Robert Mark

Structural Experimentation in Gothic Architecture

Large-scale experimentation brought Gothic cathedrals to a level of technical elegance unsurpassed until the last century

Reflecting the resurgent prosperity of Western Europe in the middle of the twelfth century, a cadre of professional builders began to push the construction of Gothic cathedrals to unprecedented heights. So began an era of structural experimentation that was not to be seen again until the construction of long-span bridges and metal-frame buildings in the second half of the nineteenth century. Our purpose here is to examine this phenomenon, whose dramatic expression culminated in the design of the interior of the Cathedral of Palma, Majorca (Fig. 1), and to suggest a possible and until now unrecognized determinant in the ending of the era.

High Gothic design

In an apparent "race" for extreme height of the church vessel (the main body of the church, excluding towers) between a number of medieval mercantile and ecclesiastical centers in the Paris region, new technical problems were encountered. Lofty clerestory walls, in addition to having to resist the outward thrust of the vaulting, were now subjected to great wind forces, as were the high wooden roofs resting upon them. As the buildings grew larger, too, the design problems were exacerbated by what must have appeared to be the almost insuperable costs of obtaining and transporting stone, often from distant quarries, and of shaping and setting it into place (the true costs of High Gothic construction can only be surmised from accounts of the costs of stone building in the later Middle Ages such as those given in ref. 1). Still another design restraint was imposed by the need to reduce the weight of the superstructure to relieve foundation loadings and hence to reduce building settlements.

It was the combination of all these factors that led to the invention of the flying buttress and the consequent redefining of the style of Gothic building. The first true flying buttresses were used to provide stability to the nave clerestory of Notre Dame in Paris shortly before 1180. By the turn of the century, at the cathedrals of Chartres and Bourges, the potential of this new structural device was realized, and the clerestory wall was reduced to a skeletal frame enclosing large areas of glass.

Surviving records from the period tell almost nothing of the design techniques employed for so marked a technical achievement. We stand on firm ground, however, in ruling out the use of any kind of scientific methodology; more than four centuries would pass before the appearance of Galileo's seminal work in mechanics. The absence of structural theory eliminates also the possibility of quantitative modeling at small scale. Hence, the builders could not have predicted with any certainty whether or not structural elements perfectly valid in smaller buildings would perform reliably at the large scale of the new construction. An important exception, however, is gross stability—against overturning under only dead-weight loadings—which is not dependent upon scale. Indeed, a bench-top-size scale model could have served to indicate the gross stability of a full-scale building. This fact of structural behavior helped to offset some of the problems of new, large-scale design even though it was probably not grasped by the medieval builders.

To try to discern possible medieval structural design techniques we have performed detailed analyses of several major Gothic churches. Perhaps the most important insight came from an early study of the buttressing system of the nave of Amiens Cathedral (*2, 3*). The analysis revealed that the pinnacle (cover) placed atop the outer edges of the pier-buttresses (the towerlike structures along the perimeter of a church which resist the outward thrust of the flying buttresses) helped to maintain integrity of the pier-buttress by overcoming *local* tension caused by the combination of dead-weight and wind loadings: the weight of the pinnacle engenders compression in the pier-buttress that cancels the tension. The pinnacle acts as a prestressing element. This finding was startling because the technical function of the pinnacle is masked by its overpowering decorative role and because *gross* stability considerations would have placed the pinnacle on the inside rather than on the outside edge of the pier-buttress (*4*).

In view of the master builder's inability to predict structural behavior

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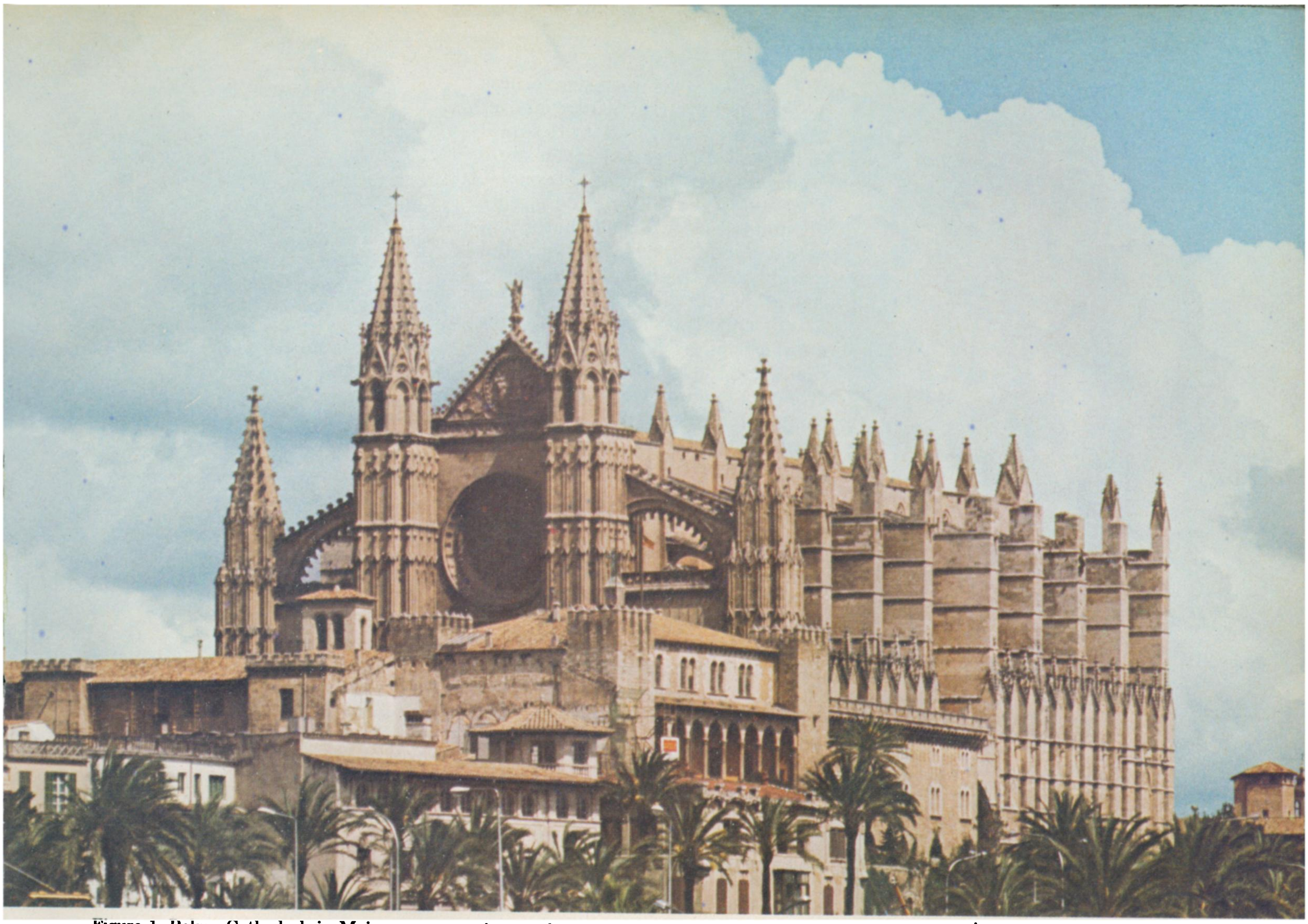


Figure 1. Palma Cathedral, in Majorca, was begun late in the thirteenth century. The western towers (toward the viewer) and the pinnacles atop the massive pier-buttresses are nineteenth-century additions. The lower tier of buttresses supports the walls of chapels set within the bays. (Photograph by M. Dean.)

scientifically, the elegance of the medieval structural solution demanded further explanation. We suggested that the details of design were worked out with a crude type of experimental stress analysis performed during construction: tensile cracking observed in the weak lime mortar between the stones during the relatively long period of construction could have led to refinements in design. Building programs in fact often called for the erection of one bay at a time. In these instances, the first bays could have acted as experimental, full-scale models to provide much of the missing information about behavior and to fix the form of the new building elements. The Amiens pinnacle can be taken as an elegant product of this design approach.

A less sanguine view of the state of the design art emerged from another of our studies, on the influence of the choir of Bourges Cathedral on subsequent building. The Bourges choir, constructed contemporaneously with Chartres and of similar overall vessel dimensions, is a much simpler, lighter, and far more daring structure than Chartres (Fig. 2). But in spite of the technical superiority of Bourges to Chartres, or, in fact, to any contemporary building, the form of its structure was not prescribed for any other major High Gothic church. The original design was even altered when the Bourges nave addition was begun by another master, a decade after the completion of the choir. Our conclusion in this instance was that High Gothic builders generally did not fully understand the principles and consequences of construction with flying buttresses. The original master's immediate successors at Bourges timidly altered his design of the bay section for no important structural gain, while others who followed his spatial program for the interior elevations of a number of important churches ignored the technical innovations of his work. Because the problems addressed by the experiment at Bourges were not understood, the technical beauty of its solution appears to have been generally unappreciated (5).

However, it should not be inferred from this conclusion that structural experimentation did not continue in later Gothic design. That it did can be demonstrated by the great variation in the structural systems employed. Perhaps this is best illustrated at microscale, by examining the ratio of height to width (the "slenderness ratio") of a critical structural member from a number of major Gothic cathedrals, namely, the main arcade pier supporting the clerestory wall.

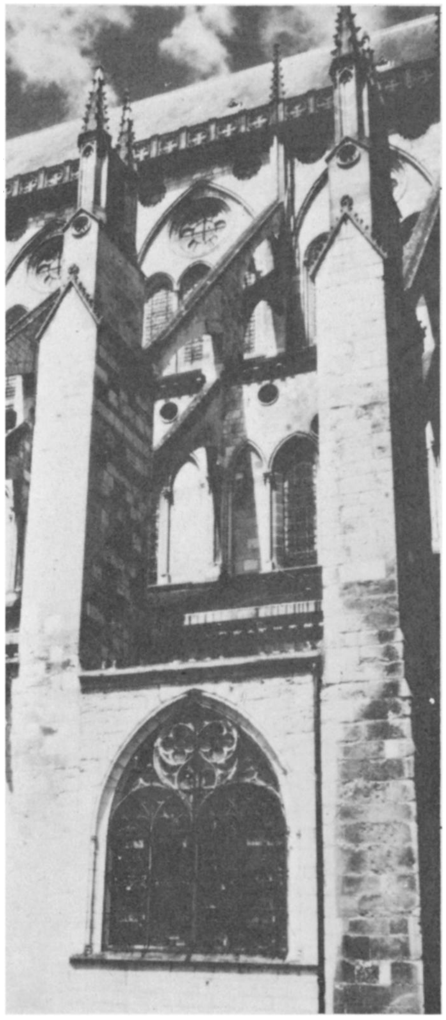


Figure 2. Buttressing of the Bourges Cathedral choir (1195–1214) is the lightest of any of the major churches of the Gothic period. The elegance of the steeply sloped flying buttresses of Bourges was apparently not fully appreciated by medieval architects, who did not immitate them. The pinnacles are nineteenth-century additions and are not structurally needed. (Photograph by R. Mark.)

Table 1 reveals that the contemporary designs of Chartres and Bourges show as great a difference in the slenderness ratios of their piers as they do in almost every other element, and adds further credence to our previous observation that the designer of the Bourges choir was far more daring than the designer of Chartres (*6*). Through Reims, Amiens, Cologne, and Beauvais, the most important classical High Gothic cathedrals following Chartres, there is a gradual increase in pier-slenderness ratio, a parameter not directly related to vault height (which ranges from 38 m at Reims to 48 m at Beauvais) or to any other obvious vessel dimension.

At the giant Catalonian cathedral of Palma on the island of Majorca, south of Barcelona, the pier-slenderness ratio jumps by almost 50 percent over any used previously, and the technical and visual difference is even more dramatic than the numbers convey. The piers of the earlier buildings are surrounded by attached shafts that were not accounted for in Table 1 but that make the piers look much heavier and in fact do lend considerable reinforcement to them. Palma's lithe masonry piers have no attached shafts and the result (Fig. 3), striking even to a modern eye accustomed to thin reinforced concrete construction, must have appeared to be miraculous in the Middle Ages.

Palma Cathedral

Palma is among the tallest Gothic cathedrals in all of Europe. When the design of the nave was conceived in the mid-fourteenth century, only the heights of the vaults of the choirs of Beauvais in France and of Cologne in Germany exceeded its 44 m. A more modest church was originally planned after the Christian reconquest of the Balearic Islands in 1229. The first campaign of construction left the east end of the building, the choir, largely completed in 1327. The second campaign, which raised the nave to extreme height, was not begun until about 1357: The high nave was erected one bay at a time, with the first, "prototype" bay completed in the 1370s. By the turn of the century, three high bays were standing; construction slowed afterward, however, so that the entire building vessel was not complete until the sixteenth century (*7*).

Probably because of its remote location, relatively little has been written about this major building and almost nothing in English except for a slight monograph by the American architect, Ralph Adams Cram, who described its interior as follows:

> The vast and lofty nave is even more open and spacious than . . . any Gothic church in the North. It is a forest of silvery columns that open out into vaults without the interruption of conventional capitals, with, beyond, long ranges of vaulted chapels. . . . The eastern composition is striking to a degree. The choir is, to the apex of its vault, only two thirds the height of the nave vault, leaving above an eastern wall in which is set one of the largest rose windows in the world, 38 feet in diameter, and filled, not with Gothic tracery, but with a Moorish geometrical pattern in stone. [*8*]

Table 1. Dimensions of piers in Gothic cathedrals

Site and date construction began	*Height (m)**	*Width (m)†*	*Slenderness Ratio*
Chartres, 1194 (nave)	8.0	1.8	4.4
Bourges, 1195 (choir)	14.9	1.6	9.3
Reims, 1210 (nave)	9.6	1.6	6.0
Amiens, 1220 (nave)	12.5	1.5	8.3
Beauvais, 1225 (choir)	14.6	1.5	9.7
Cologne, 1248 (choir)	11.9	1.3	9.2
Palma, c. 1350 (nave)	22.0	1.6	13.8

* Distance from top of base to bottom of capital, i.e. straight section length of load-bearing, coursed construction.
† Diameter for round piers, distance between flats for hexagonal piers.

Table 2. Comparative dimensions (in meters) of the Reims and Palma naves

Dimension	*Reims*	*Palma*
Spans*		
central aisle width	14.5	19.5
side aisle width	7.7	10.0
bay spacing	7.2	8.8
Pier-buttress		
height above ground (excluding pinnacle)	33.6	38.8
width at ground level	5.0	8.5
Roof		
peak height above ground	58.0	47.0
peak height above parapet	15.3	3.5

* Measured between pier centerlines.

But although Palma's interior elevation is unique, analysis of its structural system reveals, as with the misinterpretation of Bourges, that aspects of the design were not well understood by its architect.

A comparison of the cross section of Palma with Reims Cathedral (Fig. 4) serves to mark the structural "evolution" of Palma from the classical, High Gothic model. Cram's observation of Palma's interior openness and spaciousness is quantified in Table 2. Both Figure 4 and Table 2 reveal that the gain in interior space has been won at the literal expense of building massive pier-buttresses. This great mass, however, is not devoted only to a structural role. It is also utilized spatially by the creation of chapels between the pier buttresses along the perimeter of the church. The mark of these chapels on the building exterior is the pairs of chapel-wall buttresses between adjacent pier-buttresses, which contribute to Palma's unique

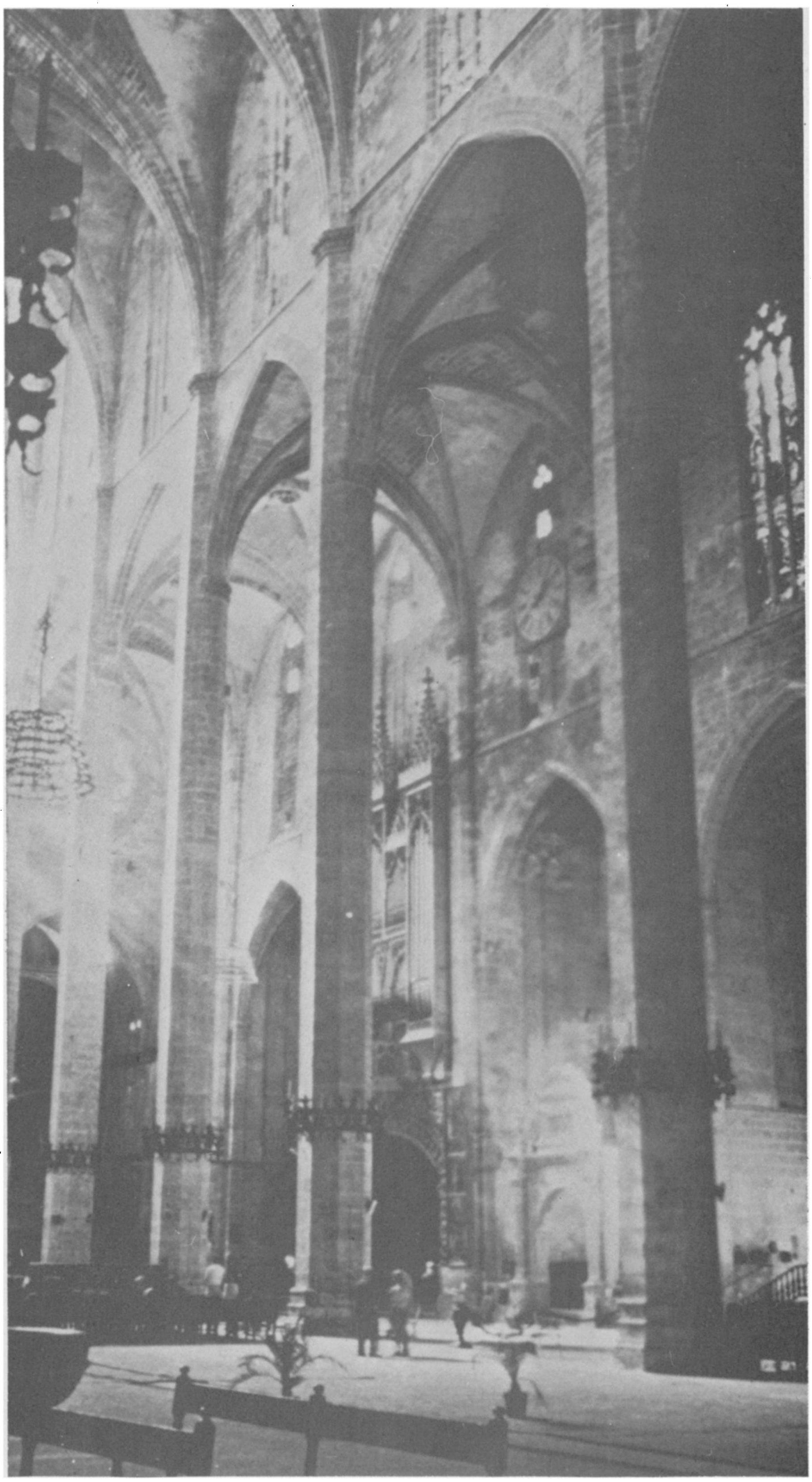


Figure 3. An atmosphere of vast spaciousness is created in the interior of Palma Cathedral by the bold use of wide bay dimensions and the extremely slender high piers along the central arcade. The piers are of coursed masonry and contain no reinforcement.

form. Heavy buttresses flanking chapels in this manner were used previously in the walls of fortified churches in southern France; indeed, this design element at Palma was likely to have been taken from French models such as the Cathedral of Albi, begun in 1282.

Unlike their northern counterparts, the southern Gothic churches characteristically have low roofs. This is important from a technical standpoint: the wind loads acting on the high wooden roofs of the northern churches are quite significant, and the effect of these forces contributed to the evolution of flying-buttress design (*3*). There is hardly any equivalent loading on the structure of southern buildings. Hence, in a high wind of the same magnitude, Palma would be subjected to a lower total lateral force than Reims, even though it has a much higher interior vessel. Furthermore, the distribution of these wind forces on Palma is less severe than on the classical High Gothic buildings and particularly so on the clerestory wall, because of the almost complete elimination of a concentrated load transfer from a high roof at the extremity of the clerestory parapet.

Structural modeling

Analysis of the long vessels of Gothic cathedrals is facilitated by their repeating, modular bay design. For purposes of analysis the buildings can be considered to be supported by a series of parallel, transverse planar frames consisting of the principal load-bearing structural elements: piers, buttresses, lateral walls, and ribbed vaults. To be sure, the ends of the linear vessel are usually of three-dimensional form, but because of the greater stiffness and strength of this type of structure, they are rarely subjected to the problems found in the more open, straight bay sections. When the vaults of the Beauvais choir collapsed in 1284, for example, the structure of its apse (the hemicyclic eastern end of the vessel) remained firm, and it stands today essentially as it was originally constructed (*9*). Hence, transverse bay sections from individual buildings may be taken as representative of their particular structural solutions.

A second, important simplification is the assumption that the structural forces within the masonry frame are distributed as they would be in an equivalent frame constructed from a

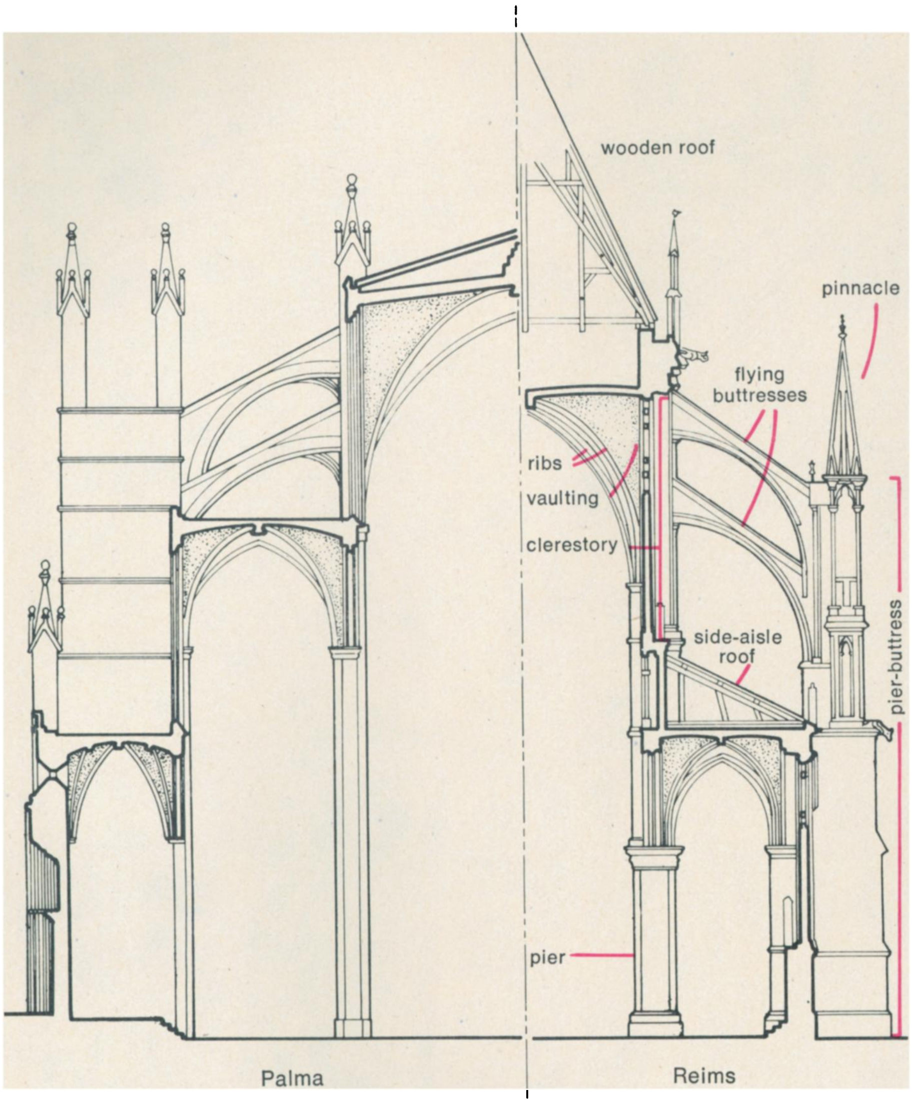


Figure 4. Comparison of the naves of Palma and Reims (begun 1210) cathedrals indicates the great size and relative spaciousness of the Palma design. (Drawing by R. Voyosevich.)

perfectly elastic, homogeneous material. This assumption has been shown to be adequate for predicting structural behavior in tests of reinforced concrete structures subjected to service loadings, even though concrete is notoriously inelastic, compositionally inhomogeneous, and subject to tensile microcracking. For the simplification to be applied to masonry, it must also be assumed that the entire frame is undergoing compressive action—that is, that all the individual stones are pressed against adjacent stones by compressive forces within the interior of the structure. This assumption coincides with criteria for successful medieval masonry performance, because, as we have noted, the tensile strength of medieval mortar is extremely low. Hence, structural continuity cannot be maintained if any substantial amount of tensile stress is present. Even small tensile stresses can cause cracking and begin a process of local disintegration, especially on the exterior of a masonry building subject to weathering. Previous studies have indicated that compressive stresses indeed prevail, and that there are usually only a few highly localized regions of tension. In several instances, we were able to show that these regions require special care from custodial staffs (*3, 5*).

A final assumption inherent in this type of analysis is that gravity begins to act only after the construction of the building is completed. In fact, this is not far from reality with respect to the vaulting and the flying buttresses. These were usually assembled on rigid centering and hence were not subject to dead-weight loadings until their completion, when the centering was removed. At the other end of the time scale, long-term, dead-weight loadings can cause unrecoverable flow of masonry (but wind loadings, which are of variable magnitude and blow from every quarter, will not). Nevertheless, if the basic support and form of a structure remain unchanged with time, the distribution of internal forces will be little altered from the initial elastic distribution indicated by the model. In fact, this phenomenon also underlies the use of models of certain viscoelastic plastics to predict elastic response (*10*).

Palma was analyzed using the relatively simple experimental technique that we have previously applied to study a number of historic buildings, small-scale photoelastic modeling. Stress-free epoxy models are loaded with arrays of weights representing the distributions of wind and dead-weight forces acting on the building. The epoxy models are brought to a rubbery state (at about 140°C) in a controlled-circulation oven and then slowly cooled, restoring the epoxy to its room-temperature glassy state. The relatively large model deformations that take place at the higher temperature are locked in after cooling so that the loadings may then be removed with negligible effect. The unloaded model is then viewed through polarizing filters, and the interference pattern (isochromatics), interpreted with calibration and scaling theory, can predict the force distributions in the full-scale structure. (Further details on model loading for dead-weight simulation and for scaling between model and prototype may be found in ref. *11*).

The structural system of the Palma nave was modeled at a scale of 1:144 (Fig. 5). As we were seeking general force distributions rather than localized stress concentrations—which are sought, for example, when the modeling method is applied to airframe analysis—no effort was made to detail the cross sections of the component structural elements; the action of the deeply cross-ribbed vault, a three-dimensional structure, was simulated in the model as a planar arch. The heavily loaded foundations were also assumed to give complete

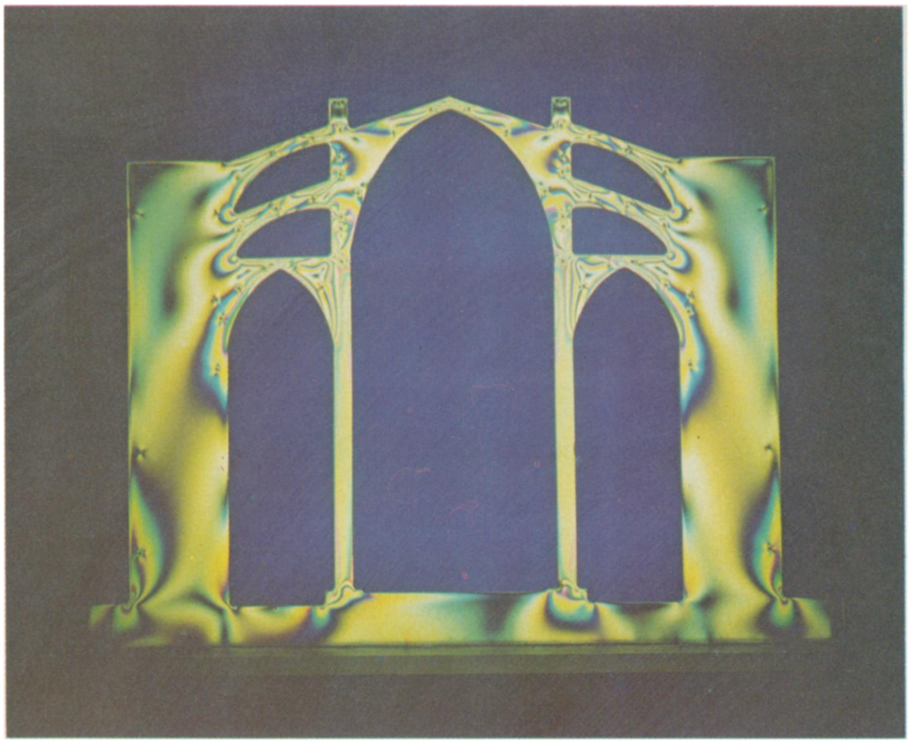


Figure 5. The polarized-light interference pattern in a photoelastic model of the Palma nave gives a contour map of stress intensity. Under simulated dead-weight loading, the piers display almost uniform interference, which indicates that they are subjected to only negligible amounts of bending stress. (Photograph by R. Mark.)

fixity to the bases of the piers—that is, no deformations were permitted at ground level. Dead-weight load distributions were taken from Bellver (*12*) and applied to the model in a similar pattern at a scale of 1:150,000 as an array of point loadings.

A second loading was performed using data on Palma wind velocity over the period 1943–74 obtained from the Spanish Ministerio del Aire, the Servicio Meteorologico Nacional, and the Climatic Center of the United States Air Force. (The first, dead-load pattern was "erased" when the model was heated for the second loading.) From these data, the greatest expected wind velocity at the level of the cathedral roof was taken as 130 km/h. The wind-pressure distribution with this value was applied to the model according to a formula suggested by Davenport (*13*) at a scale of 1:21,650.

The most significant feature of the isochromatics is the almost uniform pattern in the dead-weight–loaded main piers, which signifies negligible bending. The absence of bending in the piers, a phenomenon that must be unique among the major Gothic churches, helps to explain the stability of these very slender main structural elements. The indicated stress level corresponding to these model data is $1.45(10)^6$Pa (210 psi). But since the weight of the lower 30 m of the piers was not simulated in the test, the stress from the pier weight must be algebraically added to the stress from the model loading, giving a total compression stress at the base of the pier of $2.14(10)^6$Pa (310 psi), a moderate value for this construction.

Under wind loading alone, the maximum stresses throughout the structure are low compared with northern High Gothic buildings: of the order of $0.5(10)^6$Pa (70 psi) in the pier. The only regions indicating possible problems are at the ends of the flying buttresses, where bending from the effect of winds, added to the bending already present from the dead-weight loading, produces tension of sufficient magnitude to engender cracking.

Marcel Durliat refers to the rebuilding of the high vaults at the beginning of the eighteenth century, but he gives no hint as to the cause of their failure (*7*). The results of the analysis and the present state of the flying buttresses, a number of which are propped (Fig. 6), combine to make the flyers prime candidates for a possible cause. They are long and, what is more crucial, they are not sloped greatly. As it is, the upper

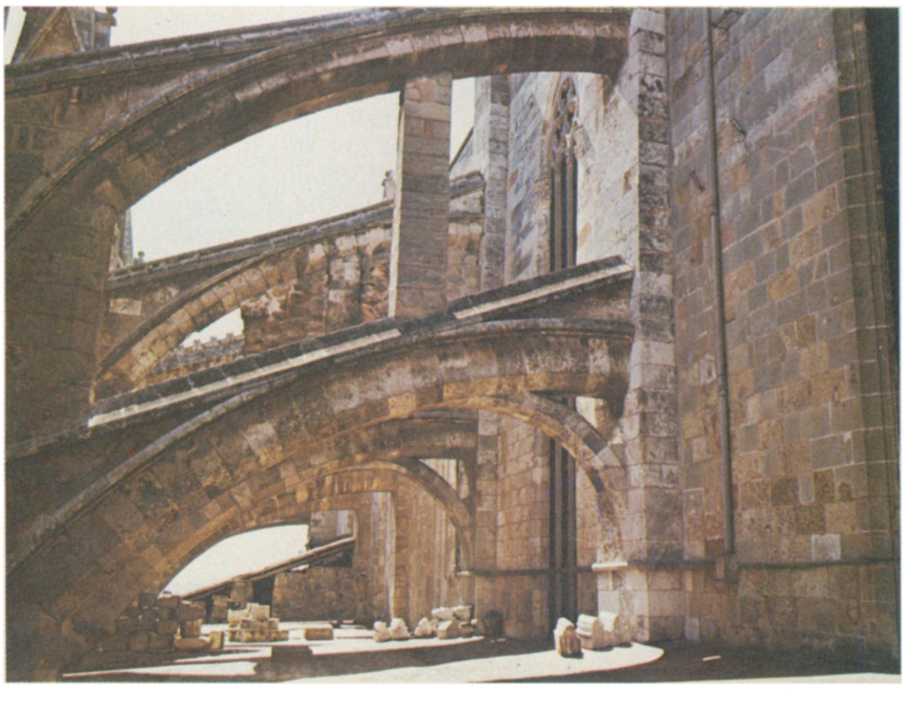


Figure 6. The long, heavy, and relatively flat (compared with Bourges) flying buttresses of the Palma nave require additional strengthening. Note the added propping of the upper flyers and the extra arches from the wall on the right supporting the lower flying buttresses. (Photograph by R. Mark.)

flyers, which would have functioned as a brace against wind loads if a high roof had been used, serve little purpose, and the fact that they are not under appreciable loading contributes to their malfunction. A single more steeply sloped tier of flying buttresses together with steeply sloped, transverse walls over the side aisles would certainly have provided more reliable support for the vaults.

The design of the cathedral of Palma, then, though singularly successful with regard to interior space, was not a complete structural triumph. As was generally true of all the large churches built after the beginning of the thirteenth century, the lesson of the light, steeply sloped flying buttresses of Bourges was lost at Palma. Nevertheless, because of the unique openness of its interior, Palma must be taken as a high point in the process of Gothic structural innovation—a process that would soon end, partially, we shall suggest in the next section, as the result of a fundamental change in the transmission of technological information.

Late Gothic: The impact of technical writing

After the middle of the fourteenth century, following widespread economic decline and the advent of the Black Death, conditions across Europe were no longer generally conducive to planning great Gothic churches. In this climate a modified type of Gothic basilican-church interior elevation became more common, particularly in Germany. In these so-called hall churches, the heights of all three aisles were made almost equal, and the high, central clerestory of the nave was eliminated. In this way, a large floor plan could be maintained without the expense—if, as many would affirm, without the elegance—of carrying the building interior to extreme height. An immense wooden roof spanning the three aisles of the hall church nave could, however, continue to present a massive exterior, as shown in Figure 7. Buttressing to support the resultant outward thrusts of the multiple vaults and the wind load, which was reduced by the general lowering of the building profile, was greatly simplified. Flying buttresses were replaced by wall buttresses, the simple reinforcement of the relatively low exterior walls by an out-standing masonry "leg" between the windows.

More is known about design techniques for late German Gothic buildings of this type than about High Gothic planning, for several of the architects' notebooks from this later period have been preserved. Lon R. Shelby has reported on these and noted that they dealt largely with the use of geometrical figures (circles, squares, triangles, octagons) to construct the configurations of architectural elements (*14*). Fortunately, we also have certain structural design rules set out in the *Instructions* written in 1516 by a master mason at Heidelberg, Lorenz Lechler, for the benefit of his son (*15*). In addition to presenting geometric schemes for planning the configuration of a class of hall churches, Lechler gives specific advice on structural details such as wall thickness, window-opening sizes, and buttress and vault-rib dimensions.

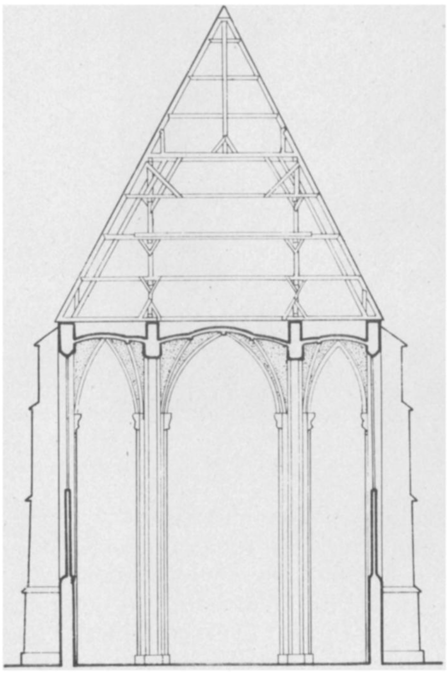


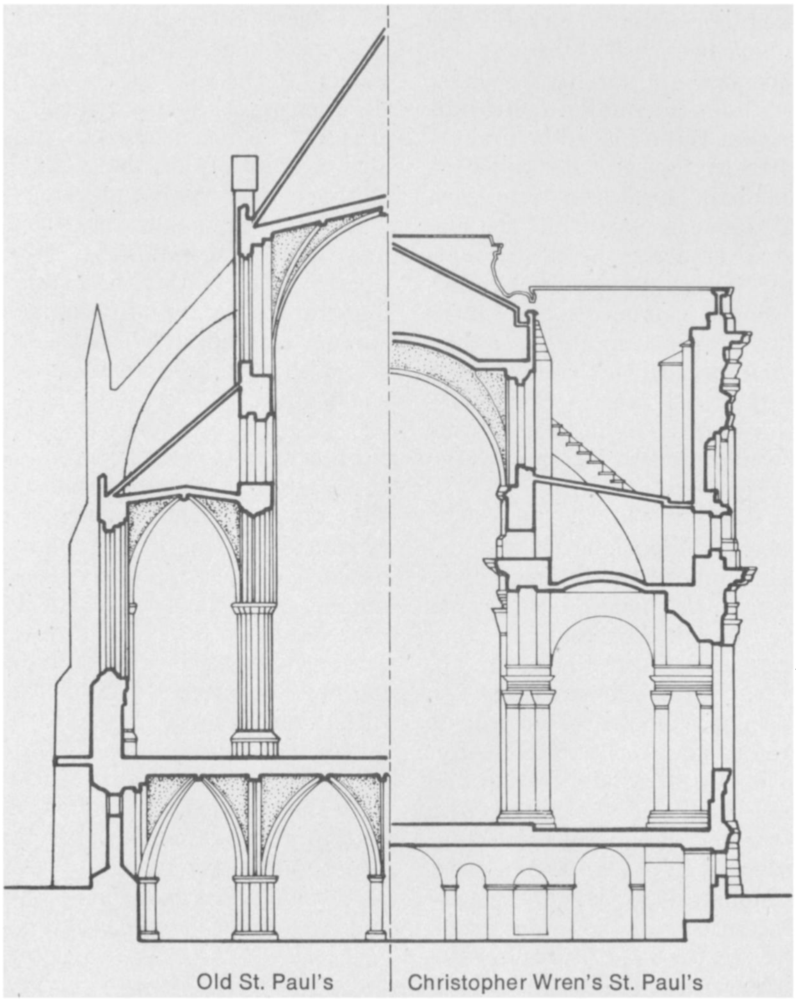
Figure 7. A section through the nave of a typical late German Gothic hall church shows how the classical high clerestory has been eliminated and the buttressing greatly simplified. A huge timber-frame roof was often used to cover the vaults of all three aisles. (Drawing by R. Voyosevich.)

Although he does not clearly state their interdependence, the dimensions of all the building elements are in effect related to the interior span of the central aisle, which Lechler recommends keeping between six and nine meters. For example, he advises that the height of the central-aisle vault keystone be made equal to one and one-half or two times the span of the central aisle. The wall thickness is essentially one-tenth of the span, as is the breadth of the outstanding leg of the wall buttress at ground level. The buttress extends from the outside edge of the wall about two-tenths of the span, giving a total wall-buttress depth at ground level of three-tenths of the span of the central aisle. Thus, for a church with a 9 m central-aisle span, the vault keystone elevation may be 13.5 m or 18 m, while the total depth of buttressing in both cases is about 2.7 m. In fact, holding the buttress depth constant for various building heights is sensible only with regard to resisting the outward thrust of the vaults, where stability against overturning is a function of the total wall-buttress weight: the higher vault produces greater overturning moment at the buttress base, which in turn is resisted by the greater weight of a correspondingly higher buttress. Evidently, the rule does not take into consideration the effects of wind or any other problems associated with taller building design, but since Lechler's buildings are relatively small, this omission was not serious.

Lechler's criteria seem to have been based on his observations of existing buildings, and although he did advise his son to use his own judgment and not necessarily to "follow [the text] in all things," the very existence of the work must have had the effect of standardizing preexisting building form. No theory is offered that might guide experimentation; hence the only prudent course for assuring safe design of the building structure would have been to follow the details of the text.

The significance of the apparent beginning of such technical writing and, shortly thereafter, the possibility of its wide dissemination in print at this phase of European cultural development has not yet been fully elucidated. Bert Hall has suggested that one important effect was to allow a new range of speculation; he observes that although it is risky to extrapolate

Figure 8. A comparison of Old St. Paul's choir (begun 1258, destroyed 1666) with Wren's "New" St. Paul's (1675–1710) indicates an apparent retrogression of structural design. The original church, although not as high as Bourges or Reims, was considerably taller and used lighter structural elements than Wren's baroque building. (Drawing by R. Voyosevich.)



from Leonardo to his less gifted contemporaries, there is some reason to believe that other technical authors did approximate his method of inventing "on paper" (*16*). For the more developed technical arts such as architecture, however, the effect might have been just the opposite: the intrinsic power of written design rules and the publication of drawings of existing buildings could have tended to codify them. Furthermore, once certain building types were established and rules for their construction accepted, there was little reason to modify them. This situation prevailed until the pressing needs of nineteenth-century industrial development and its introduction of new construction materials brought the more common use of scientific methods into structural design. After the fourteenth century, experimentation with building structure still took place, but it became rare and was usually confined to unusual structures where rules might not exist.

Post-Gothic design

A seeming paradox in Wren's St. Paul's Cathedral, constructed well past the end of the Gothic era, between 1675 and 1710, can now be explained in terms of the two contrasting modes of design that have been described. A comparison of the cross section of the "new" choir with that of Old St. Paul's, which occupied the same site prior to the 1666 fire, reveals the conservativeness of Wren's structural design (Fig. 8). In fact, our technical studies indicated that the combined clerestory wall buttress and

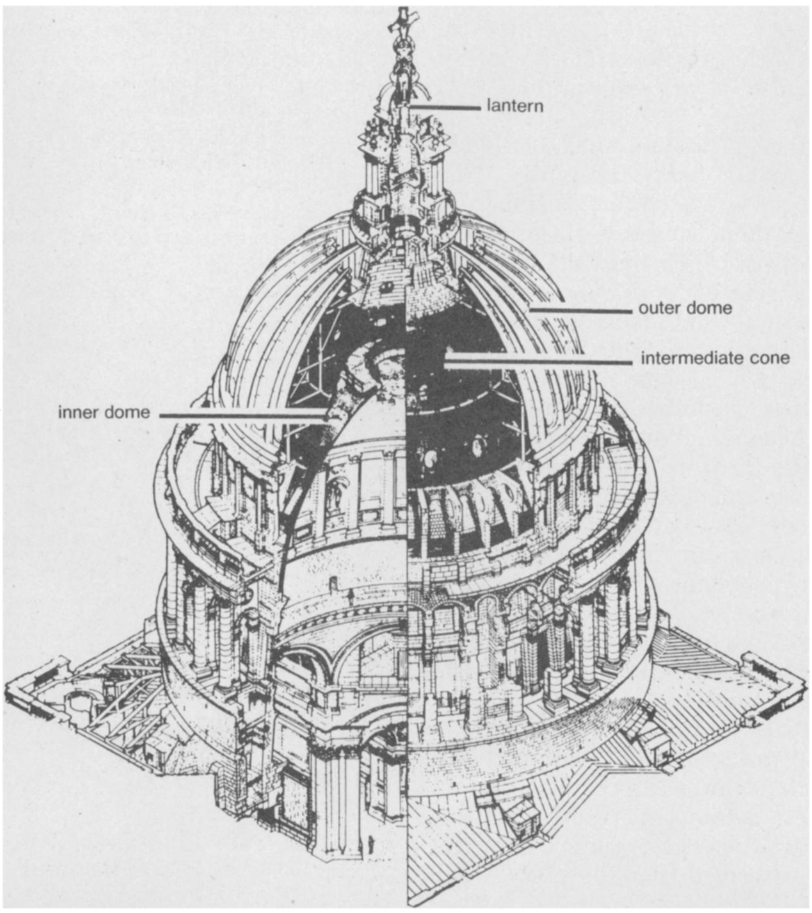


Figure 9. The dome of Wren's St. Paul's is composed of three separate shells. The inner, open dome and the conical shell supporting the lantern at the top are of brick, 18 inches thick. The light-weight outer dome is composed of lead-sheathed timber and is also supported by the conical intermediate shell. (Drawing by R. W. Brook-Greaves and W. Godfrey Allen.)

massive piers (slenderness ratio: 3.5) would have been well able to provide the necessary support to the clerestory without the hidden flying buttresses that Wren placed behind extremely heavy, raised outer walls. On the other hand, his design of the great central dome is masterful. He succeeded in creating the profile of a majestic outer dome with a minimum-weight structure of lead-sheathed timber supported by a thin, chain-reinforced brick cone—which also supports a lantern of 850 tons—and a separate, light, inner brick dome well suited to interior spatial needs (Fig. 9).

The general dimensions of the structural elements in the finished choir section are little changed from Wren's Warrant Design (a preliminary set of drawings submitted for royal approval to begin construction; *17*). This design is known to have been prepared in some haste in 1675, after his earlier Great Model Design had been rejected, and the speed with which the new design was carried out suggests that Wren drew on preexisting models (*18*). By mid-seventeenth century, all the major architectural treatises of the Italian Renaissance were available throughout Europe, often in translation. And indeed, Wren's biographers cite a number of these for the sources of many of the architectural elements of St. Paul's.

The dome project, on the other hand, was treated very differently. The many surviving Wren drawings of various dome schemes are undated, but between 1689 and 1694 there are several references in his notes to experimental dome models, which indicate that he was still at work on the design at that late period in construction. The other very large domes that he might have used as design models, those of the cathedrals of Florence and of Rome, were of heavy masonry. They had been complex and expensive to construct and both were having problems with cracking. This fact, of which Wren was probably aware, could have stiffened his resolve to arrive at a more "Gothic-experimental" solution.

Had Wren arrived at this final dome design at an earlier stage of the project, before construction of the central supporting piers, he might have perceived that the piers could have been lightened, and some of today's problems with differential settlement of the heavy structure under the dome might have been avoided. In effect, Wren's dome recapitulates the design solution of the light High Gothic clerestory. His piecemeal approach to design, however, resembles more closely the methods of the early phases of the Gothic than it does of mature Gothic buildings, such as Amiens Cathedral, where the design seems to have been consistent from the beginning.

Further studies need to be carried out to support fully this thesis concerning the impact of the introduction of technical writing on architectural design. But there is already consensus among historians that until the nineteenth century, the level of structural experimentation in building never approached its Gothic zenith. This effect is most clearly observed in a comparison of the interior of the baroque St. Paul's Cathedral with the Gothic cathedral of Palma. Except in the dome, the adventure of experimentation which so characterizes Palma is conspicuously absent in Christopher Wren's building.

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"It sounds like an implosion."