THE CONSTRUCTION OF LOMBARD AND GOTHIC VAULTS

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I

THE rib vault has been recognized by modern archæologists as the cardinal and essential feature of Gothic architecture, the motive upon the development of which the builders of the XII century in the Ile-de-France concentrated their energies, and from which followed as logical and almost inevitable consequences the various structural and ornamental forms characteristic of the Gothic style. Recent historians of architecture have abandoned the methods of the old-school archæologists, who regarded medieval buildings, without consideration of their structural significance, as so much ornament to be analysed from a purely æsthetic viewpoint. These modern writers have instead studied in the greatest detail the story of the evolution of the rib vault in the Ile-de-France, the many experiments essayed in its applications, and the various forms it assumed, until the ultimate Gothic type was found. They have demonstrated the patience and perseverance of the medieval builders, who at first gropingly, later more confidently, but always without faltering, surmounted obstacle after obstacle until they had created a new and pregnant art. The result of these studies has been to emphasize ever more strongly the importance of the rib vault as the generating principle of Gothic architecture.

One question, however, apparently no historian of architecture has yet stopped to ask himself. Granted that the extraordinary evolution of Gothic architecture was due primarily to the rib vault, how did the builders of the transitional period first come to adopt this form? Why did they choose it in preference to the groin vault, the barrel vault, or the dome? The earliest examples are clumsy and ponderous constructions possessing over other types of vault none of the advantages structural or æsthetic, of which the form later proved itself capable. It is absurd to suppose that the masons were gifted with prophetic foresight, and consciously set themselves the task of evolving a new style with super-human knowledge of the results to which the use of the rib vault should lead them a century later. The explanation must be that the rib vault, even on the modest scale in which it was first employed, possessed certain definite advantages that were lacking in other types of vault. These advantages were not æsthetic, since the

earliest rib vaults are certainly not more beautiful than contemporary groin or barrel vaults. They were not structural, that is, they did not effect the ultimate stability of the building, the concentration and counter-balancing of thrusts and the like, for the earliest rib vaults are of small dimensions and placed on thick walls, often even under towers; hence any other form of vault would have stood quite as well. The only possible explanation is that rib vaults were easier, or less expensive than others to build. This, in fact, was the case, for rib vaults may be constructed with the aid of a very light centering in wood, whereas a groin or barrel vault requires a heavy centering. The conclusion therefore seems inevitable that the desire to dispense with temporary wooden sub-structures was the sole motive which induced the French builders to adopt the rib vault, from the logical evolution and development of which Gothic architecture came into being.

When the fact that rib vaults were constructed practically without centering is born in mind, it is easy to understand many heretofore puzzling features of transitional and Gothic architecture. For example, doming has always been recognized as an essential characteristic of Gothic vaults. Two explanations have been offered to explain this doming: one, that the builders were not sufficiently skilled in descriptive geometry to be able to bring the crowns of all the arches to the same height; the other, that the doming had the purpose of concentrating the weight and thrust of the vault on the diagonals. Neither is satisfactory. Since the builders knew enough geometry to enable them to bring the crowns of the arches of a groin vault all to the same level, they could certainly have done the same thing with the rib vault, had they so desired. On the other hand, as I have already said, the question of thrust did not enter into these early vaults. The true explanation I shall show to be, that the domed form facilitated construction without centering. The same thing may be said of various other distortions and irregularities of early vaults, all of which cease to be enigmas the moment it is remembered that the primary aim of the builders was to dispense as largely as possible with temporary wooden sub-structures. Similarly, it becomes possible to understand why rib vaults were in early times placed under towers, even in churches in which other forms of vault were used elsewhere. Since it was awkward to erect a centering between four solid walls, a type of vault which could be erected without centering was preferred.

Thus a knowledge of the fact that it was a fundamental and essential principle with the Gothic builders to erect their vaults as nearly as possible without centering, throws a new light upon transitional and Gothic architecture. By aid of this knowledge it becomes possible to appreciate the daring and skill of the masons who learned thus to build, free-hand as it were, in space; it becomes possible to understand what the builders were striving for in the transitional

period, and to grasp the purpose of the many different experiments they tried in the construction of vaults.

The desire to economize wood led to the introduction of the rib vault, not only in France, but in Lombardy as well, where, indeed, the French doubtless learned the construction. The Lombards carried the principle so far that, in certain cases, wood was entirely dispensed with in the edifice, various expedients being found to erect even a roof without it. In regions where wood was abundant, however, vaults were erected with centering, and in these regions the rib vault was never employed. It is evident that the Lombards used the rib vault not from any preference for the form, but solely because it could be constructed without centering.

Rib vaults therefore were invented in Lombardy as a simple device to economize wood. They were adopted by the French builders for the same purpose. The same desire to dispense with temporary wooden substructures governed the development of architecture during the entire transitional period, and eventually lead to the birth of Gothic.

If space permitted, it would be interesting to trace across the centuries the chronological development and growth of this principle. I shall, however, confine myself to a demonstration of the fact that the principle existed, beginning with a brief summary of certain known methods of vault construction used by the Roman and Byzantine builders, since these are analogous to, and partly explain, medieval constructions. I shall then take up the rib vaults of France, of which the study offers less difficulty since there is extant an abundant series of well preserved monuments. The French principles of construction once understood, it will not be difficult to see that the Lombard methods were parallel and similar, but not identical. Without knowledge of the methods employed in France, it would be difficult to discover the Lombard methods, owing to the fact that comparatively few examples of Lombard vaulted constructions have escaped the vandalism of the barocco centuries and the equally deplorable barbarism of restorations executed during the last forty years — restorations which have almost invariably destroyed what they pretended to preserve. Moreover these few examples are, in the great majority of cases, covered with plaster and intonaco, so that a study of the masonry is impossible. It is necessary therefore to leave the study of Lombard vaults for the last, even at the expense of violating strict historical sequence.

II

Choisy [1] has shown that in the construction of their vaults the Romans sought primarily to avoid expensive temporary centering in wood.[2] A light skeleton of

[1] Auguste Choisy, *L'art de bâtir chez les Romains.* Paris, Ducher & Cie., 1873. Folio.

[2] The very futility of the objections urged against his conclusions in this particular by certain English

timber was erected, a mere mould, of the shape and form of the vault to be built. On this mould was placed a sort of permanent centering of light bricks or tiles, not heavy enough to crush the mould, but strong enough when finished to act as a centering for the massive[1] of the vault (which consisted of a rubble concrete) and to prevent any deformation or rupture of the wooden mould. (Figs. 1 and 2.) This permanent centering was formed in various ways, always, however, with the same end in view. Sometimes broad flat tiles were laid in one or two layers broad-side on the mould, making a complete and self-supporting arch above it, the joints of the tiles being covered with other smaller tiles, and certain ones being placed vertically to give a key for the superimposed concrete (Fig. 1). At other times the bricks were placed so as to form a continuous open-work skeleton in whose rectangular or rather wedge-shaped interstices was placed the cement rubble forming the massive. Again, the bricks of the permanent centering were disposed to form ribs or chains crossing the vault at convenient intervals. This last was the system commonly employed in connection with groin vaults (Fig. 2). The chains were often composed of bricks so laid as to afford an irregular outline with their protruding or receding members which formed a key for the rubble massive, always applied in horizontal courses or layers; they followed the lines of the groins and sometimes also those of the longitudinal and transverse arches. Sometimes the two methods, that of flat tiles and that of interior chains, were used simultaneously. But in all cases the purpose was the same — i.e., to afford a permanent centering in brick, which, placed on top of a light wooden mould, might enable the builders to construct the vault without other temporary wooden centering than the mould itself. Once finished, the vault became a solid concrete mass to which the chains or ribs adhered as an integral part, but in which they performed no strengthening nor structural function. It is well to insist on this fundamental and essential fact, for a recent writer of authority has published a groin vault in the familiar ruin of the Roman Campagna known as "Sette Basi" (Fig. 2), as having projecting ribs. Such a construction would be entirely foreign to the spirit of the Roman art of building. To erect a vault of this kind with salient ribs would require a most elaborate and uselessly complicated centering, since grooves would have to be made in it for the ribs. Moreover, the ribs would not then perform nearly so well their only structural function, that of acting as a centering, since their projection would prevent their being properly keyed into the vaults. At present, as may be seen in the photograph (Fig. 2) the ribs of this vault actually do project slightly from the surface. The vault having been

writers is, perhaps, the most convincing argument for the general soundness of his deductions, as, I think, any impartial archæologist who has examined on the spot, Choisy's book in hand, the ruins of Rome and the Campagna will be forced to admit.

[1] I employ this word to denote the body or core of the vault as distinct from the ribs.

FIG. 1. Vault in Ruin known as "Roma Vecchia", near Via Appia about 7 kilometers from Rome.

FIG. 2. Ancient ruin, known as "Sette Basi", Via Tuscolana, about $7\frac{1}{2}$ kilometers from Rome.

FIG. 3. Amphitheater, Champlieu, (Oise).

exposed for centuries to the corrosion of water and the atmosphere has weathered irregularly; consequently the massive, consisting of more perishable materials, has chipped off and disappeared faster than the bricks. The same uneven weathering may be observed in the vaults of the Thermæ of Diocletian, and in the ruins of the Palatine.

Vaults constructed on the Roman principle should, theoretically, exercise but little thrust, being when finished a solid mass of concrete. As a matter of fact, however, the elasticity of the concrete causes them to exercise considerable outward pressure, which, as the Romans perfectly understood, required buttressing. Notwithstanding the fact that Roman walls were commonly of such enormous thickness as to be able to bear these thrusts without need of external re-enforcement, the architects nevertheless contrived their plans with great ingenuity so that the thrust of one vault should be neutralized by that of another, or so that an interior spur wall strengthened the exterior wall at the critical points. Exterior salient buttresses seem to have been avoided, probably for æsthetic reasons. That the Romans were fully aware of the possibility of their use, however, and employed them when it was not possible to place the buttress internally, is proved by the fact that such buttresses were actually used to re-enforce a sort of apse in the "Sette Basi" and also to strengthen the exterior wall of the Amphitheatre of Champlieu, Oise (Fig. 3), and in other instances as well. The buttresses of Champlieu were perhaps added to the original construction, but still in the Roman period (not in the Merovingian, as has been stated), a fact proved by the character of the masonry. They are especially significant, for the wall being merely a retaining wall for the solid mass on which was supported the cavea, an interior buttress became an impossibility. Thus it is evident that the Romans were perfectly acquainted with the possibilities of external buttressing, and employed it when necessary, although they preferred internal buttressing. The buttresses of Champlieu even end in a sloping glacis, a feature which has heretofore been considered exclusively Gothic. I insist upon these buttresses of Champlieu because they prove that external buttressing of vaults, a system which has been considered purely medieval, was in fact, like many another detail of vault construction, merely a survival of Roman tradition.

Roman vaults with brick chains and ribs were of course in general erected not throughout the empire but only where suitable materials could be found, i.e., in Rome itself and its environs, although the system was more extended than usually supposed, since a half-dome with brick ribs is found in the so-called Palace of Constantine at Arles. In the provinces the vaults were in general constructed of ashlar masonry, to erect which a full centering was very frequently employed; but in the Amphitheatre and so-called Temple of Diana at Nîmes, in the Pont-du-Gard, and in a host of monuments of Syria and Africa, various

ingenious devices to economize centering, even in such vaults, were used. These various expedients, although highly interesting and instructive in themselves, need not be described here, since they have already been admirably studied by Choisy and do not concern the subject under examination except in so far that they all demonstrate the striving of the Roman architects to build vaults with a minimum of temporary wooden centering.

The Byzantine builders, in the construction of their vaults, as in so much else, merely developed and extended Roman principles.[1] With true Greek subtlety of intellect they grappled with the problem of discovering means to erect vaults without centering, and hit upon a vast number of clever and ingenious devices to compass this end. The subject became a passion with them, and governed the whole development of their architecture, even more than it had that of Roman architecture. Of all the many expedients they found by which either to dispense with entirely, or to reduce to a minimum, the use of centering in the construction of vaults, only one seems to have influenced medieval architecture in the Occident. That was the device of giving the groined vault a domical form (Fig. 4). A vault of this shape could be, and was, erected by the aid of six light wooden arches, two following the lines of the groins, now made semi-circular and no longer elliptical, and the four others following the walls and transverse arches. The vaults being constructed of brick, the courses marked 1 in our diagram (Fig. 4)[2] could be laid, the adhesion of the mortar sufficing to keep the bricks in place. Then could be placed the courses 2 and then those 3 and so on, the inclined surfaces of the vault giving each brick a point of partial support on the brick below it in the same course and against the bricks of the preceding course, so that the adhesion of the mortar sufficed to hold it in position. Owing to the domed shape of the vault, each course assumed the form of a segment of a circle, and thus, when completed, became a sort of arch which was self-supporting. Only for the middle courses 5 was the help of a cerce perhaps necessary. In the construction of vaults of this character, the Byzantine architects found it useful to employ for the wall arches a salient wall rib in masonry, instead of a centering in wood. This could be constructed without centering by the well known Byzantine method. Salient ribs in masonry were substituted also for the centering following the line of the transverse arches.

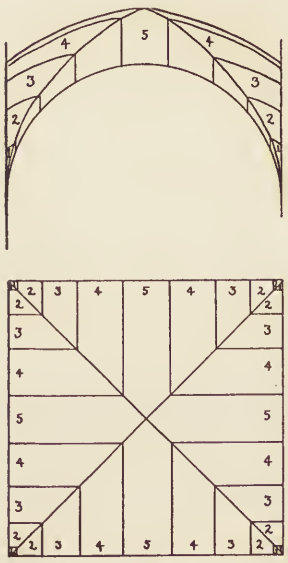

Fig. 4

[1] Auguste Choisy, *L'art de bâtir chez les Byzantins.* Paris, Société Anonyme de Publications Périodiques, 1883. Folio.

[2] For the sake of clearness the width of the courses has of course been much exaggerated in this diagram.

A firm permanent centering in masonry was desirable at this point not only to aid in the construction but to conceal and strengthen any imperfections in the conjunction of the masonry of two adjoining vaults, and to guard this critical point against any possible deformation. Moreover, the use of these transverse ribs made it possible to erect one vault quite independently of the neighboring one. Byzantine groin vaults of the domed type were introduced into Italy at an early epoch, and several are still perfectly preserved at S. Vitale of Ravenna. It is probable that they were also erected elsewhere in the peninsula, for Byzantine influence during the V and VI centuries was by no means limited to the shores of the Adriatic — witness the chapel of S. Satiro at S. Ambrogio of Milan, S. Lorenzo in the same city, and the baptistry of the Cathedral of Naples.

In the East the Byzantine builders learned how to dispense entirely with the use of centering in the erection of groin vaults, disposing the stone courses after the manner of a dome, as in Figs. 5 and 6. Groin vaults of the type of Fig. 5 I

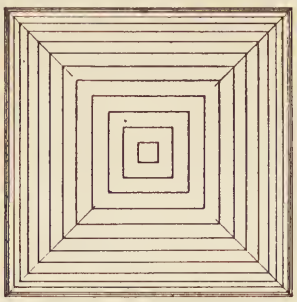

Fig. 5

Fig. 6

have never observed in the West; vaults of the type of Fig. 6, however, are found in the Porta Ticinese of Milan and at Santa Maria Maggiore of Lomello.[1]

Such in outline were those Roman and Byzantine methods of construction, which offer some analogy to the methods of the medieval builders. In construction as in ornament ancient traditions never died. Under the hands of medieval architects, building methods underwent transformations and changes, assumed new forms and developments, but they always retained something of their original classical form. This was due not only to the existence of a continuous tradition but also to the fact that Roman ruins existed well nigh throughout Europe, ever present as object lessons to the masons. Thus it happened that just as the Corinthian capital survived throughout the Middle Ages, sometimes almost in its original form, at others developed or simplified, so Roman and Byzantine principles of construction were the basis from which were developed all medieval achievements in the art of building.

[1] These vaults I have published in *Arte e Storia*, Anno xxx, 1911, p. 196.

III

When these Roman and Byzantine methods of construction, so admirably demonstrated by Choisy, are borne in mind, it is not difficult to discover the method of construction employed in a Gothic rib vault. Indeed, Viollet-le-Duc [1] and Choisy [2] have both recognized that Gothic vaults were erected practically without the use of other centering than a light frame for the ribs and a cerce for the the upper courses. Neither of these writers, however, appears to have realized the significance of the fact.

It is obvious, and I think has so been recognized by every writer on the subject, that the ribs of a rib vault were erected first. They were always self-supporting arches, even when broken or curved in plan. The proof of this statement is that in many ruined abbeys, such as that of Ourscamps, for example, the ribs still stand intact, although the massive of the vault has fallen; and these ribs still stand not only in the bays where the vaulting was rectangular, but in the ambulatory where the compartments are of irregular shape and the ribs broken in plan. Since these broken ribs are self-supporting now that the massive has disappeared, they must have been equally self-supporting before it was built.

A very light centering would suffice to erect the ribs. Especially if the arches were pointed, the voussoirs of the lower part of the arch would be self-supporting, and the lightest kind of a frame would enable the builders to slip in the upper voussoirs forming the key.

When the ribs had been erected, the massive of the vault could be constructed for a certain distance, about one third of its height, without any centering at all.

The remainder of the courses were erected by the use of a simple movable cerce (Fig. 7) hung on the ribs and moved to the next course after each in turn had been completed, each course when finished being arched and self-supporting on the principle already explained (Fig. 4). That is why Gothic vaults always preserved something of the domical form — a simple fact for which so many far-fetched explanations have been offered.[3]

Fig. 7

[1] *Dictionnaire raisonné de l'architecture française du XI au XVI siècle.* Paris, Bauce, 1854–68. 11 vols. Especially article on *Construction.*

[2] *Histoire de l'architecture.* Paris, Gauthier-Villars, 1899. 2 vols. 8vo.

[3] In this connection it is interesting to cite a passage of Suger (*De Consecratione*, ed. A. Lecoy de la Marche, *Œuvres complètes de Suger.* Paris, Renouard, 1867. 8vo., p. 230) which gives documentary confirmation of what has been said above in regard to the construction of Gothic vaults:

Nec illud etiam silere dignum duximus, quod dum præfatum novi augmenti opus capitellis et arcubus superioribus et ad altitudinis cacumen produceretur, *cum necdum principales arcus singulariter veluti voltarum cumulo cohærerent*, terribilis et pene tolerabilis obnubilatione nubium, inundatione imbrium, impetu validissimo ventorum subito tempestatis exorta est procella; quæ usque adeo invaluit, ut non solum validas domos, sed

IV

Such was the theory of Gothic rib vault construction. The workings of the system in actual practice will be evident upon examination of some of the peculiarities of extant French vaults of the Gothic and transitional periods.

In large vaults over naves in the Ile-de-France, as far as my observation goes, there is usually a sharp break in the character of the masonry at the point where it became necessary to employ a cerce (Fig. 10). Below this point, large stones are used; above, so as not to overcharge the light centering, the courses are narrow and light, although sometimes the stones resting on the wall rib and hence supported by it in large part are heavier (Left hand bay, Fig. 9). In such vaults the history of the construction is written almost as plainly as if the cerce had been left in position.

Similarly it happens very frequently, in fact it is not too strong to say gener-

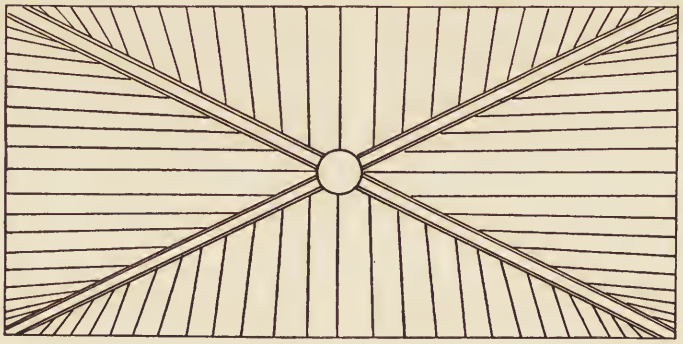

Fig. 8

ally, in Gothic vaults, that the courses, instead of being normal to the walls, tend to converge towards the central key-stone, as in Fig. 8. The purpose evidently was to incline the courses more, and to give each stone a firmer point of support on the stone placed below it, thus relieving the cerce of a corresponding amount of weight. Gothic builders were not only logical, but as subtle and ingenious as the Byzantine architects.

etiam lapideas turres et ligneas tristegas concusserit. Ea tempestate, quadam die, anniversario gloriosi Dagoberti regis, cum venerabilis Carnotensis episcopus Gaufredus missas gratiarum pro anima ejusdem in conventu ad altare principale festive celebraret, tantus oppositorum ventorum impetus præfatos *arcus nullo suffultos podio, nullis renitentes suffragiis* impingebat, ut miserabiliter tremuli, et quasi hinc et inde fluctuantes subito pestiferam minarentur ruinam. Quorum quidem operturarumque impulsionem cum episcopus expavesceret, sæpe manum benedictionis in ea parte extendebat, et brachium sancti senis Simeonis signando instanter opponebat, ut manifeste nulla suî constantia, sed sola Dei pietate et Sanctorum merito ruinam evadere appareret. Sicque cum multis in locis firmissimis, ut putabatur, ædificiis multa ruinarum incommoda intulisset, virtute repulsa divina, *titubantibus in alto solis et recentibus arcubus*, nihil proferre prævaluit incommodi.

In the vaults the stone courses are seldom perfectly regular. It is, indeed, not rare to find them as irregularly disposed as in Fig. 9, one stone being cut to fill an odd-shaped opening between two others, courses twisting and dying away, at times frankly broken. Obviously the stones of such vaults were never, as has been too often repeated, cut in the quarry to fit their final position. The convex and ungeometrical forms the stones assume in this irregular masonry prove that a mason has taken the stones, squared at the quarry without any idea of adapting them to a particular place, and has cut them down to occupy their present position. Even ribs were only roughly blocked out before being put in place, and the mouldings were carved afterwards. This is proved by the fact that at Foulanques (Oise), Cambronne (Oise), Béthisy-St.-Pierre (Oise) (Fig. 11) and elsewhere, the roughly blocked out ribs still exist, the mouldings never having been executed.

In many transitional vaults, such as the one of Crézancy (Aisne) of which I give a photograph (Fig. 12), one rib is perfectly straight, the other is bent. Unfortunately in the case here illustrated the vault has been smeared with plaster and this painted with imitation stone joints which belie the real ones. It is easy to see, however, that the straight arch was constructed first, and that its keystone had an amortisement to which the second diagonal was to be attached. But the unskillful builders placed this amortisement not quite true, not precisely in the direction of the springing of the second diagonal. Therefore to join the diagonal to the amortisement, it was necessary to twist the former.

The entire transitional period resolves itself into a series of experiments on the part of the builders to erect vaults with a minimum of centering. The dislike of wasting energy on a purely temporary structure was probably the reason they wished to dispense with centering, for I do not believe that there was any actual scarcity of wood, a material fairly abundant in Northern France, and never stinted in constructing the roofs of the great cathedrals, often a veritable forest of timbers.[1]

[1] Yet that it was at times hard to find is proved by a passage of Suger: Cumque pro trabium inventione tam nostros quam Parisienses lignorum artifices consuluissemus, responsum nobis est pro eorum existimatione verum, in finibus istis propter silvarum inopiam minime inveniri posse, vel ab Autissiodorensi pago necessario devehi oportere. Cumque omnes in hoc ipso consonarent, nosque super hoc tam pro laboris magnitudine quam pro operis longa delatione gravaremur, nocte quadam, a matutinarum obsequio regressus, lecto cogitare cœpi meipsum per omnes partium istarum silvas debere procedere, circumquaque perlustrare, moras istas et labores, si hic inveniri possent, alleviare. Moxque rejectis curis aliis, summo mane arripiens, cum carpentariis et trabium mensuris ad silvam quæ dicitur Ivilina acceleravimus. Cumque per terram nostram Capreolensis vallis transiremus, accitis servientibus nostris nostrarum custodibus et aliarum silvarum peritis, adjurando fide et sacramento eos consuluimus, si ejus mensuræ ibidem trabes invenire quocumque labore veleremus. Qui subridens, si auderent, potius deriderent; admirantes si nos plane nesciremus in tota terra nihil tale inveniri posse, maxime cum Milo Capreolensis castellanus homo noster, qui medietatem silvæ a nobis cum alio feodo habet, cum sustinuisset tam a domino rege quam ab Amalrico de Monte Forti longo

Fig. 9. St.-Léger, Soissons, (Aisne).
Vaults of Choir.

Fig. 10. Cathédrale, Soissons, (Aisne).
Nave Vaults.

Fig. 11. St. - Pierre, Béthisy - St. - Pierre, (Oise).
South side aisle.

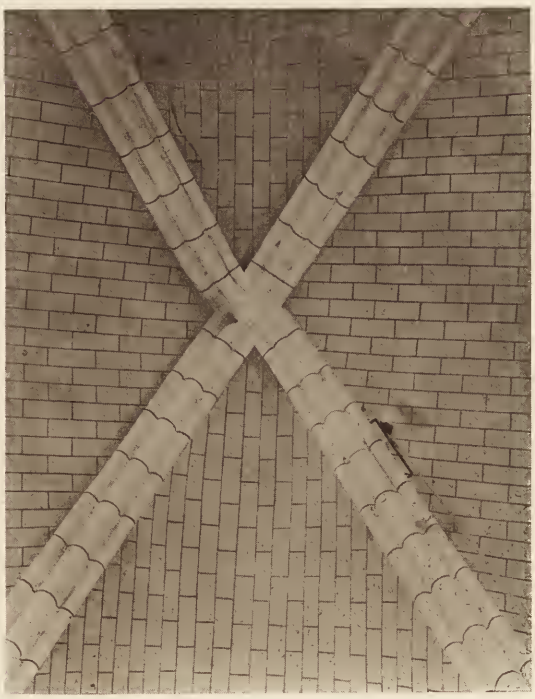

Fig. 12. Notre - Dame, Crézancy, (Aisne).
Vault of Crossing.

Fig. 13. Crouy-sur-Ourcq, (Seine-et-Oise). Vault under Tower.

Fig. 14. St. - Pierre, Acy-en-Multien, (Oise). Vault beneath Tower.

Fig. 15. Sts. - Gervais-et-Protais, Rhuis, (Oise). South side aisle, Vault of eastern Chapel.

Fig. 16. Sts. - Gervais-et-Protais, Rhuis, (Oise). North side aisle, Vault of eastern Chapel.

But though wood was available, it was costly to work; the practical spirit of the French masons caused them to seek means to erect vaults not only as well, but as simply and as economically as possible. Hence they had recourse to the rib vault.

In the earliest examples of rib vaults in the Ile-de-France, such as those in the churches of Crouy-sur-Ourcq, Seine-et-Oise (Fig. 13) or Acy-en-Multien, Oise (Fig. 14), the advantages of doming and of wall ribs were not yet appreciated. The diagonals were made needlessly heavy and must have required a very clumsy centering. But in the rib vault of Rhuis, Oise (Fig. 15), which according to Mr. Lefèvre-Portalis[1] is the oldest of the Soissonnais, the ribs are already lighter, and there is a slight but perceptible doming.[2] This vault was not erected with a solid centering. It is sufficient to compare it with the groin vault in the symmetrical position in the north aisle (Fig. 16), which was erected with centering and which is not domed, to be convinced of the fact. It is equally certain that the vaults of Acy-en-Multien and Crouy-sur-Ourcq though not domed were also built without solid centering, as was perfectly possible in vaults of such restrained dimensions. In fact, long after the advantages of doming were thoroughly understood, the transitional builders reduced it to a minimum or dispensed with it altogether in certain vaults of small size, as, for example, those of the ambulatory of Morienval, since such were easily built without this aid, even when no centering was used. It is a safe assertion that all domed or ribbed vaults of the XII century were constructed without solid centering. If the reader doubts, let him imagine the difficulty of grooving a wooden centering around the ribs, or moulding its surface to the complex double curvature of a domical vault. The early rib vaults of the Ile-de-France were introduced in side aisles or under towers, and were of small dimensions. The builders had long been accustomed to build in these positions groin vaults of whose stability there was nothing to be feared. If they abandoned groin vaults for rib vaults, it was because they wished to dispense with solid centering.

tempore guerras, ad tristegas et propugnacula facienda nihil tale illibatum vel intactum præteriisset. Nos autem quicquid dicebant respuentes, quadam fidei nostræ audacia silvam perlustrare cœpimus, et versus quidem primam horam trabem unam mensuræ sufficientem invenimus. Quid ultra? usque ad nonam aut citius per fruteta, per opacitatem silvarum, per densitatem spinarum, duodecim trabes (tot enim necessariæ erant) in admirationem omnium præsertim circumstantium assignavimus, et ad basilicam sanctam deportatas cum exultatione novi operis operturæ superponi fecimus, ad laudem et gloriam Domini Jesu, qui sibi sanctisque Martyribus, a manibus raptorum protegens, sicut facere voluit, reservaverat. Nec igitur superflua, necque minus continens id circa divina extitit largitio, quæ in pondere et mensura omnia moderari, omnia dare constituit, cum ultra quam oportuit nulla ulterius inveniri potuerit. — Sugerii, *De Consecratione*, ed. A. Lecoy de la Marche, *Œuvres complètes de Suger*, Paris, Renouard, 1867. 8vo., p.p. 221–222.

[1] *Architecture religieuse dans l'ancien diocèse de Soissons.* Paris, Plon Nourrit & Cie., 1894. Folio. Vol. II, p. 222.

[2] This fact, which has been denied, I have tested by measures on the spot.

The rib vault of the porch at Moissac, Tarne-et-Garonne (Fig. 18), was peculiarly constructed. The diagonals, .70 meters broad, are composed, not of a single set of voussoirs, but of jointed masonry. The stereotomy of this masonry at the intersection makes it evident that both diagonals were erected at the same time, not one before the other as was usual (Fig. 17). The vault has heavy wall ribs in two orders, but is not domed. The builders have, however, found a substitute for doming in a new expedient. The diagonals are heavily loaded with a new set of voussoirs at their haunches; this superimposed masonry dies away toward the crown and the springing. While undoubtedly intended in part as a buttress to protect the vault against any possible upward rupture caused by the not inconsiderable thrust of these clumsy diagonals, this loading had another purpose as well. It considerably increased the curve of the vault surface and hence facilitated construction without centering.

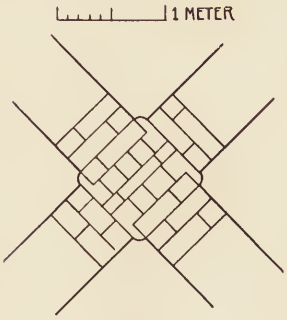

Fig. 17

The rib vault of Ste.-Croix at Quimperlé, Finistère, (Fig. 22), was similar in type (at least as far as it is possible to judge from the modern copy, which is all we have left to study it by), except that the diagonals were not loaded. This vault is notable because of its considerable size (7.36 x 6.46 meters), and the height at which it was erected. Groin or barrel vaults were used elsewhere in the church, and I was long puzzled as to why a rib vault should have been chosen only for the cupola. The fact, however, has a perfectly simple explanation. This cupola was originally surmounted by a tower. It would have been exceedingly difficult to erect a vault on a solid centering in such a position. Not only would much labor have been wasted in transporting the material to be used, since this would have had to be first raised to the roof, then transferred to the top of the tower walls, and finally lowered again to the vault where it was to be employed — but it would also have been a very delicate task to shape from above a wooden centering to the form desired. In a rib vault, however, these difficulties could be avoided, since the absence of solid centering made it possible to preserve an opening of communication between the extrados and the floor below until the very moment of the completion of the vault. The masons could hence work from below instead of from above. For this reason rib vaults were preferred to other forms under towers, not only at Quimperlé, but in many transitional edifices of the Ile-de-France.

Much more skillfully executed is the vault of St.-Victor of Marseille (Fig. 20). Here the diagonals are much reduced in width and have only a single set of voussoirs. One diagonal was constructed before the other, as the stone-cutting at the intersection proves, since one is a continuous arch against which the two half

Fig. 18. St. - Nicolas, Moissac, (Tarn-et-Garonne). Vault of Narthex.

Fig. 19. Cathédrale, Fréjus, (Var).

Fig. 20. St. - Victor, Marseille. Vault of Porch.

Fig. 21. St. - Guilhem-le-Desert, (Hérault). Vault of Narthex.

arches of the other abut. The vault is slightly domed, and wall ribs are employed. This is the earliest vault in France that I have observed, where larger stone courses are used in the part which is below the point where the use of a cerce became necessary. It was hence obviously erected without solid centering. The diagonals, it is true, tend to disappear, but this fact is easily explained. In the upper part, where the vault required centering, the diagonals are not submerged, and were made use of in the construction of the vault. Towards the springing the rib was submerged a little in the massive, as could easily be done where the stones of the vault were self-supporting, to accommodate the springing of the vault to the profile of its somewhat clumsy supports.

At St.-Guilhem-le-Desert, Hérault, there is a rib vault (Fig. 21) of a different type, which, however, exemplifies precisely the same principles. The vault is not domed, but its restrained dimensions (4.30 x 4.90 meters) and the thick strong mortar employed, together with the wall ribs (which although they die away, supported the centering at the critical points) made possible its construction without solid centering.

Much more skilfully constructed are the vaults of the cathedral of Fréjus, Var (Fig. 19), which are probably also the earliest rib vaults extant in France, erected over a nave. The compartments are nearly square, but the vaults are more domed in the transverse than in the longitudinal direction, a peculiarity thoroughly Italian. The transverse ribs have a decidedly horse-shoe form, while the diagonals and wall ribs are approximately semicircular. The wall arches die away towards their springing as at St.-Guilhem-le-Desert. The masonry courses tend to radiate towards the key-stone, the earliest example of this expedient I have observed outside of Italy. These vaults, remarkably similar to those of Corneto-Tarquinia, were evidently erected by builders in full possession of the Italian tradition. The builders had also studied to advantage the Roman ruins in which Fréjus is so rich, as is shown by the fact that the ribs of the vault are received on a heavy pilaster, or spur wall, which really forms an effective buttress. Thus it becomes evident that the masons of Fréjus, in their efforts to erect vaults economically and scientifically, besides studying Roman methods of buttressing, had imported from Italy the rib vault, entirely extraneous to the local style of the Riviera; and that they had done this because that form offered over all the others the great structural advantage of not requiring a solid temporary centering.

The French master-builders were not slow to perceive the fact that doming greatly facilitated the construction of a rib vault without solid centering. The expedient timidly tried, as we have seen, at Rhuis and at St.-Victor of Marseille, was boldly applied at Fréjus and at Ste.-Croix of Quimperlé. It was soon taken up and carried to an almost exaggerated extent by the builders of the Ile-de-

France, who studied to give their vault surfaces the greatest inclination possible. Thus at Bellefontaine, Oise (Fig. 23), the diagonals are pointed. At Bury, Oise, the opposite expedient is tried in the side aisles for the purpose of producing the same effect, i.e., of avoiding horizontal surfaces in the vault. The curve of the diagonals is depressed, the main arches are pointed, the transverse arches stilted, pointed, and loaded (Fig. 24). Thus the intersection of the diagonals is lower than the crown of the main and wall arches but higher than that of the transverse arches. So horizontal surfaces are reduced to a minimum.

While the principle of doming was thus taken up enthusiastically from the first, the French builders were slow to recognize the advantages of wall ribs, which continued to be frequently dispensed with until a comparatively late epoch of the transition. In Italian monuments of the XI and XII centuries, wherever vaults are constructed of bricks, wall ribs are invariably employed, even when diagonal ribs are omitted; in vaults constructed of stone, on the other hand, wall ribs are invariably lacking. Since in France vaults are always constructed of stone, I suspect that this circumstance is not without bearing upon the fact that wall ribs were frequently omitted, and that the latter were considered less necessary in ashlar than in brick constructions. Nor is the reason hard to see. When wall ribs are omitted, it is necessary to cut the inner facing of the wall to the form of an arch, so that the vault may rest upon the ledge thus formed. In brick constructions this process is tedious, since a great quantity of bricks, all normally rectangular, must be cut to the required form. In ashlar constructions, on the other hand, the stones must be cut in any event, and, since they are larger than bricks, a far smaller number need be given an irregular form. Moreover, a wall rib in brick may be constructed without centering by the Byzantine method, whereas it is exceedingly difficult to erect in this manner a wall rib in stone, since the weight of the voussoirs is more than the adhesion of the mortar suffices to support. For these reasons in the early period vaults in bricks were constructed with wall ribs, and vaults in stone without wall ribs. Gradually, however, the advantages of the wall rib, which held the vault against the wall without cutting its surface and hence weakening it, came to be appreciated, and wall ribs were universally adopted even in ashlar vaults.

From the peculiarities of rib vaults above enumerated, and from many others which might be adduced, it is evident that economy of centering was a primary consideration with the builders of the transitional and Gothic periods. The principle, it is true, was sometimes violated, especially in the outlying provinces; it was occasionally modified even in the Ile-de-France. But these exceptions only make clearer the force of the rule, that the great advantage of the rib vault, the reason it was adopted by the medieval builders, was the fact that it could be constructed without solid centering.

Fig. 22. Ste. - Croix, Quimperlé, (Finistère).

Fig. 23. Prieuré, Bellefontaine, about 4 kilometers from Nampcel, (Oise).

Fig. 24. Sts. - Pierre-Jacques-et-Lucien, Bury, (Oise). North side aisle.

Fig. 25. Notre-Dame-du-Port, Clermont-Ferrand, (Puy-de-Dôme). North side aisle.

The most conspicuous examples of ribs not used as centering are found in the churches of Anjou, where, as is well known, ribs were applied, almost ornamentally, to vaults essentially domes in their character. Similarly in Normandy vaults were constructed often of very small and odd-shaped stones laid in irregular courses that even change their direction at right angles. In churches that are still open to the cult such vaults are almost invariably covered with stucco, so that it is impossible to study their structure; in the ruined abbey of Hambye, however, certain vaults are exposed in which the utterly irregular character of the courses makes it evident that a centering must have been employed. In England all sorts of additional ribs, dividing up into small compartments the space to be vaulted, were introduced. This was merely carrying the French system one step further, but the extra ribs ended by degenerating into mere ornament, largely owing to the fact that the introduction of ridge-ribs made it necessary that the doming of the vaults should be abandoned. These and other similar instances of later vaults constructed with centering are merely isolated examples of peculiar constructions; throughout the Gothic period the rib vault continued in general to be erected without solid centering.

The desire to dispense with solid centering was doubtless the reason for the adoption of the rib vault by the French builders in the transitional period. Previous to its introduction, they had discovered no means to erect vaults without wooden substructures. The familiar hollow spires of Loches erected on the corbel principle are the most conspicuous attempt at such a construction that I know, but these are a comparatively late experiment and not a very happy one. In Auvergne and Normandy are common groin vaults which instead of being domed are depressed at the center (Fig. 26). This form was probably designed to concentrate the thrust on the groins and relieve the transverse and longitudinal arches. I have never found any evidence that such vaults were constructed without centering, although their form would permit of it.[1] Such as I have observed are of orderless rubble, and consequently must have been constructed on a solid centering, which it is much easier to shape for a vault of this sort than for a domed groin vault (Figs. 25, 28). Ribs were often applied to barrel vaults, as in the choir of Vieils Maisons, Aisne (Fig. 27). In such vaults, however, the ribs could not have been serviceable as centering and must have been useful solely to strengthen the vault and prevent any possible deformation. Thus it becomes evident that of the various forms of vault known to the transitional builders at the time they adapted the rib vaults, the latter only could be erected without solid centering. Domed groin vaults form the only exception to this

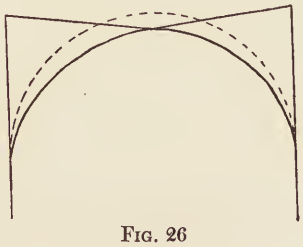

Fig. 26

[1] See what has been said above of Bury.

rule. Such vaults were never common in France, but isolated examples of the construction exist. The vaults of the side aisles at Morienval are modern, but are probably correctly restored as domed. The groin vaults of the crypt of St.-Medard at Soissons are also domed. These and other instances show that the French builders became acquainted at about the same time with both the Lombard methods for reducing centering. They seem to have consistently preferred the rib to the domed groin construction, however, even over small areas; and the reason was doubtless that the rib construction adapted itself better to stone, the building material universally employed in France. Stones being heavier than bricks placed a greater weight on the centering underneath the groin during construction; hence it was desirable to make this centering a rigid stone arch rather than a flimsy wooden sub-structure.

That the ribs of a rib vault, especially in the Gothic period, came to assume other functions besides that of serving as a centering during the construction, is not to be denied, grossly as the importance of these functions has been exaggerated by certain writers. The ribs doubtless materially strengthened the groins, which are the weak point of the vault surface; they also tended to prevent deformations, removed all danger of the cells slipping, and re-enforced the angle joints. Once completed, however, the vault was no longer absolutely dependent upon them for its stability, and in the majority of cases it is probable that the ribs could be removed from beneath Gothic vaults without injury to the vaults themselves.

In the ruined abbey of Longpont, Aisne (Figs. 29, 30, 31, 32, 35), there are vaults whose massive still stands although the ribs have fallen from beneath them. Groin vaults can be self-supporting and sufficiently strong as every one knows (Fig. 34); hence the one great advantage of the rib over the groin form was its greater ease of construction.

A similar consideration was undoubtedly an important factor in causing the Gothic architects to adopt the pointed arch, since this form contains more vertical and less horizontal surfaces than a round arch. It can consequently be erected with lighter centering. And in Gothic pointed arches the joints do not radiate towards the center, the voussoirs being cut normal to the intrados or even less (Fig. 32). Consequently the weight of each stone, even during construction, was carried largely by the one below it instead of by the centering.

Thus every detail of Gothic rib vaults was governed by strict logic of construction and disposed with a view to the greatest possible economy of centering. This same generating principle caused the introduction of the rib vault in the Ile-de-France in the transitional period; governed each new form that was given it, every peculiarity that it assumed; and finally, through the perfection of the rib vault, led to the invention of Gothic architecture. It is evident that this process of construction is of the gravest importance for the

Fig. 27. St.-Croix, Vieils-Maisons, (Aisne). Choir.

Fig. 28. St. - Nicolas, Caen, (Calvados). South side aisle.

Fig. 29. Abbaye, Longpont, (Aisne).

Fig. 30. Abbaye, Longpont, (Aisne). South side aisle.

Fig. 31. Abbaye, Longpont, (Aisne). South side aisle.

Fig. 32. Abbaye, Longpont, (Aisne). North side aisle.

Fig. 33. S. Felice, Cimitile, (Caserta), Crypt.

Fig. 34. St.-Morent, Margival, (Aisne). Crossing.

Fig. 35. Abbaye, Longpont, (Aisne). Vaults of north side aisle.

Fig. 36. Abbazia, near Sesto Calende, (Milano). Crypt.

history of art, and is one with which the student of medieval architecture must seriously reckon.

V

A STUDY of the process of construction throws an equal light on the early rib vaults of Lombardy. It was in Lombardy that this type of vault originated, and when the method of construction which we have learned from a study of the French vaults is borne in mind, it is easy to trace the various steps in the evolution of this motive, so significant for the history of medieval art. The Lombard monuments will also furnish the clearest sort of proof that the rib vault originated in the desire to economize centering, and was ever employed with this single end in view.

Whereas in France during the Carlovingian and Romanesque periods there had been only one method employed for constructing vaults, that of solid centering, in Lombardy on the other hand, from the VI century to the XIII, there existed side by side two traditions: the Byzantine, by which domed groin vaults, usually with wall and transverse ribs, were constructed on a light centering; and the Latin, by which undomed groin vaults, barrel vaults and cupolas were erected with the aid of a complete centering.

To prove the survival of the Byzantine type during the dark ages, it is sufficient to cite the domical groin vaults of the eastern bays of the side aisles of Agliate (Milano),[1] and the groin vault that covers the nave of S. Fedelino on the lake of Mezzola.

Of the Latin tradition we find examples in the eastern bays of the side aisles of S. Ambrogio at Milan, and in S. Satiro of the same city. Moreover, a great number of crypts of the VI to X centuries throughout Italy are covered with groin vaults erected on a curious principle that requires a word of explanation. At S. Salvatore of Brescia, it will be remembered, the columns of the crypt bore arches; these arches carried walls, parallel the one to the other, on which were placed slabs of stone forming the pavement of the choir. That is, the crypt was not vaulted at all, but covered with a series of lintels supported on arches. Such a system is the basis of the construction of a vast number of crypts erected throughout Italy not only during the dark ages, but in the eleventh and twelfth centuries. The state of ruin into which has fallen the crypt of S. Felice at Cimitile (Napoli) makes it easy to understand the construction. Here arches were sprung from every column in four directions, and the wall continued upward above them (Fig. 33). Then in the quadrangles so formed were built on centers groin vaults, merely stuck on to the sides of the walls above the arches. On the abaci of the capitals, the vaults nearly or quite submerged the arches, there not

[1] These have been restored but apparently in their original form.

being sufficient space for these to project; near the crown, on the other hand, the arches were very salient. Transverse ribs thus dying away towards the springing are found for the first time, I believe, in the transept ends of the tomb of Galla Placidia at Ravenna, but they were here used in connection with a barrel, not a groin vault. The motive was of great effect used decoratively, and, applied to arches, became characteristic of the Lombard style of the XI and XII centuries — witness Santa Maria Maggiore of Lomello, and S. Savino of Piacenza. As the transverse arches died away towards the springing, the groin in its lower part was worked to a sharp point to carry up the angle of the capital. In certain instances, especially in later crypts such as those of Gravedona or Sesto Calende (Fig. 36), the vaults are domed, and were probably constructed without solid centering; the massive may even be carried on the arches which in that case would become ribs. But wherever I have been able to study the earlier vaults (in the majority of cases it is of course impossible to investigate without damaging the building) the construction is like that of Cimitile, i.e., the vaults are not carried on top of the transverse arches but are merely plastered against them. Whether constructed with or without centering, such are not true Byzantine vaults.

Barrel vaults, cloistered vaults, and half domes were, I believe, generally constructed on centering, not only during the dark ages but in the XI and XII centuries as well. The structure of most of them is unfortunately inaccessible, but those I have been able to observe seem to be constructed of loose materials laid in such a way as to preclude the possibility of construction without centering.[1]

Early in the XI century new principles of construction came to be adopted by the Lombard master-builders. Scarcity of wood seems to have been the cause which induced the architects to abandon the traditional methods of the Carlovingian builders. A veritable architectural revolution ensued, of which, however, we have here to speak of only one phase, though that, perhaps, the most significant — I mean the practical construction of vaults.

If we survey those monuments of the XI and XII centuries which are commonly designated by the term Lombard, we observe that the geographical distribution of the school is peculiarly irregular. The churches of Corneto-Tarquinia on the southern confines of the Maremma resemble those of Milan much more closely than do those erected at Como only some forty kilometers distant. Such a state of affairs is entirely different from conditions in France, for example,

[1] In the illustrations, Figs. 37, 38, 39, 40, 41, 42, 43, I give a series of photographs illustrating the types of vault above described, and especially the parallel use of domed and non-domed groin vaults in crypts and other portions of the edifice in monuments from all regions of Lombardy from the VIII to the XII century. Since the photographs speak sufficiently clearly for themselves, it will not be necessary to describe them.

Fig. 37. S. Pietro al Monte, near Civate, (Como). Crypt.

Fig. 38. S. Teodoro, Pavia. Crypt.

Fig. 39. S. Stefano, Lenno, (Como). Crypt.

Fig. 40. Duomo Vecchio Brescia. Crypt.

Fig. 41. S. Maria del Solario, Brescia. Vault in crypt.

Fig. 42. Madonna del Castello, Almenno S. Salvatore, (Bergamo).

Fig. 43. S. Vincenzo, Galliano, near Cantù, (Como). Crypt.

where all the contemporaneous monuments of a given region closely resemble each other and form a local school. The explanation is that, whereas in France, a country of broad flat uniform plains, in any given province the building materials available were about the same everywhere, in Italy, cut up by mountains into regions of varied geological character, they differed widely, even in localities not far removed one from the other. The development of Lombard architecture was determined by the materials the builders found available.

Lombard buildings were constructed of brick, stone, and wood. According as one or the other of these materials was superabundant or failing, the architecture shaped itself. It was to dispense with wood that the builders sought to erect vaulted edifices. The proofs are many. At Como and in other localities at the foot of the Alps where wood was abundant, vaulted construction was long avoided and never more than partially adopted. In the whole province of Como not a single vaulted Romanesque church has come down to us, and doubtless none was ever erected.

During the XI century, this school, which has been suspected of being the center from which radiated the influence of the Lombard master-builders, was notably behind all the neighboring schools in regard to everything that touches vaulted construction. Moreover, the hard, flint-like stone which was the building material usually adopted in this region, was quite unfitted for the construction of vaults, being too hard and brittle to be shaped accurately into voussoirs or even into regular courses.

In all the Lombardy plain, however, throughout that vast triangle the sides of which are determined by the Alps, the Apennines, and the Adriatic, brick was the building material which the builders found themselves forced to use. This vast alluvial region is practically without stone, while clays for terra cottas and bricks abound. Wood is scarce, and even to-day is employed with parsimony.[1] In the XI century it is probable that trees were as scarce in the neighborhood of Milan as they are now. Moreover, in those times it was not easy to import timber. The frequent wars with the surrounding city states must have totally interrupted for long periods any peaceful commerce; the roads were doubtless very bad; and means of transportation aside from the most primitive there were none. We can imagine therefore that at Milan the price of wood was so high as to be well-nigh prohibitive. The architects had to find a means of roofing their edifices with bricks, and of erecting vaults without the use of elaborate

[1] The fires which devastated Milan in 1071 and 1075 were doubtless fed by the thatched roofs with which the houses in that epoch were covered. That brick was commonly employed to construct the walls of even modest edifices in Lombard towns during the XI and XII centuries is demonstrated by the heaps of brick still existing at Lodi Vecchio. Medieval diplomas make frequent mention of woods which were evidently regarded as exceedingly valuable possessions. It is probable that the trees were seldom allowed to grow large enough to supply timbers for a church roof.

centering. To do this they had recourse to the rib vault. They dispensed in many cases even with the wooden roof over their vaults which the French builders almost invariably used. In the Annunziata of Corneto-Tarquinia a solid bed of mortar is laid on the upper surface of the vaults and is worked to the form of a gable on which the tiles are laid directly. At S. Savino of Piacenza, before the lamentable restoration, the vaults supported a series of brick arches which carried the tiles without the use of any wood. That the builders thus carried their saving of wood so far as to place all this vast weight, in a most dangerous and daring manner, directly on the great vaults, which even without extra charge were insufficiently buttressed, shows that economy of wood was carried to the last degree. At Modena, where wood was probably not so costly, perhaps because of forests still existing in the Apennines,[1] the cathedral of the XII century was roofed in wood; at Bologna, where wood was scarce, vaults quite similar to those of Milan were erected much earlier in the church of Santo Stefano.

Corneto-Tarquinia stands in the midst of a plain on which grows no timber. Even to-day the poorest houses are vaulted; wooden ceilings are unknown. On the other hand there is an abundance of stone, easily cut, in every way adapted for building. The builders eagerly abandoned the wooden-roofed basilica, to substitute therefor Lombard rib vaults easily erected with a minimum centering (Fig. 45). Thus it is evident that the scarcity of timber in certain parts of Italy drove the builders to adapt vault construction and discover devices to erect vaults without the use of wooden centering.

Milan and the plain about it was evidently the center in which was developed and from which radiated the new method of construction. It took the better part of a century to perfect the system, and the goal was arrived at only by a long series of experiments with many hesitations and even back-slidings. The first step was to apply the Byzantine domed rib vaults, the tradition of constructing which with light centering had never, as we have seen, died out, to the side aisles. Next transverse arches were thrown across the nave. By means of these arches the heavier timbers that would otherwise have been required for the roof could be dispensed with. As early as c. 1025 we find that the art of building had already arrived at this point at Lomello. The third step was to vault the nave. It must be remembered that to do this with centering offered no difficulty for the Lombard builders. Even in the IX century the choirs of S. Ambrogio of Milan and of Agliate had been successfully barrel-vaulted. But the point was to build the nave vaults without centering, or rather with a light and inexpensive one. At Stradella it was evidently the intention to erect such groin vaults on a very oblong plan. With a Byzantine domed groin vault, it was almost as easy to cover an oblong as a square plan, one of the great advantages of this system, with

[1] See the diploma of Berengar I, 899 ed. Muratori A. I. M. A., ed. A. IV, 279.

Fig. 44. S. Ambrogio, Milano.

Fig. 45. S. Giacomo, Corneto-Tarquinia, (Roma).

Fig. 46. S. Savino, Piacenza. Nave.

its absence of wooden mould, being its superior flexibility. In earlier times, when vaults were confined to crypts and side aisles, they had been, as a matter of fact, usually erected on a plan approximately square; but when the builders had need of an oblong vault they did not hesitate to build it. It was not the shape, but the size of the nave vaults which caused the difficulty, for it was a delicate task to erect on a cerce the long courses necessitated by vaults of such dimensions. The vaults at Stradella, though projected, were never erected; nor is there proof that during the XI century any similar vaults were ever executed.

At Sannazzaro Sesia, in 1040, however, the nave was actually vaulted, the vaults having a full set of ribs including diagonals. The reason for the introduction of ribs in these nave vaults it is easy to see. Owing to the considerable size of the nave and the weight that had to be carried by the centerings under the groins during execution, it was found that if a groin vault was to be erected these centerings must be made heavy and cumbrous. It was less expensive to erect a light wooden arch, sufficient to serve as centering for the heavy brick diagonals; these once erected served as a firm and sufficient centering for the vault. Moreover, after the vault was completed, the ribs strengthened it, prevented cracks at the groins, and tended to oppose deformation, precisely as do the ribs of a French vault. The motive once found for structural reasons seems to have pleased æsthetically also; at any rate, rib vaults were introduced in the returned aisle of Sannazzaro Sesia and in the narthex of S. Ambrogio, although the spaces to be vaulted were no larger than in the groin-vaulted side aisles.[1]

There remained only one further step to be taken in the development of the Lombard style, that of combining the rib vault as developed at Sannazzaro Sesia with the alternate system as developed in connection with the transverse arch at Lomello, Calvenzano, and Lodi Vecchio. The advantages of this combination (Fig. 46) were two-fold. In the first place it made it possible to vault the space comprised by two bays with four centerings (erected under the various arches) instead of the seven that would otherwise be required. In the second place it raised the crossing of the diagonals considerably (the arches all being semicircular), thus giving the vault surface a more domical form and one consequently easier

[1] Nevertheless the rule holds that the Lombards never adopted the rib vault with enthusiasm. There is not extant a single Lombard church where it is used throughout. In general, wherever the builders dared, they omitted the diagonal ribs. Thus the side aisles were always covered with groin vaults, and rib vaults were at a comparatively early date abandoned even in naves. At S. Savino of Piacenza, the two eastern bays of the nave are rib-vaulted, but the later western bay has a groin vault. The builders appear to have abandoned rib vaults the moment they dared to construct domical groin vaults (which also did not require centering) of the required size without diagonal ribs. Thus it was the knowledge of how to construct groin vaults without centering — a knowledge which the French builders did not possess — that prevented the Lombards from developing to its utmost possibilities the rib vault.

to construct. On the other hand, the courses between the diagonals and the transverse ribs became longer, but no longer than those between the wall arches and the diagonals in either case. The first extant monument where this system is applied is S. Ambrogio of Milan (Fig. 44).

The wars of the XII century, culminating in the destruction of Milan in 1162, were fatal to the development of Lombard architecture, and there are scarcely enough monuments extant at Milan to enable us to trace the causes of the decline into which it fell. Probably lack of abutment for the vaults was the principal one, and that which prevented the Lombard builders from anticipating the discovery of Gothic. The thrust of vaults they seem never to have fully understood, nor to have realized that the resultant of the thrusts of a vault is a curve, and that consequently piers supporting a vault should be stepped outwards towards their base. Buttresses are sometimes applied to the outside walls, it is true, but they are never sufficiently developed for a structure in brick. The abutting walls built across the transverse arches of the galleries to reinforce the nave vaults were always used in an illogical manner; they appear to have been copied from Roman edifices without much understanding of their real function. At S. Ambrogio they seem to have been originally applied to each bay indifferently, although the system was alternate; at S. Savino of Piacenza, Sagra S. Michele, and Rivolta d'Adda, they were placed with something more like caprice than intelligent experiment. The Lombard builders were logical as a rule, almost as logical as the early Gothic architects, and I realize that it is dangerous to reproach them with inconsequence merely because their aims are not clear. In this case, however, the result seems to justify the charge, for their vaults have proved almost without exception to be insecure. Even the use of tie-rods in wood and metal — a tradition inherited from the Byzantines — has failed to hold them together. In only two points have I observed anything like the subtle understanding of the principles of equilibrium which guided the northern architects. One is found at S. Ambrogio, Calvenzano, and in certain other edifices where the alternate system is used, and consists in making the responds of the side aisles alternately heavier and lighter. The builders have evidently reasoned out that the thrust against the alternate piers is transmitted across the buttressing vaults of gallery or aisle and ends by being exerted against the outside wall, which is accordingly strengthened at the critical point. The builders of the cathedral of Paris, nearly a century later, made the same observation. The Lombard builders, however, did not perceive that it would have been better to strengthen the outside, rather than the inside, face of the wall.

The second point of subtlety was the use of wooden chains in the walls. This is an old Byzantine tradition, admirable in theory but not always successful in practice. Indeed, Mr. de Dartein has showed how disastrous its effects frequently

were in Lombard buildings. Wood is a perishable material, which in the course of time rots and disappears. If then the masonry actually rest upon it, so that the disintegration of the wood be liable to cause weakness or lesions, the construction is vicious. If, however, it be comparatively so small a part of the wall area that this is sufficiently strong when the wood has disappeared, the construction is ingenious and admirable. These wooden chains are in this case merely designed to bind the masonry together and prevent cracks during the period in which the freshly laid mortar is liable to compression and the masonry to unequal settlement.

About the year 1120 rib vaults of the true Lombard type, such as we find at S. Ambrogio, seem to have passed out of use. Since they had been found unstable, many builders returned to the old wooden roof, usually supported on transverse arches; those who were still forced by the scarcity of timber to use vaults, discovered that by making the shells very thin, groin vaults could be erected, even over a nave, on a very light centering. The ribs, therefore, were much reduced in size (S. Pietro in Ciel d'Oro of Pavia) and finally abandoned altogether (S. Lanfranco of the same city). Moreover, with the constructive skill the builders had now acquired they became quite indifferent to the economical advantages of a square plan, and learned to construct vaults on oblong plans with almost as light a centering. So the alternate system came to be gradually abandoned.

The history of the rib vault in Lombardy proves, therefore, that this construction originated as a modification of the domed groin vault erected without solid centering; that the diagonal ribs were added merely to facilitate the construction of vaults of large dimensions; and that rib vaults were employed only in those regions of Italy where wood was rare and expensive, vaults erected on a full centering being employed elsewhere.

Thus it is clear that the striving to economize wooden centering in the construction of vaults, plays a very important role in the history of medieval architecture. The Romans displayed great ingenuity in devising means to accomplish this end, erecting centerings which were not merely temporary, but part of the completed vault; the Byzantine architects with the same object in view invented the domed groin vault, which became known in Italy from an early period and continued in use, together with other types of vault constructed on solid centering, throughout the Carlovingian period. In the XI century the scarcity of wood in the Lombard plain led to the invention of the rib vault and its introduction in the naves of certain churches, since the construction of domed groin vaults in such a position exceeded the skill of the early builders. Only exceptionally was the rib vault employed except over naves. It was never adopted in those regions of Italy where wood was abundant, and was generally

abandoned when other means of erecting nave vaults without centering were discovered. The desire to economize centering led the French builders to adopt the Lombard rib vault in preference to the other forms of vault to them known, all of which required solid centering. Applied at first generally beneath towers, in ambulatories, or in other positions where a solid centering was especially inconvenient, it came gradually to supplant all other types of vault. As a direct result of its development arose that new architecture which is called Gothic. Throughout the Gothic period rib vaults continued, save in exceptional cases, to be erected without solid centering.

Evidently the fact that rib vaults were thus constructed is one of no mean importance for the history of art.

APPENDIX

ONE of the chief advantages of the rib vault was the fact that it could be applied not only to quadripartite rectangular spaces but equally well to irregular plans, to the trapezoidal compartments of an ambulatory or annular gallery, to the semi-circular vault of an apse, or to the polygonal vault of a chevet. It also lent itself with facility to the sexpartite form of a vault. The warped and ungeometrical surfaces of any of these irregular types of vault would have rendered exceedingly difficult and expensive their construction on solid centering. The system of ribs, on the other hand, adapted itself with ease to such constructions. Building free-hand and without centering, the masons were able to depart from geometric forms at their will.

The experiments of the French builders with vaults of such types have been so often described that they need here only be referred to. Every student of medieval art is familiar with these typical forms of Gothic architecture and is aware of the ease and fluency with which the architects finally learned to construct them. It was only the fact that such vaults could be erected without centering that made Gothic architecture possible. This point can not be illustrated more forcibly than by a study of the annular vaults erected in those parts of Lombardy, where, owing to the abundance of timber, the builders had not adopted the rib vault. I shall describe in some detail in this Appendix a series of such constructions, since they make it evident that rib vaults were employed only to economize centering, and were seldom if ever introduced merely with a view to increasing the elegance of the design. From these vaults it will also be possible to illustrate the fact that the Lombard builders often used simultaneously the two methods of construction: that with, and that without, a solid centering.

The vaults of the ambulatory of Santo Stefano at Verona (Fig. 48) are the oldest annular vaults of Lombardy that I know. They have been modernized, but not so completely that their original form can not be recognized. The ambulatory is divided into rectangular compartments by means of wedge-shaped transverse arches, really triangular barrel vaults. The rectangular spaces were covered with domed groin vaults erected without centering. The crypt of the ambulatory is covered with a barrel vault and with one groin vault at the east end, all erected with centering (Fig. 47).

In the Rotonda of Brescia the arrangement is different. The circular aisle is here broken up, on the plan instituted at Aachen, into alternately triangular

spaces, by transverse arches (Fig. 49). The rectangular spaces are covered with slightly domed groin vaults, which cover the wall and transverse ribs towards their springing. These vaults seem to have been constructed without solid centering, precisely like the ambulatory vaults above described. Although the ribs disappear, they probably have a structural function.

In the church of S. Tommaso of Almenno the side aisle and gallery are both vaulted. In the side aisles transverse arches reach from each capital to the side aisle responds. Those arches are much stilted, as are also the arches of the main arcade; the wall arches, supplied with ribs, are much depressed; the groins are also depressed and sometimes curved in plan (Fig. 50). Obviously a distorted and awkward surface such as this could only have been vaulted by the use of a solid board centering, and in this case the traces of this centering are still clearly preserved in the plaster. The transverse ribs, which tend to die away towards the springing, and the wall ribs must have had a merely decorative purpose. In the gallery (Figs, 51, 52) the vaults are of a different type, being inclined outwards. This very probably was done partly to buttress the dome, partly to adapt their extrados to the form of the roof it must carry. The capitals of the responds are placed lower than those of the columns facing the nave, so that the transverse ribs acquire a curiously distorted form. The wall rib, being much depressed, has its crown at a level much lower than that of the transverse and arcade arches. By a distortion, apparently made purposely, though its reason is difficult to understand, the highest point of the transverse arches is thrown at a point nearer the outer than the inner wall. The groins, however, though broken, tend to intersect at a point which is very near the inner edge of the vault. The transverse arches thus seem to sink into the surface of the vault at its outer edge, and would be totally submerged, were not the space hollowed out, as it were, to receive them. The vaults here too bear undoubted signs of having been erected on a wooden centering. How difficult to erect and expensive such a centering must have been, even in a small edifice situated in a region where wood was abundant, need not be insisted upon.

Vaults of this type were carried to their perfection in the galleries of the transept of S. Fedele, Como (Fig. 53), where the sloping vaults are used in connection with compartments alternately triangular and rectangular, as in the Rotonda of Brescia. But the transverse arches are not distorted, their inner extrados being loaded to bring them up to the level of the sloping vaults. The vaults are extraordinarily thin, being only six inches in thickness, and were doubtless constructed in this manner to make it possible to lay the slates of the roof directly upon them, as well as to transmit to the outer walls the thrust of the great half domes of the transept ends. They were erected with solid centering; indeed it is very rarely that the builders of the province of Como dispensed

Fig. 47. S. Stefano, Verona. Ambulatory of crypt.

Fig. 48. S. Stefano, Verona. Ambulatory.

Fig. 49. Duomo Vecchio, Brescia. Side aisle.

Fig. 50. S. Tommaso, Almenno S. Salvatore, (Bergamo). Side aisle.

FIG. 51. S. Tommaso, Almenno S. Salvatore, (Bergamo). Gallery.

FIG. 52. S. Tommaso, Almenno S. Salvatore, (Bergamo). Gallery.

IG. 53. S. Fedele, Como. Gallery of north Transept.

FIG. 54. S. Pietro, Asti, (Alessandria).

Fig. 55. S. Flaviano, Montefiascone, (Roma). Vaults of north side aisle.

Fig. 56. Cattedrale, Aversa, (Caserta). Ambulatory.

Fig. 57. S. Sepolcro at S. Stefano, Bologna. Side aisle.

with this aid. These are the most elegant annular vaults of the Romanesque period extant in Lombardy.

In S. Pietro of Asti we have a church which shows in its ornamental features considerable influence of the school of Milan. The vaults of the annular aisle were not, however, supplied with diagonal ribs. The arches of the main arcade and of the transverse ribs are stilted and die away in their lower parts; the groins become correspondingly sharply accentuated as they approach the supporting capitals. The number of supports is equal in the exterior and interior perimeter. The vaults have been modernized, but the very shape of the compartments proves that they could not have been erected without solid centering (Fig. 54).

Doubtless of entirely similar construction were the vaults of the aisle of San Sepolcro (Santo Stefano) at Bologna (Fig. 57), but these two, unfortunately, have been made over to such an extent that it is impossible to determine their original form. Owing to the irregular plan of this edifice, the compartments to be vaulted are more irregular than those at S. Pietro of Asti, and certainly a solid centering must have been employed.

From these instances it will be seen that the Lombards never succeeded in erecting groin vaults over annular galleries or ambulatories without centering, except when, as in Santo Stefano of Verona or the Rotonda of Brescia, they had recourse to the expedient, not particularly successful, of dividing the space to be vaulted into compartments alternately rectangular and triangular. When this was not done it was necessary to employ a solid centering. However, by the use of ribs it was possible to erect vaults over a trapezoidal space without the use of centering.

To the extent of my knowledge there is extant in Northern Italy no example of the use of diagonal ribs to simplify the construction of annular vaults. That is not to say, however, that such a construction was never employed. At least in Southern Italy, in edifices evidently built in more or less exact imitation of Lombard models, the desire to economize centering in the erection of vaults over annular aisles seems to have led to the adoption of rib vaults in two important instances, the cathedral of Aversa and S. Flaviano of Montefiascone. In both, when the ribs had once been constructed, the remainder of the vault was erected by the aid of a simple cerce. Such a method of construction was doubtless far easier and less expensive than a solid centering, especially in a country where wood was scarce. In these early examples, which make one think of the early transitional vaults of France, the builders had not skill enough to make the most possible out of the system. At Aversa (Fig. 56) the ribs are straight in plan, hence intersecting out of center, enormously heavy, and the whole construction is clumsy. The later ambulatory of Montefiascone (Fig. 55) introduces triangular compartments, has ribs which are broken in plan and much lighter, some

even being given a round profile. The builders had evidently progressed some distance on the road which leads towards Gothic, but no further experiments along this line seem to have been made in Italy.

Corneto-Tarquinia (Provincia di Roma) affords another interesting example of the use of ribs to economize centering in the erection of a vault. Ribs were applied to the half dome of the apse of Santa Maria di Castello (Fig. 62). These ribs once built, the remainder of the vault could be constructed without further centering, for in this case the ribs tend to converge towards the key-stone where the construction became more difficult. The same expedient, it will be recalled, was resorted to by the builders of Northern France (Fig. 59). The French builders, to facilitate the placing of the windows, gradually lobed and raised the compartments until the Gothic chevet vault resulted. But in Italy this step was never taken.

In the church of S. Pancrazio at Corneto is a sexpartite vault (Figs. 58, 60). This church is of a single aisle and very wide, being almost square in plan. Constructing in stone without solid centering, the builders did not dare attempt to cover the entire church with a single great rib vault. They therefore divided it into two oblong compartments. But even so the size of the spaces and the flatness of the surfaces dismayed them, so they determined to erect an intermediate transverse arch. They thus obtained nearly vertical surfaces for almost the entire extent of the two great compartments, the length of the courses of which had offered difficulties. This vault, however, shows merely the hesitation of inexperience. Wishing to economize, the builders in the end erected a vault probably almost as expensive as if they had used solid centering. The experiment was not repeated. Even in the western bay of this same church there is substituted a transverse arch in three spans supporting a wooden roof in place of the similar vault it was doubtless the intention to erect.

The philosophy of this vault is therefore in part different, in part similar, to that of the sexpartite vaults of Northern France (Fig. 61). There the builders were moved not so much by timidity as by the desire to economize centering. Just as the Lombards preferred to vault their naves on square plans with an alternate system, dispensing thus with three superfluous centering arches, the French adopted an alternate system with nave vaults embracing two bays. But they carried their logic of economy farther. If all the weight of the vaults was to be concentrated on the alternate piers, these had to be made unduly heavy, and the intermediate piers, even though lightened, failed to receive all the charge they were capable of carrying. Such a lack of economy was repellent to the logical spirit of the French builders. To remedy it they introduced even at the expense of additional centering an extra intermediate transverse arch. Thus they succeeded in covering a double bay by the aid of nine centering arches instead of the

Fig. 58. S. Pancrazio, Corneto-Tarquinia, (Roma). Vault of Nave.

Fig. 59. St. Remi, Bruyère-sur-Fère, (Aisne). Choir and Apse.

Fig. 60. S. Pancrazio, Corneto-Tarquinia, (Roma).

Fig. 61. S.-Etienne, Caen, (Calvados). Nave vaults.

Fig. 62. S. Maria di Castello, Corneto-Tarquinia, (Roma). Apse.

Fig. 63. S. Fè al Po, Cavagnolo, (Torino).

eleven that would be necessary for a vault erected on a uniform system. Furthermore, four of the six compartments consisted of sharply inclined surfaces the courses of which it was easy to construct with the aid of a cerce. The alternate piers were relieved, moreover, of a disproportionate share of the charge. For these reasons, the sexpartite form was preferred in France during the XII century, although the quadripartite oblong form was perfectly well known to the builders. It will be recalled that St.-Étienne of Beauvais, where the nave was rib vaulted in oblong compartments, antedates St.-Denis, the earliest example of sexpartite vaults in the Ile-de-France.

The sexpartite form in France was probably abandoned because the great length of the diagonals raised the crown of the vaults to such a height that it became necessary to raise correspondingly the walls so that the roof should clear them. This raising of the walls wasted material, and moreover increased the weight that must be carried by the piers; so the builders concluded that it was better to return to the uniform system even at the expense of erecting two more centering arches for their vaults.

Centering was always used, so far as I am aware, in the erection of barrel vaults in Lombardy, and these, it will be recalled, were regularly used in the choirs and transepts. Santa Fe of Cavagnolo, Torino (Fig. 63), even has a nave completely barrel-vaulted. In France as well, in the full Gothic period, certain vaults were undoubtedly erected with solid centering. But although the medieval builders, whether in Italy or in France, never went as far as the Byzantine builders in their efforts to dispense with temporary wooden structures, and always continued to use even a solid centering in certain contingencies, nevertheless the desire to build vaults without a cumbrous and expensive centering in wood was a guiding principle in the development of architecture in Lombardy and France in the XI and XII centuries, and was the chief if not the sole motive that led to the introduction of the rib vault.

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