese Emanuelian art, from the king Emanuele I (1495-1521).

beams placed in a famous known example of ribbed ceiling in reinforced concrete. The contemporary specimen of Anneberg develops in a more whimsical mode the theme of the isostatics, and a still more similar phenomenon is made evident with the ribs of the value of the room of Vladislao II in the castle of Prague, constructed in the period between the fourteenth and the fifteenth centuries. Those ribworks were and still are deemed decorative games, absurdly intricate, decadently arbitrary. Yet, on the contrary, they respond to a mechanical intuition more refined than an entire generation of architects could have attained in a collective and methodical experiment. Photography shows the marvelous aspect in it, which, however, must be imagined in the original order because it is actually disturbed by the unfeeling—and truly absurd—pictorial decoration of succeeding periods. It is interesting to observe in it the intricate planimetric scheme, which, however, becomes

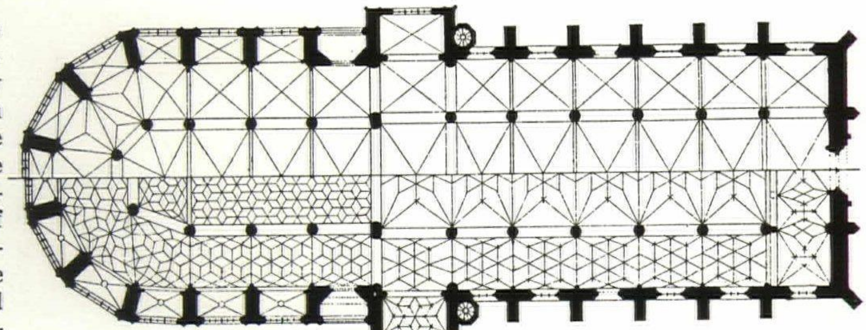


Fig. 33

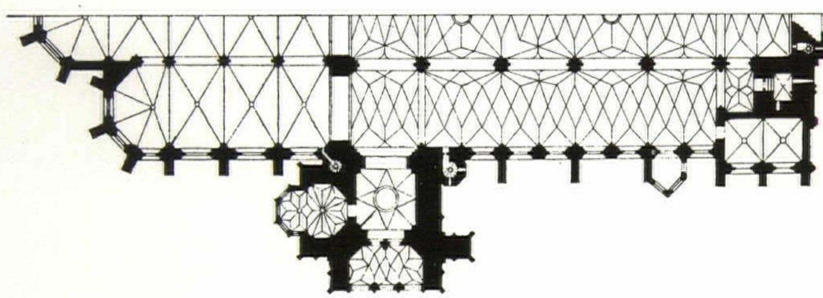


Fig. 34

Figure 33. Church of the Holy Cross at Gnund. The top section as it was originally in 1320-1380; below as the vaults were transformed between 1440 and 1480 utilizing the fanciful technique of reticulations.

Figure 34. St. Stephens in Vienna from the XIVth and XVth centuries.

unexpectedly simple if we succeed in following the principal drawing *(Fig. 36e)*, underlined by the schematicized summary designated at the right, where it is the projection of a complex of four bundles of presumble isostatics departing from the principal keystone, imagined loaded, and descending to the four columns placed at the vertices of the net.

Is this disconnected coincidence or calculated formal conception? Here is a query under which one will still be obliged to investigate also even in experimental phases, given the instrumental methods we have today, but which certainly give new insight to the critical evaluation of works of that radiant time. It is that even without letting ourselves be dragged along excessively over a ground of stimuli of ideas which some people fear constitute dangerously misunderstood technicalities in the field of art.

Another group of problems involving Gothic coverings of large spaces gravitates on the "reticulated vault", of which little is said in the works on architectural technique and in the histories of the arts.

The reticulated vault can arise as a derivation of the star vault when other arches not arising from the impost are founded on the ogive and its tiercerons.

The vault in the servant's dining room of the castle of Issogne in the Val d'Aosta *(Fig. 35)* is perhaps one of the most simple reticulations. From the corner capitals are originated only the ogives, which go transverse to arches contained in vertical planes parallel to those of the ogives but founded on capitals situated in the middle of the walls and cutting the ogives at the quarter points. It is of a surprising elegance and is of an immediate expressiveness.

Generally the reticulated vault comes into use, however, when more vaults are inserted in series, for example in the chain of vaults

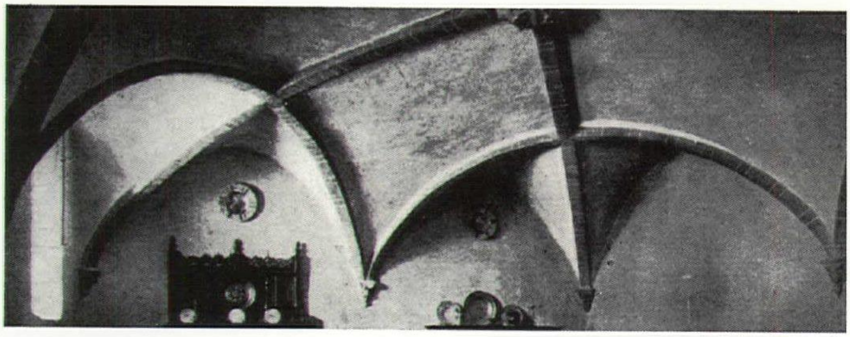


Figure 35. Ogival vault in the Castello d'Issogne in the Valle d'Aosta. The diagonals are cut by arches supported on the imposts of the walls.

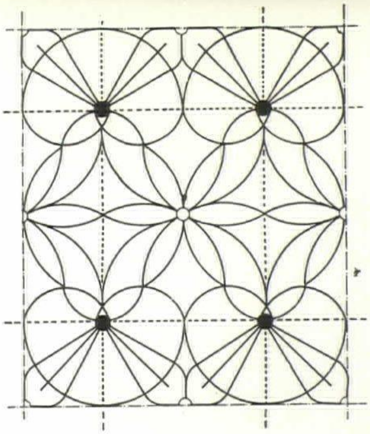


Fig. 36a

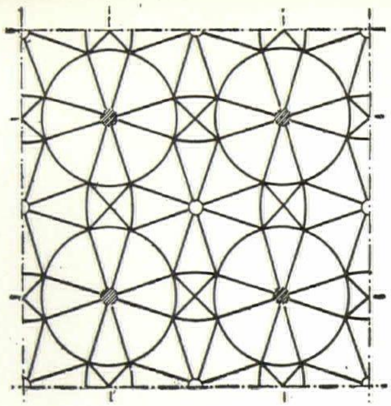


Fig. 36b

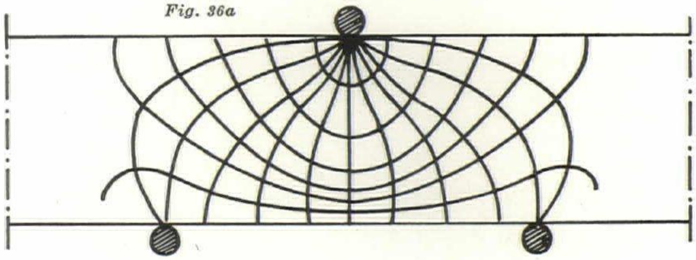


Fig. 36c

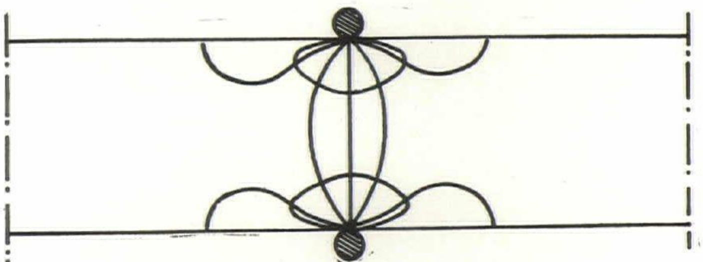


Fig. 36d

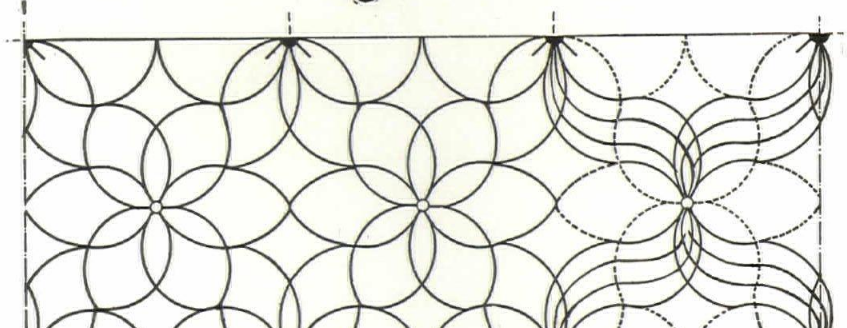


Fig. 36e

making up a nave when one intends to create a continuous unified structure architecturally and technically.

It is always a late work, of the second half of the fifteenth century and later. At Dinkelsbuhl in the Church of St. George *(Fig. 42)* there are numerous and refined examples.

Reticulated vaults can be classified bearing in mind a concept of formal generation which views ribwork contained in verticle planes variably inclined with respect to the axial verticle plane of the nave. Such planes can contain in the same net the axis of the column on which the first normal transverse arch (actual or imaginary) bears and a point of the final transverse arch (also existing or imaginary).

At the foot of *(Fig. 37)* there are three explanatory axonometrics; in the first case the selected point in the terminal arch of the net is placed in the anterior quarter re-

Figure 36. Star vaults reciprocally interpenetrating in the church of St. Anna at Annaburg (at left at the top) and in the church of Jeronimous at Belem near Lisbon (at right at the top).
The isostatic lines in a simple beam with supports at a distance (c) or approaching one another to the limit where they coincide. (d) One notes the sinuous deviation of such lines of the nets joined to the points of support and the points of the placement of the loads. The plan of the room of Vladislao II at Prague (e) with, at the side, the presumed traceries of the isostatic lines, from which the architect has selected two, the perimetal ones of the bundle derived from the flow of the tensions and compressions.

gion (of the arch); in the second case the point is in the zone of the keystone; in the third case it is in the posterior quarter zone (of the arch). One could foresee the case of a point placed in correspondence with the posterior column, and then one would fall back in the outlining of a normal underclassed ogive at the rank of the 12th order foreseen in this vault. The traces of the intersection between the cylindrical surface of the fundamental barrel and such vertical oblique planes are indicated dotted in the three small axonometrics shown and comprise axes of ribwork which in reality one encounters in the various manifold historical cases. Consequently, there were listed four collected columns (vertical):

I. The cases in which the principal reticulation is dominated by the diagonals interwoven with other ribworks (for example I, one has the diagonal ogive interwoven with oblique arches which proceed from keystone to keystone of the peripheral arches of the net):

II. The cases in which ribworks predominate which proceed from the columns in the anterior quarter zone (in the last horizontal rows, the third and the fourth, two or three oblique ribs depart from the column to intersect the net, which call to mind the generation of star vaults, but are treated by formal analogies and not by real relationship to those types; such spurious types come to be called pseudo-stellar vaults and were already encountered as a case of the genus, III_4);

III. The cases in which ribs which go from the columns to the zone of the keystone are predominant.

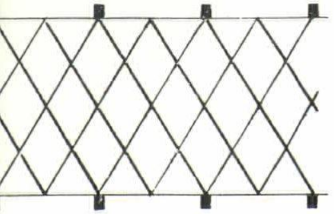
IV. The cases of the connection between the columns and the posterior quarter regions.

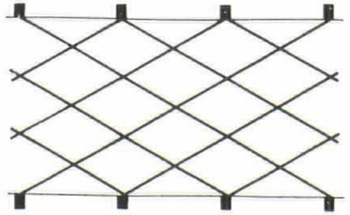
Then come other possibilities of geometric generation:

V. Linking up of characteristic points (quarters or keystones) of longitudinal arches of the perimeter of the net with other points of similar arches or of the transverse perimetric arches.

VI & VII. Linking up of characteristic points of the transverse peripheral arches with other characteristic points of the intermediate transverse arches actually laid out on the vault. From such intermediate points useful to the drawing there is shown the projection on the horizontal plane through dashes outside the net. All of the figures of columns VI and VII have the appearance of one, three, or five transverse orthogonal intermediate planes. But these orthogonal intermediate planes appear even in the lower lines of the first column, because such lines take into consideration, as has already been said, spurious or composite forms for which there could be instituted a rule of reciprocity between VI_2 and II_3.

Figure 37. (Right) Systematic Table of the Formal generation of reticulated vaults.





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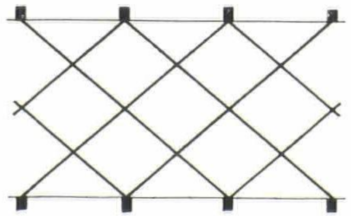

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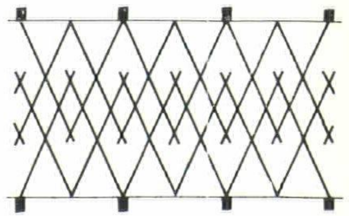

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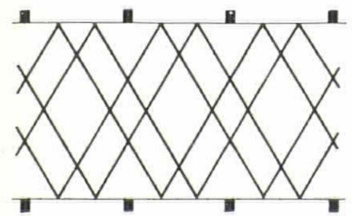

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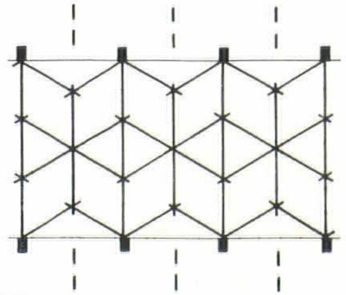

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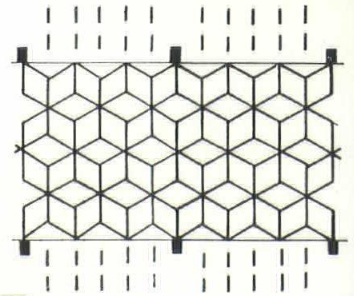

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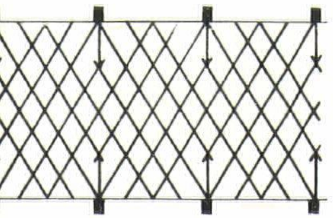

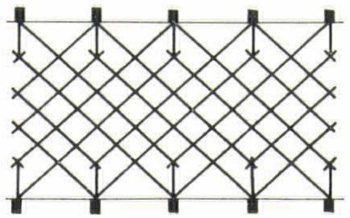

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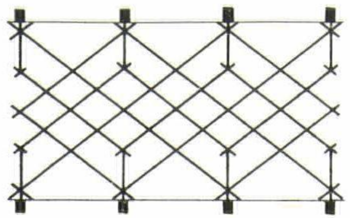

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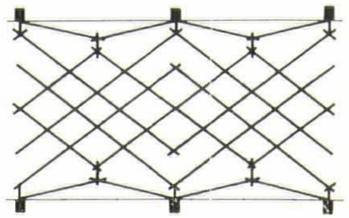

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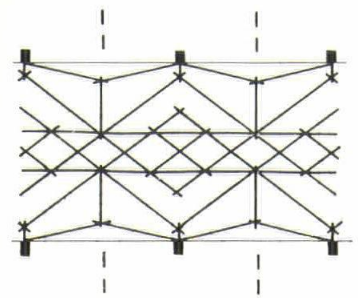

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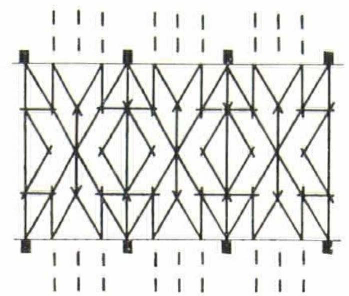

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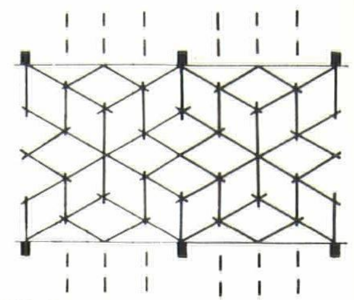

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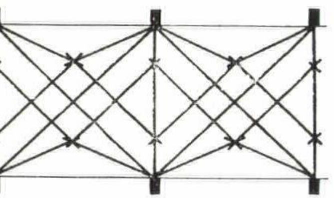

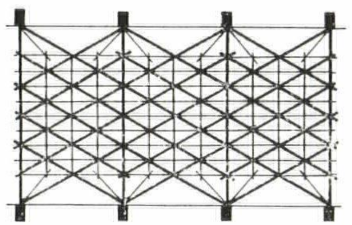

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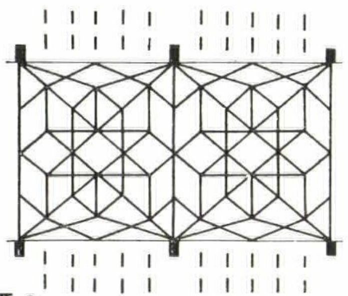

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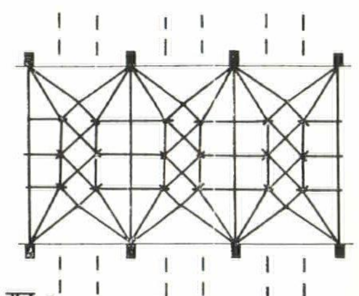

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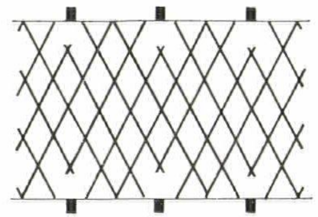

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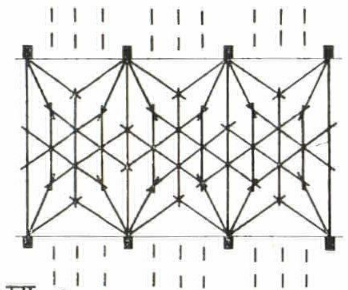

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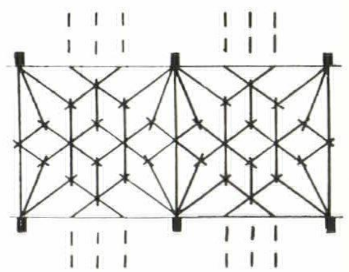
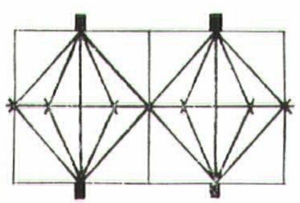
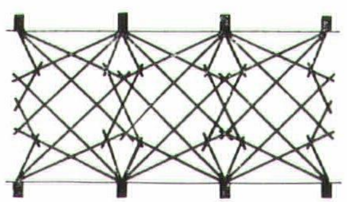


VII 3





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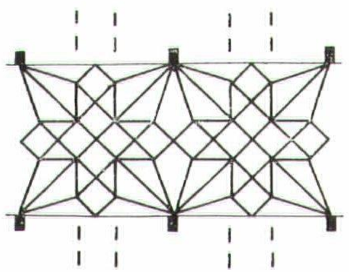
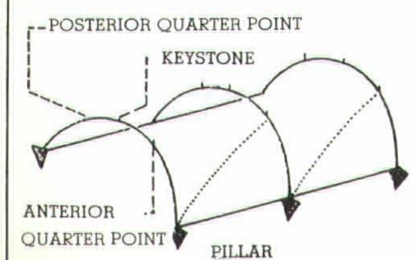
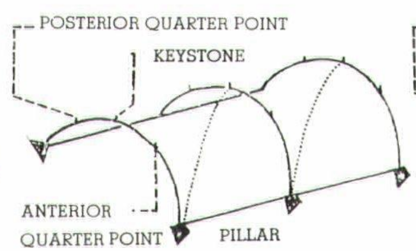


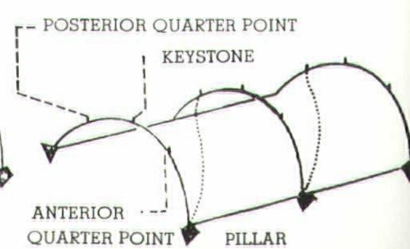
III 4

IV 4

FORMAL GENERATION OF RETICULATED VAULTS







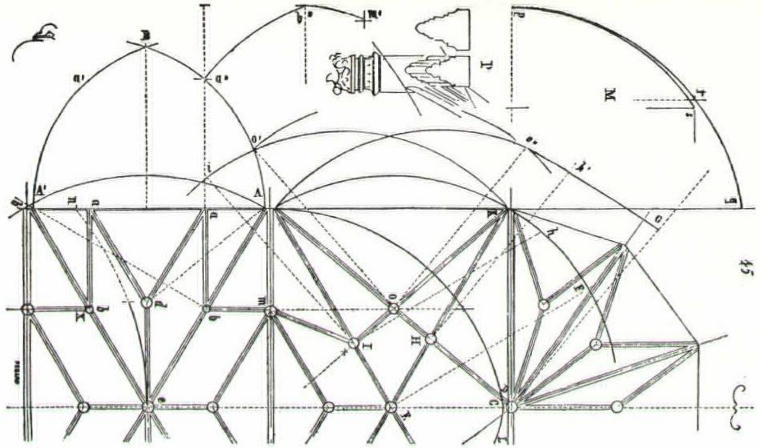


Figure 38. Church of St. Florentin (Yonne) later demolished and redone by the architect Pieple with simple ogives in a period in which literary criticism held dignified for art only the austere forms of the XIIth and XIIIth centuries. The criticisms made by Viollet-le-Duc on the statics of this example do not have a serious foundation.

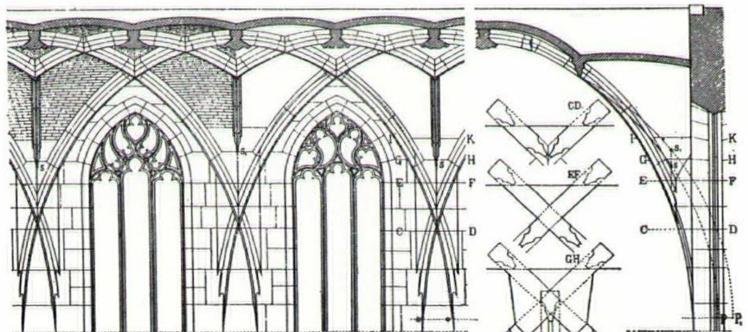


Figure 39. Longitudinal and transverse sections of the reticulated vault in the church of the Madonna at Leinzingen. Note the different elevations of the supports of the various diagonal and orthogonal ribwork.

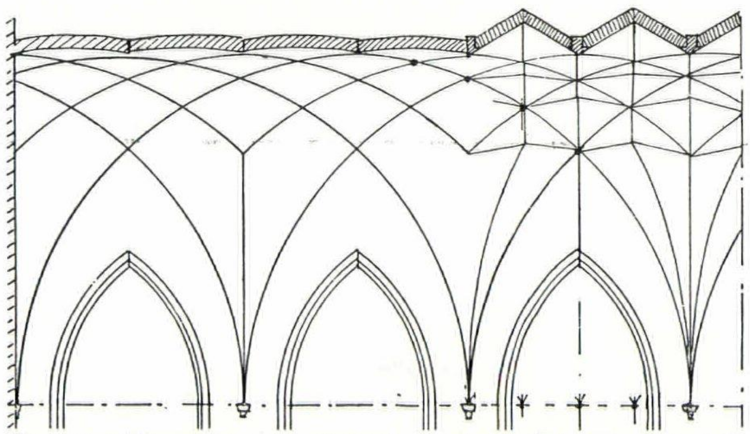


Figure 40. Difference between a reticulated vault "netzgewölbe" and cellular vault "zellengewölbe" consisting only in the minor or major concavity of diaphragms placed to stiffen the small nets of the principal reticulation of the ribwork.

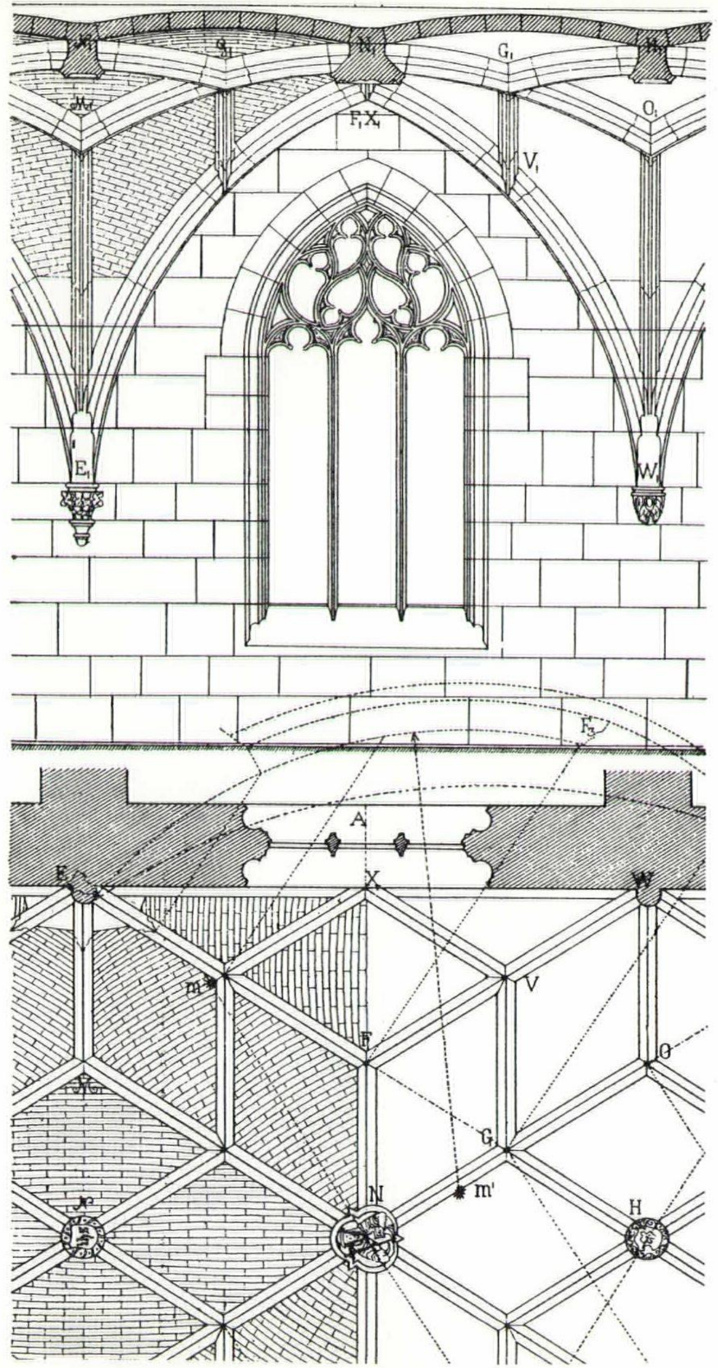


Figure 41. Reticulated vault, called by the Germans "netzgewölbe" in the Oratorio of Maulbronn. The sections of the secondary vaults and their dispositions are very instructive concerning the static regimen of the structural complex. The claw projections on the windows resolve, besides an architectonic problem relating to the illumination, a static exigency of eliminating the zones in which the ribs would have worked in tension.

For the convenience of the designer there are derived from Viollet-le-Duc and from Egle[18] two typical drawings with the related figures of folding. One deals with projecting vaults in the Church of Saint Florentine (Yonne) *(Fig. 38)* and in the Oratorio of Maulbronn *(Fig. 41)*, a city many times cited, which is a mine of ideas of reticulated spaces technically interesting and artistically valuable.

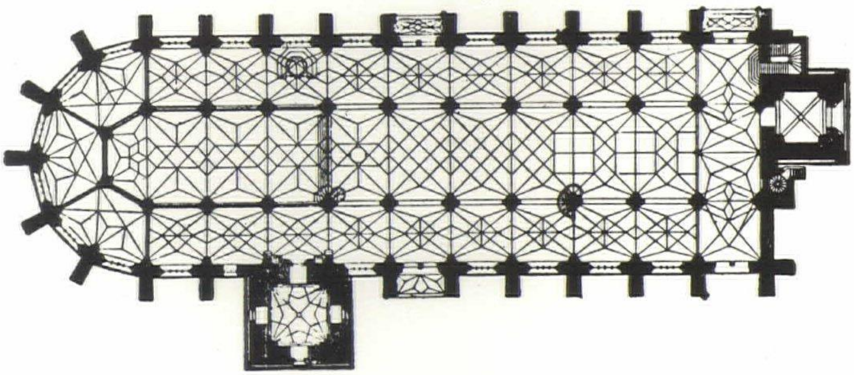
The plan of the Church of Saint Thiebaut at Thann (Haut-Rhin) *(Fig. 43)* with reticulated vaults dating from the end of the fourteenth century (while the star vaults of the added parts are of 1431) and of the City Hall of Breslavia *(Fig. 44)* at the first floor dating from the fifteenth century, show what unified installation can be conferred on an architecture by means of this outlining of reticules. This could correspond for so long a time to a current-enough technique, as would be our

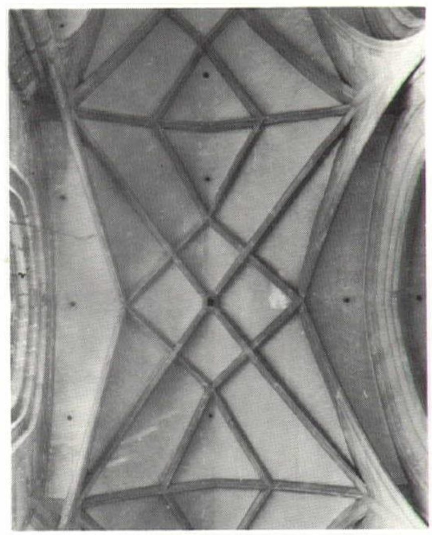
[18] Egle, *Baustil-und Bauformenlehre auf geschichtlicher Grundlage*, Verlag Wittwer Stuttgart.

ordinary reinforced concrete for which exist specialists who have no other profession than to arrange in advance the metallic reinforcing and their bendings on the architectural design of others. During that time, on the contrary, that simple trade of organizing the lines of resisting force in a vault could not exempt itself from the obligation of creating architecture, and therefore to dream in order that others may dream.

We can say, speaking parenthetically, that these were times to be envious of—an era of men whose technical knowledge was not less than those of the crystollogists.

But whereas today crystollography is a cold instrument standing between man and minerals and coming out of no such close relationship, on the contrary, in the Gothic era all that applied geometry springing up between man and his technical means of construction could have evolved from a rapport of the craft and could have exceeded the function of the animated and self-offered instrument to become affected and moving images of cultural and





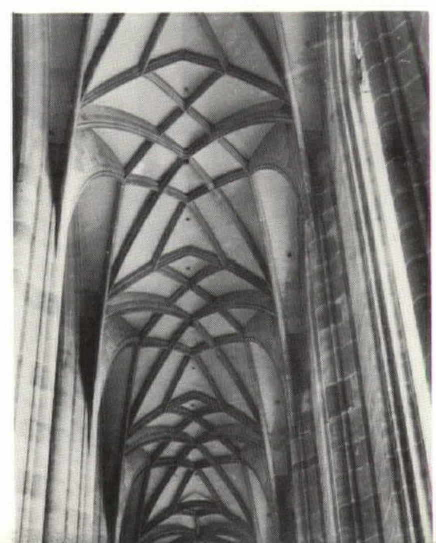


Figure 42. The star and reticulated vaults of the church of St. George at Dinkelsbuhl are organized in a composition of enthusiastic ensemble (1448-92).

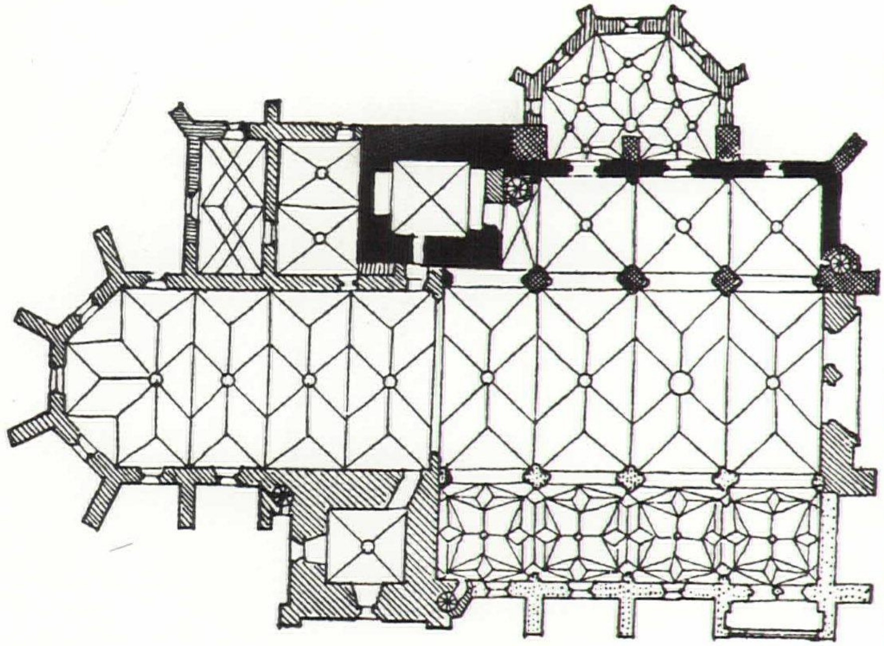


Figure 43. The church of St. Thiebaut at Thann (Haut-Rhin) with reticulated vaults of the end of XIVth century in the central nave and with interpenetrating star vaults in the left nave from 1431.

spiritual worlds. The spirit of the time selected from that geometry to make of it incandescent material on which to print its face. Both the collectivities and the individuals of the time, organizing works of art which could have been called collegiate and individual self-portraits together, sang an abstract music and poetry of more profound significance than the arid formula games of our abstract artists behind which do not exist the choral collaboration of the society and the accumulation of sufficiently mature elaborations.

Observing and contemplating these examples of gothic architecture one grasps the significance to civilization of the maturity of the ideas. Let us confront them with the small, and even blessed, structuralistic aspirations of the art realized in reinforced concrete in thin shells and in corrugated vaults, and we are not able to conceal from ourselves how primitively rough are the works of our time.

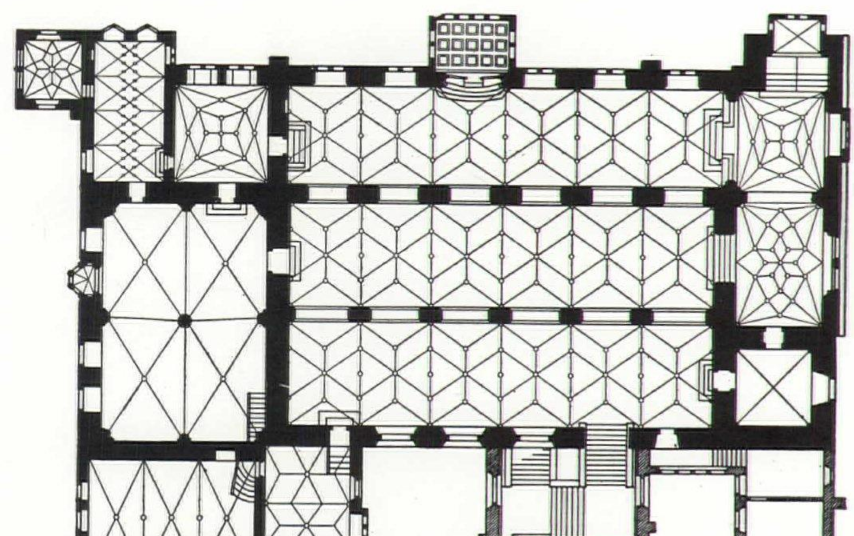


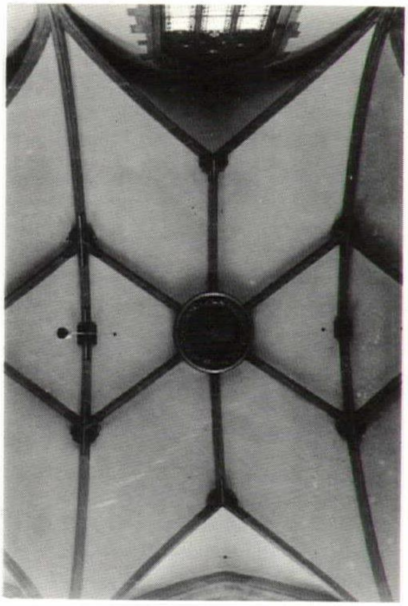
Figure 44. Star and reticulated vaults in the City Hall at Breslavia, on the first floor (XVth century).

The enraptured catharsis which takes hold of the heart and the mind inside the Church of St. George in Dinkelsbuhl was prepared by filtering ideas and forms in the years which passed from 1448 to 1492.

It has been said that a profound complacency of the mind echoes together with the joy of the heart. Either it is a case of the Zellengewölbe or Netzgewölbe; that is to say of a cellular vault or of a reticulated vault, those small more or less concave diaphragms which fill in a stiffened manner the minuscular nets of the reticulation of the ribwork. No matter how the stone vault is organized it is always the most slender structure; a leaf of material which forms an umbrella over the lower underlying spaces; a laminar of minimum conceivable thickness. The lightness of such a cover is not comparable with that of the Roman and Byzantine vaults, the Romanesque and Renaissance, and Baroque. The weight of the vaults reduces to a minimum and a minimum it will always be, even if with the progress of our science of construction we had intended to undertake a competition with the Gothic people, utilizing the same materials which they used, stone and brick, without traces of metal.

A simple little discourse will convince us that the Gothic people could not have utilized a lesser mass of material than that used; that they exploit it with superior confidence to that which was used in the resistance of stone and of brick in all other epochs; that stone or brick were not placed in the work in points and in ways in which they could not act efficiently.

At those points where stone or brick would work badly, the Gothic architect had contrived various shrewd solutions to do away with the useless and risky experience; for example, in reticulated vaults, wisely placed between cylindrical groins, which seem to be placed



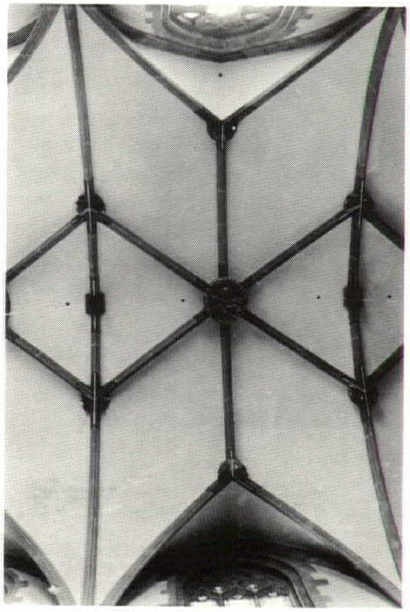


Figure 45-46. Reticulated Valuts in the Church of St. Thiebaut at Thann.

there for reasons purely distributive or for illumination, but which in reality have a predominant static reason. Cited are two sections, one longitudinal and the other transverse of the soffit work of the Church of the Madonna at Leinzengen *(Figs. 39 and 40)*.

The principal and ideal barrel vault on which the ribwork runs is frequently suppressed. Perhaps this is done more frequently than could be thought before the consideration which emerges from the analysis of the state of tension which is developed in a barrel vault supported on only a few points and without continuity on the longitudinal walls of the perimeter.

There has been included here a small figure in which three types of barrel vaults realizable with diverse techniques are compared *(Fig. 47)*: (I) a reticulated Gothic vault, made up of ribwork and of diaphragms all in stone or brickwork; (II) a reticulated metallic vault, made up of only rods in tubular or profiled steel, with the nets empty; (III) a thin shell in ordinary reinforced concrete in which a metallic reinforcing becomes incorporated in a layer of 4 or 5 centimeters of hardened concrete.

For didactic convenience one alludes first to the internal static behavior of the thin shell in reinforced concrete. The progress of the isostatics of compression and tension, both realized often with steel bars curved according to the same paths is indicated. The compression isostatics are indicated by continuous solid lines, which function then as stone arches and the tension isostatics by dotted lines which function as internal tension chains realizable obviously only with metallic reinforcing. More specifically, it is possible to observe that the concealed compressive arches go from column to column or else from a point to its symmetrical point on the essential and

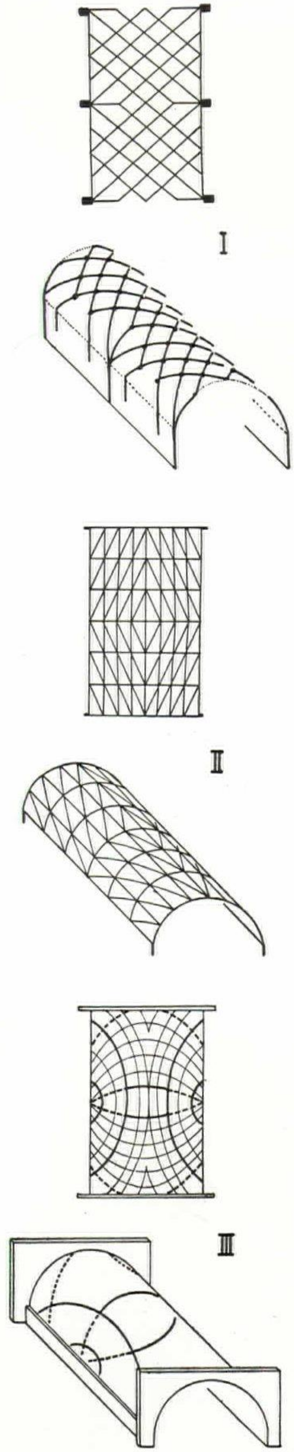


Figure 47. Schemes of barrel vaults realized with different techniques and materials: I, reticulated Gothic vault in stone and brick material acting well inresistance only to compression; II, reticulated metalic vault, in material which is best for resistance in tension; III, thin shell in ordinary reinforced concrete with dotted lines indicating the tension isostatics and continuous lines the compression isostatics. In this last the edge beams and the frontal diaphragms are necessary members.

unsubstitutable beams of the side; and still other compressible arches go from the aforementioned compressive arches to their symmetrical points beyond the middle point of the barrel vault. Vise versa the tension arches almost always tie with oblique paths the points of the beam at the lateral edge beam to points well anchored on the essential and unsubstitutable frontal spandrels. The connection in tension is also realized between points on the compressive arches and points on the edge beams, with a path similar to the cables that we see in suspension bridges with rigid beams suspended below. Having available only metal and not having the requirement of stabilizing a continuous ceiling, evidently it would be more rational to build a reticulated metal vault in which the rods would have to become oriented predominantly according to inclined tie-beams which we would see in a vault in reinforced concrete. Whence the vaults of the Schwedler type.

Figure 48. Reticulated vault in the Remter of the City Hall of Breslavia (1471-1540).

Having instead only stone or brick materials available for construction which resist compression quite well but tension very badly, it remains only to prefer the paths of the compression isostatics taking out from the barrel vault those cylindrical groins. It is now easier to understand why they exist and why they are even then generally ribbed, such ribwork having the purpose of opposing thrusts which the vault itself cannot resolve mecanically.

A miracle of static intuition! Around the columns are perceived only the ribwork of the type of the tiercerons and the orthogonal reticular drawing does not exist.

We will be able then to repeat here that for the more up-to-date aesthetics the form cannot be only the sensible manifestation or the Schopenhauer-like plastic representation of the constructive forces but certainly an essential agent of their organization into equilibrated systems. Nevertheless, it is also necessary to observe that until the most ancient times one instinctively had the opinion that the factor of beauty in vaults is the gratification for their mechanical excellence, gratification which is a plausible sentiment which can assume form in art even in the idealistic and post-idealistic philosophy. A Chinese proverb says, "Feeling by intuition in the visible forms of the vault, that the vault never sleeps." It is an image of life. A life which today we know in small part rationally, and which in large part we ought to content ourselves only to know by intuition as the ancients did, but with superior audacity to ours.

A very authoritative scientific author of our period, Danusso, says, "When I think of the structure of the Gothic Cathedral, which channels along a wise ramification the flux of the forces to guide it in its descent only to end at the barrel and at the roots; when I think of the uneasiness that the designers and builders of colossal structures such as the Baths of Caracalla, or the dome of the Pantheon, of Santa Maria del Fiore in Florence, of Saint Peter's, seeing them rising in their imposing reality, must have experienced and manfully overcome; when I think of all this, I can but recognize the historical priority of intuition on science, and bow to its creative power." [19]

We know that the histories of art, of prevalently literary form, are hardly able to understand these tremendous behind-the-scenes or antecedent facts of the artistic creation and that they prefer to see in the Gothic cathedrals romantic reproductions in stone of woods and forests or else of other arbitrary images, like that anthropormorphic invention of Auguste Rodin. The great sculptor sought to demonstrate, with his numerous and expressly made series of designs, how the French Gothic Cathedral departs from the architectonic and artistic presupposi-

[19] A. Danusso, *Quaderni della Fondazione Pesenti*, 1949.

Figure 49. (Right) Detail of the vaults of the church of St. Anna at Annasburg. Photograph by Brinckmann.

tions of two hands joined and raised to pray.

We know also that an excessively mechanistic interpretation could have carried the critic away from the point. Nevertheless, in the phenomenon of the gestation of the architectonic ideas, more than elsewhere, the technical and mathematical consciousness have influence. They contain the repercussions which the forms of the spatial geometry have in the anticipation of the static behavior and of the visual effect. Laffaille, builder of thin shells, has dwelled on this aspect of the problem. "Here, as elsewhere, the role of the mathematical analysis goes beyond the classical stage of practical application to which it was restricted in the field of the stress of materials. Mathematics then had only a role of control of the simple forms: will a post be crushed, will a beam fail under bending stresses? Here, in this particular field, mathematics allows us to predict in such a general manner the repercussions on resistant forms of the action of any forces in function of systematized edges or contours, that in their turn they become an intellectual way of thinking. This way of thinking at this degree contributes to constructive imagination, not only to indicate material limits (thickness, dimensions, spans), but in the same way as a real architectural knowledge." [20]

This "intellectual mode of thinking" is a reality which one cannot ignore for preconceived positions. To give visible form to the ideas of our epoch, as Max Bill [21] wishes, is a problem connected to the utilization, not as imitative progress, but as a process of acculation of the necessary energy to the renewal of ideas. It is a gradual accumulation of the Bergsonian meaning which on second viewing sees the elastic channeling of such energies in variable and indeterminate directions, above which are the free acts of true art.[22] The greatness of medieval art consists in its abstraction, through, however, a continual working of preparatory charge complete with experiences of quality and not impulsively primitive as certain dillitante poets of today would have it. Its greatness remains in its choosing architecture to the other arts, although in it there can be found again those filtrations of thought which truly are productive in the documentation of the civil maturity of the people. It also consists in the search for the model of the devine in more rigid, even if simplified, forms, of their models which have the pureness of natural models. The medieval abstractionists, and primarily the architects, create as nature creates not what nature has created. The medieval abstractionists would have been the most instructive examples of those artists whose more recent aesthetic has precisely instituted the productive theory of the "self-forming form," of a form which proceeds to form itself in the process of gestation in a continuous discovery of expressive means.[23]

[20] B. Laffaille, *Abhandlungen*. International Rereinigung fur Bruchenbaue und Hochbau Zurich, 1935.
[21] Max Bill, *Maillart*, 1951.
[22] Bergson, *L'evoluzione creatrice*, Milano, 1954.
[23] Pareyson, *La mia prospettiva estetica*, Padova, 1953.

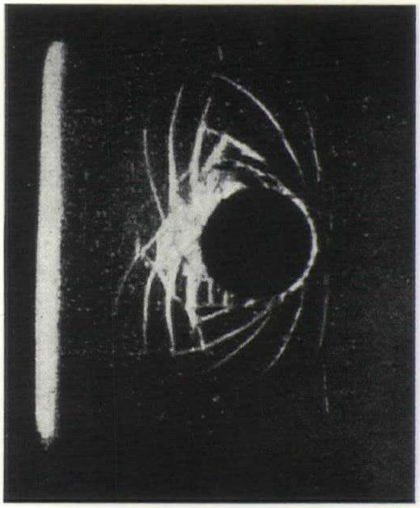


Figure 50. Figure of Krüger, lines of stress in a sheet of iron compressed from a small cylinder.

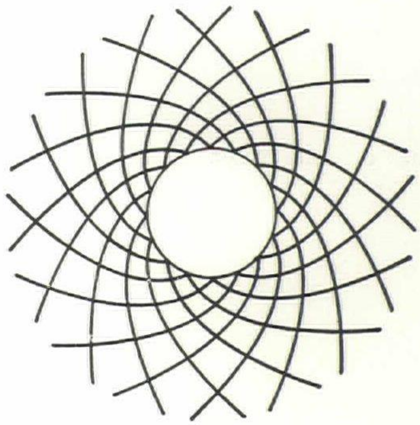


Figure 51. Orthogonal logarithmic spirals as lines of stress (from Nadai).

Within this framework can then be received and become sublime a happy intuition of Viollet-le-Duc for whom "the cathedrals are the first and the greatest effort of the modern genius applied to architecture, because they raise themselves to the center of an order of ideas opposed to the old order." [24] At the same time it can be concluded that the best and most significant phase of the Gothic, understood as clarified projections of man in stone, is really that of the maturity during the XIV and XV centuries, because the Geothian madrigal which says that "man, like the trees, reaches true perfection only in old age" has divine validity.

The knowledge which derives from the experience of that architecture is such as to build a necessary base so that the new creations, which strain the aspirations of new men, can also insert themselves in the line of an uninterrupted tradition of good quality.
We have inquired into and appraised a fertile period of research, of images which they express, against innumerable insignificant forms.

Science was most exact, exemplary, stupefying the strict discipline in the research for resisting and economical forms, in a perhaps never-equalized craving for the bodiless, for the imponderable. The work of practical builders and of parsimonious impressarios was never disjointed from the poetic authenticity of the inspiration.

Because they invented and worked poetically, the creations of the Gothic architects can be assumed as heraldic emblems of the European civilization.[25] Heraldic emblems diluted in the light like that thick flower-work of Ronsard, "diluted in the light so that its color reissues more dense and more rich."

[24] Viollet-Le-Duc, *Dictionnaire etc.*, voce "Cathedrale", pag. 385.

[25] The heraldic sense seems more evident in the numerous planimetrics in part taken from: W. Pinder, *Deutsche Dome des Mittelalters*, Konigstein in Taunus, 1950; R. De Lasteyrie, *L'Architecture Religieuse en France a l'epoque gothique*, Paris 1927, but not only heraldic is the visual aspect directed as a result of the stupendous photographs of A. E. Brinckmann, *Baukunst, die Kunstlerischen Werte in Werk des Architekten*, Wasmuth Publishing firm, Tubingen, 1956.

Pier Luigi Nervi

Some Considerations About Structural Architecture

Mr. Nervi explores the realm of structural architecture, which he feels is in great need of being clearly defined. He states what he feels are three essential conditions and in expanding on these conditions he makes positive contributions towards an approach to the means, methods, and ends of architecture.

The following lecture was delivered by Mr. Nervi on April 10, 1961, at Massachusetts Institute of Technology for its centennial celebration and is published by permission of the author.

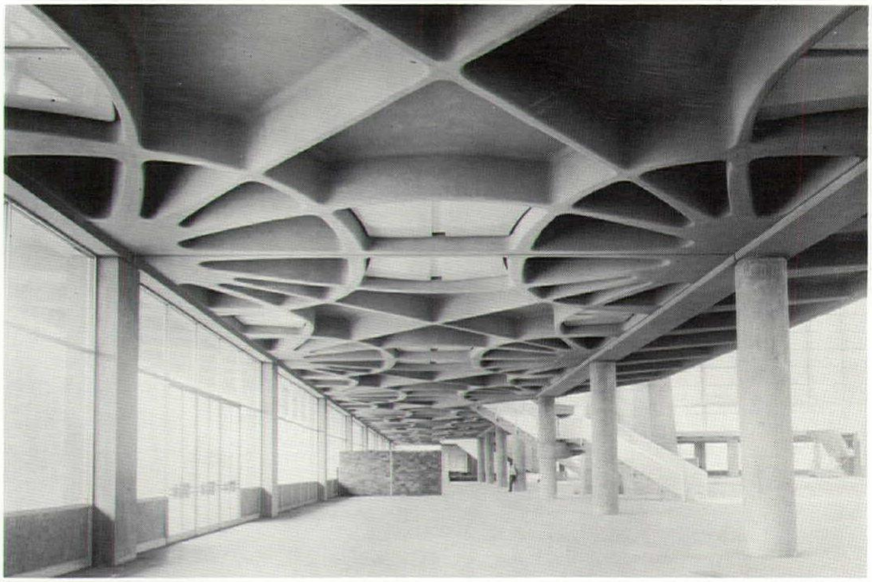
Left—Palazzo Del Lavoro—Turin, P. L. Nervi and A. Nervi

In the last few decades, the ever-increasing sizes needed for the most representative buildings of our time have brought to the forefront the problem of their structure. In many cases, structure has become a factor of such formal and dimensional importance as to become the main protagonist of its architecture. It may, therefore, be interesting to examine certain characteristics of the structural problem and try to define the basic concepts underlying true structural architecture.

Structural architecture as we see today, or as we may expect to develop in the near future, has not many examples in history until about the middle of the Nineteenth Century. In fact, the only example of true structural architecture—that is, of structure which is visible from both outside and inside and is the determinant of architectural design—is the Goth—more precisely the great Gothic cathedrals.

The great masonry structures of the Roman period cannot be defined as true examples of structural architecture because of the static nature of the masonry bulk and of its planimetric disposition, which prevent the structure from becoming apparent either outside or inside. In fact, if we look at that wonderful work of art which is the Pantheon in Rome, we do not find any element either internal or external which may reveal to the onlooker the method by which the balance of mass was achieved nor how thick the walls might be which gave it equilibrium.

With the advent of the Renaissance and the return to the construction methods of Roman times, great masonry structures were erected, but none of them were in any sense real structural architecture. In fact, if we observe the interior of that extraordinary architectonic monument, which is St. Peter's in Rome, it is easy to see how the decorative elements not only are



Palazzo Del Lavoro—Turin

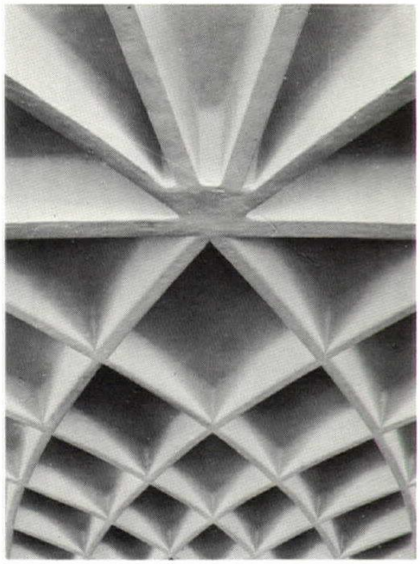
not deriving from structural reality but in many instances they display structural schemes which have nothing to do with reality.

I believe therefore that it is desirable to give a definition of the essential characteristics of real structural-architecture. A clear definition seems to me very important, because in recent architectural critiques we find real confusion of terms. Structural architecture is confused with false or merely formal structural systems.

I believe the essential conditions of structural architecture to be as follows:
1. It must give a convincing answer to a real and authentic static necessity and be determined by it.
2. A static constructive scheme should become visible and comprehensible inside and outside.
3. It must express frankly the material with which the structure is executed and find in the technological characteristics of the material itself the sources and ways, as well as the details of its architecture.

The first condition refers to the effective presence of a static problem of such nature as to demand a great resisting system and to the fact that it becomes visible and comprehensible to the person looking at it. Structural architecture needs great dimensions. This is important to remember; sometimes one sees structural solutions of very slight static importance, such as little projections, small doors, or short spans designed in a way which would require much greater dimensions to be right. The result is that we receive an unpleasant sensation which is similar to a caricature of something which is important and worthy of respect.

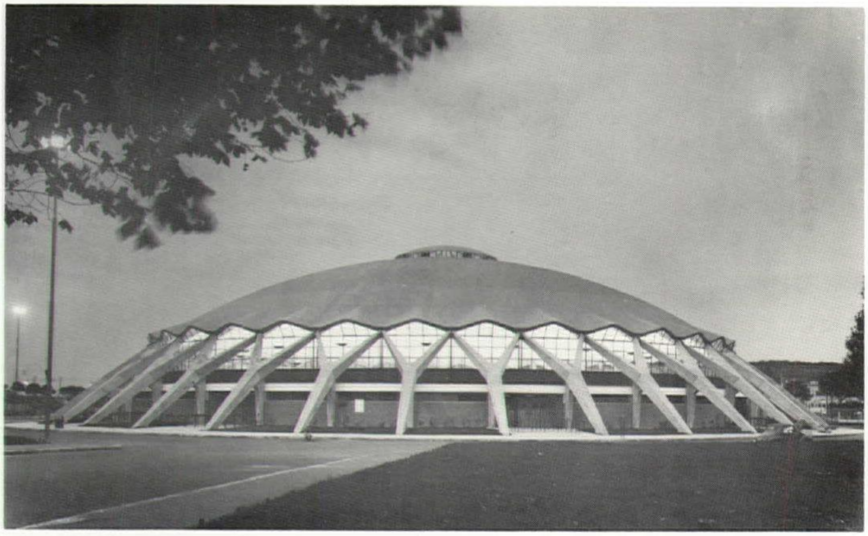
Similarly, from my point of view, we cannot define structural architecture as those works in which a formal idea is developed almost as a piece of sculpture of limited scope in itself but blown up many



Palazzetto Dello Sport—Rome, P. L. Nervi and A. Vitellozzi times in size through technical acrobatics and pretending to acquire architectonic definitions and functions.

True structural architecture is the result of a dialogue between the designer and the natural laws which regulate the equilibrium between forces acting upon a material and its capacity to resist them. The severity of this equilibrium defines the tone of the dialogue and its conclusions.

To design a structural architecture means to translate in intuitive terms or through mathematical calculations an equation posed by natural laws in such a way that the results are understood even to the layman, who more or less consciously must evaluate the essential lines and derive from them a sense of satisfaction. It is in fact true (and it is proven by the wonder intuition of all great architects and of the very good workingmen) that even the layman possess intuitive aesthetic sense, which may be confused as to its essence but gives him nevertheless satisfaction as he contemplates a structure correctly designed.



Even more difficult, just as one tries to define beauty, is to tell on what elements the aesthetics of a structure rest: that is, when does a structure become beautiful architecture. I believe that the conditions of beauty are always found in harmony of proportions, in the loving care of details, and also in the expressiveness of the elements or forms which are derived by the correctness of the assumptions.

An eloquent example of this is given by one of the most beautiful bridges by Maillart, in which the characteristic profile of the three-

Palazzetto Dello Sport—Rome, P. L. Nervi and A. Vitellozzi hinged arch is exalted probably beyond its static necessity.

As to the third condition, that is, on the appropriate use of the material which gives static substance to the structure, it seems to me so evident as not to require any special comments. More interesting is to observe that the details which provide the aesthetic expressiveness of the structure must consciously meet the special technological characteristics of the material itself. In other words, each detail of construction must be in accord with the special quality or characteristic of the material and from this accord will result architectural effectiveness. It is enough to study the Gothic buildings to value the importance of this condition. The small details, even the decorative ones, are the result of the conditions of workability or of static function of the stone itself and in such a way that it is difficult to separate in the creative act the technician from the artist.

In the last few decades, structural

Palazzo Dello Sport—Rome, P. L. Nervi

architecture has reached a more rapid and promising development, mostly because of better use of concrete of new technologies in welded steel, and in the very promising aluminum alloys. There is intrinsic beauty in aluminum; it has qualities resembling those of steel, and through extrusion one can obtain shapes of very large dimensions and of any desired profile; it possesses resistance to atmospheric agents and offers wealth of opportunities for creative structural architecture.

It is impossible for me today to examine, even briefly, all these fields of which we see every day new and ever more expressive examples. I will limit myself to some reference to concrete structures. This marvelous material, which is without precedent in the history of construction (stone made by man and capable of resisting tension), possess the great quality of not having a specific form of its own but of being ready to assume any form one wishes to give to it. As a material, it possesses all the characteristics needed to become the great protagonist of present and future structural architecture.

With concrete, the problem moves from the material itself to that of the forms which contain it. And if we are able to solve the problem relative to its execution—and we have now many means to do so—we can reach almost complete design freedom. Floor beams can assume special shapes, determined by the static demands, or they can be so disposed along curves corresponding to the preferential lines of internal stresses so as to completely fulfill all physical demands. The main structural elements may thus lose the rigidity of wood or steel beams and assume forms which express in a disciplined way the static lines of stress.

The main goals of the last few years have been to establish proper construction techniques and to perfect the details so as to obtain surfaces which are esthetically acceptable. Now the technological potentiality of concrete is such that as a method it is ready to solve any problem of structural architecture.

If we consider the near future, it is easy to observe that because of the need for professively greater dimensions in construction, structural architecture has a great future in important buildings. We must not, however, hide a grave danger, to which I have already alluded and which from my point of view seriously threatens structural architecture. It is the temptation of searching for arbitrary forms—for forms based on false structure, which then become untrue and merely superficial architecture.

Obviously, I don't have the time to fully enter this argument; but I beg those who are interested and are active in this wonderful field of structural architecture to consider this certainty of mine: namely, that beauty, or to be more accurate, architectural expression of

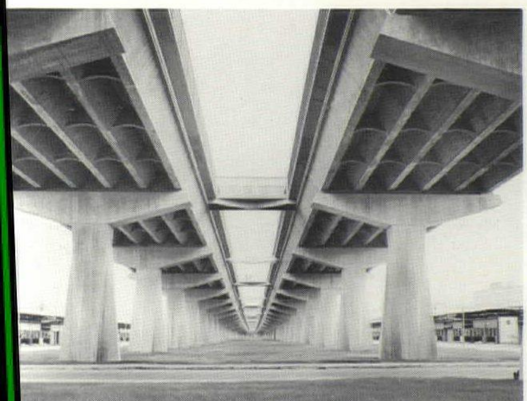
Stadio Flaminio—Rome, P. L. Nervi and A. Nervi

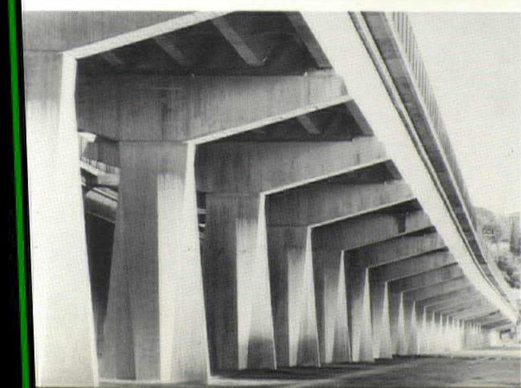
a structure, cannot be achieved without a correct static solution—that is, a solution which is natural, economical, intuitively conceived, and intuitively understood. Formal acrobatics which are today made possible by technical acrobatics may give a momentary sense of awe, but never produce the serene, lasting satisfaction given by a harmonious equilibrium made comprehensible. Structural architecture must grow from the very specific necessity of the theme of existing matter and conditions. The exterior form is the result of this joining of necessity, of meeting physical laws, of rejecting fashionable and superficial ideas. It is only by responding to physical laws that a form avoids the merely fashionable. A good structure is beyond and above the changeable trends of taste.

But this is not enough. The ever-greater sizes of architectural works will demand an ever greater adherence of their structure to static laws and to the various necessities of construction in the same manner in which high speed determines the forms which have to move at such speeds.

Mankind is discovering in many ways and in many fields that new forms which are imposed by physical laws cannot be modified by whim. All this means that we are moving towards greater obedience to natural laws; the great bridges, the jet planes, and other machines which generate and use powerful dynamic forces are very eloquent examples of this truth.

If my conclusions are right, we are witnessing the birth of a style based on truth, inspired by natural forms, characterized by purity of lines, by functional clarity common to all human endeavors and which being anchored to physical laws will evermore evolve towards a more complete final truth. Isn't this a marvelous promise?





Viapotto Di Corso Francia—Rome, Structural Design P. L. Nervi

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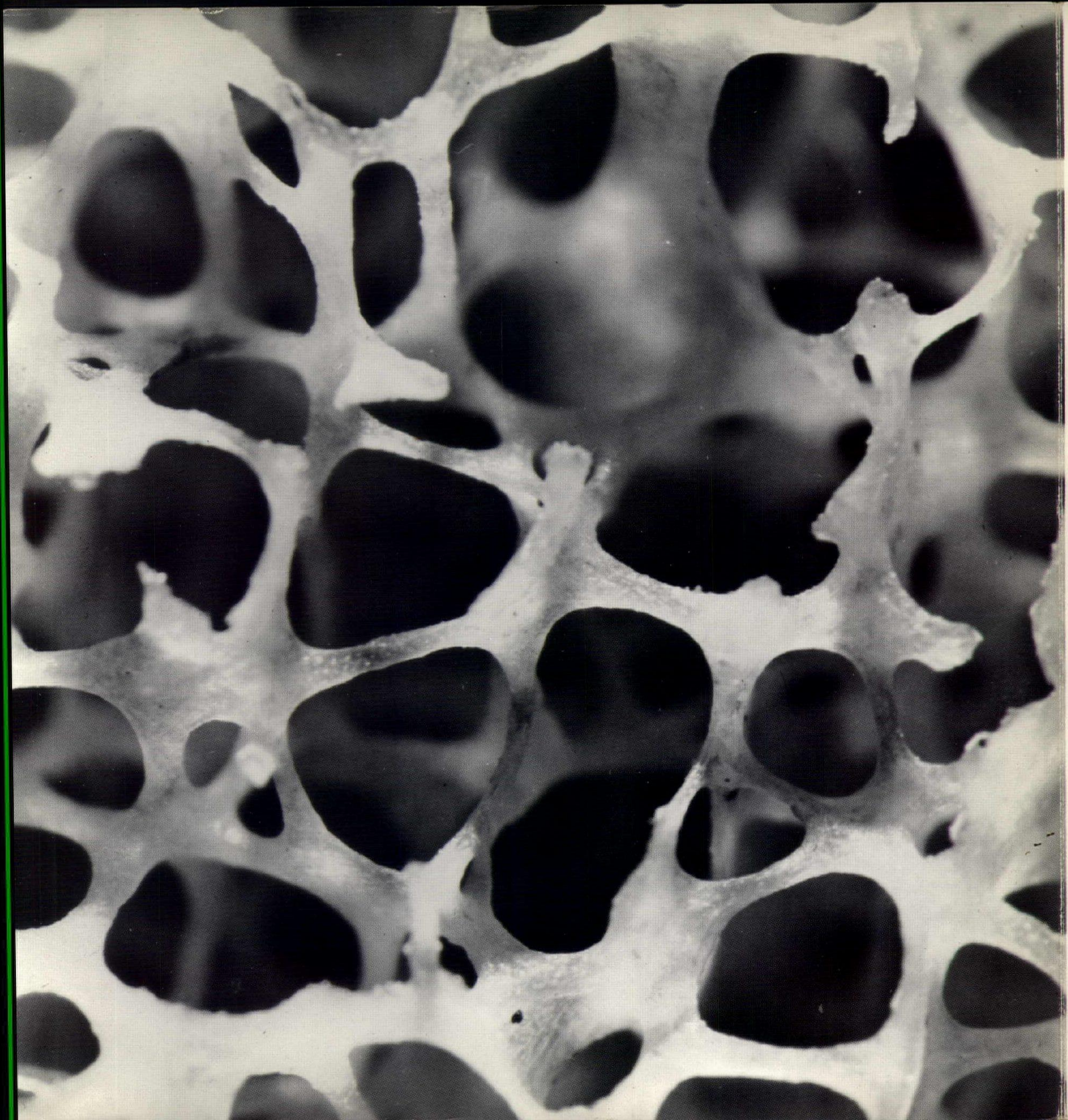

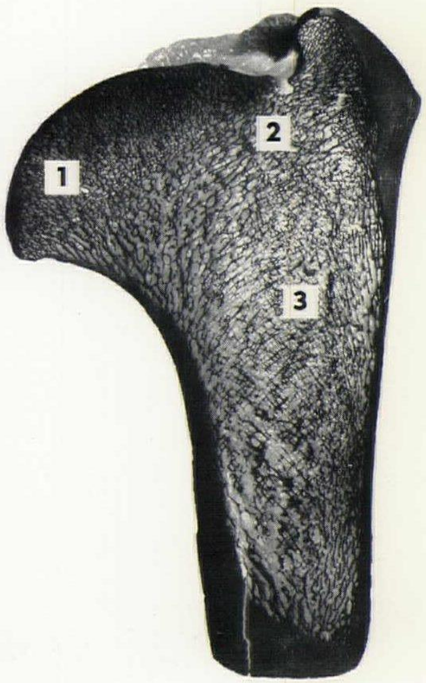

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