Gothic Structural Experimentation

Gothic builders used the cathedrals themselves as models, modifying designs as structural problems emerged. An analysis of buttressing patterns shows that information spread rapidly among building sites

by Robert Mark and William W. Clark

The cathedral of Notre-Dame de Paris, the construction of which began between 1150 and 1155, was planned to be the tallest space in Gothic architecture. Its vaulted ceilings rise some 33 meters above the floor, more than eight meters higher than those of any of its early Gothic predecessors; the relative increase in height over previous buildings, more than one-third, was the greatest of the entire era. Nevertheless the structural configuration of the Paris choir (the eastern part of the cathedral where services are sung), which was built first, was essentially similar to that of earlier, smaller churches. The outward thrust of the interior vaults against the high window wall (the clerestory) was resisted only by stone quadrant arches hidden under the sloping roof of the adjacent gallery.

In designing the somewhat wider nave, however, with its lighter and more open structure, the Paris builders evidently decided that the concealed quadrant arches were insufficient to support the high clerestory. The increased width meant that the outward thrust of the vaults was greater than the thrust in the choir. More important, in building the choir the craftsmen must have become aware of a new problem for which experience with lower churches could not have prepared them: wind speeds are significantly greater at higher elevations. Wind pressure, it is now known, is proportional to the square of wind speed, and so it has a much stronger impact on tall buildings. Concern for wind loading, we believe, led the builders of the Paris nave to introduce the flying buttress just before 1180. Although similar in structure to the concealed quadrant arch, the flying buttress was exposed and supported the wall at a higher level.

In less than two decades the flying buttress became the stylistic hallmark of Gothic building. The origins and the dissemination of such technological developments in the Middle Ages have long interested historians. Our own structural analyses of a number of medieval buildings have revealed that their designers learned from experience, using the actual buildings in the way today's engineer relies on instrumented prototypes to ascertain the structural behavior of a design. The observation of cracking in weak, newly set mortar, for example, often led to structural modifications that were undoubtedly an important source of design innovation.

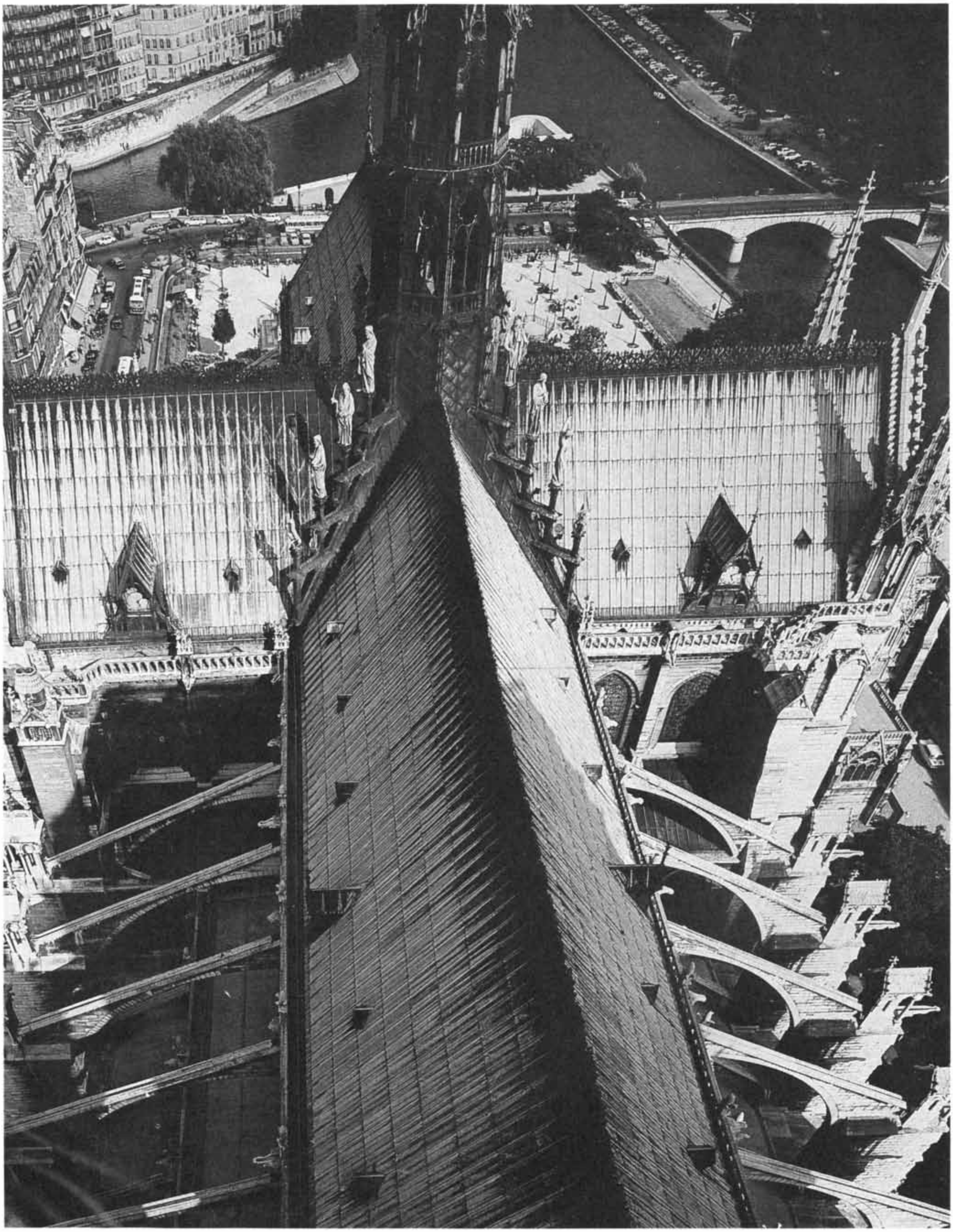
Moreover, the experience gained at one building site was transmitted to other construction projects: the earlier building acted as an approximate model to confirm the stability of a new design. Our analysis of Notre Dame and its architectural influence demonstrates a ready communication between medieval building sites and the rapid transmission of technological innovations, in particular the flying buttress. The master masons of later cathedrals, such as those at Chartres and Bourges, seem even to have been aware of flaws in the original buttressing scheme at Paris and to have modified their own designs accordingly.

The Gothic period coincided with late-medieval advances in the manufacture of cloth and an expansion of trade that produced great wealth and led to the growth of cities. The new wealth spurred a prodigious building activity that changed the face of western Europe. In northern France the success of the Gothic style can be seen in practically every village and town.

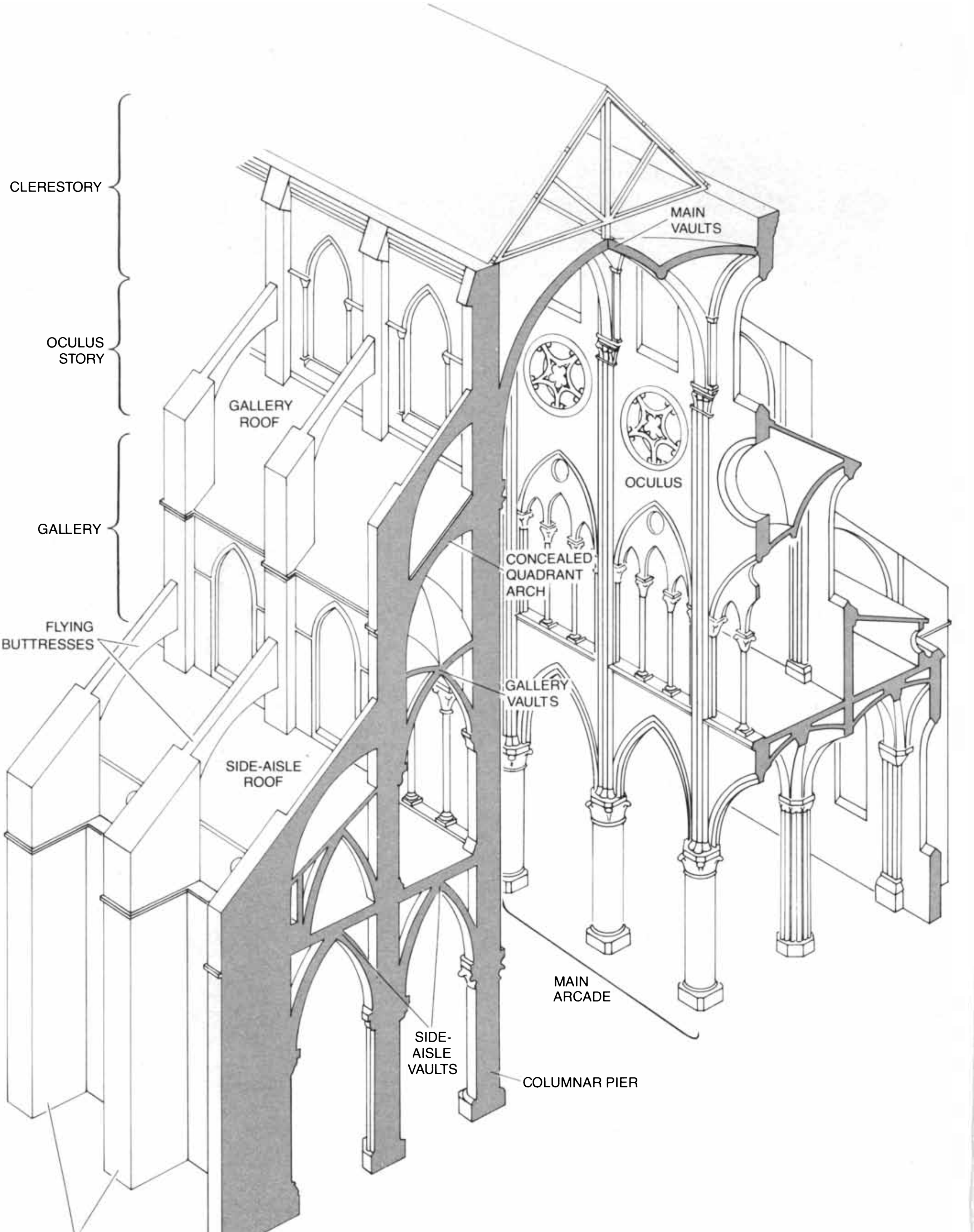
Unfortunately there are few textual records from before the 13th century to document the work of the Gothic builders and to trace communication among them. Most of the surviving written evidence consists of little more than appreciative remarks by nonspecialists, usually the patrons of a building. The classic example is the Abbot Suger's tantalizing but frustratingly incomplete descriptions of the new construction he commissioned in about 1130 for the abbey church of Saint-Denis, near Paris, the first example of the Gothic style. Another unique document is the year-by-year chronicle by the monk Gervase of the rebuilding of Canterbury Cathedral from 1174 to 1184. Neither of these texts, however, mentions any technological development or indicates that ideas were communicated from one building site to another. Nor have architectural drawings from the 12th century survived, if indeed they ever existed; the earliest evidence of the use of drawings to record and transmit architectural ideas dates from about 1225, almost at the time when Gothic construction activity began to decline.

In the absence of documents the building technology of the Gothic era is best described by studying the buildings themselves. One approach is archaeological. By noting even the most subtle changes in structure and ornament from one part of a cathedral to another it is possible to determine the order in which the different sections were built and usually to identify major episodes of construction. In some cases the construction sequence can be plotted almost year by year, as the Australian architect John James has done for the cathedral of Chartres. Through the systematic archaeological study of a series of buildings we are on the verge of being able to follow the work of individual craftsmen as they moved from site to site, carrying with them information on new construction developments. The artistic signatures of these artisans are discernible in their handling of structural and decorative details.

A second approach to studying Gothic churches relies on modern tools of structural analysis to understand how the buildings actually function. One such technique, which we have employed extensively, is called photoelastic modeling [see "The Structural Analysis of Gothic Cathedrals," by Robert Mark; Scientific American, November, 1972]. A transparent plastic model of a cathedral cross section is heated to about 150 degrees Celsius, at which



CATHEDRAL OF NOTRE-DAME DE PARIS was the tallest of the Gothic works of the 12th century. The first flying buttresses supported its vast nave. The cathedral was rebuilt extensively in the 13th and 19th centuries; the present buttresses, seen in this view from one of the west towers, are very different from the 12th-century originals. An arch embedded in the buttress wall perpendicular to the south transept (*at right in the photograph*) suggests the disposition of the original flying buttresses (*see top illustration on page 179*).



CUTAWAY VIEW OF NOTRE DAME shows the main interior elevation of the original nave (before the 13th-century rebuilding campaign) as reconstructed by the authors on the basis of archaeological and structural analyses. The upper flying buttresses transferred outward thrusts resulting from wind loading to the gallery-level fliers, which in turn transferred those thrusts to the pier buttresses. To the left of the main aisle the cross-section cut (*gray*) is through the buttresses and the piers; to the right it is through the middle of a bay.

temperature the plastic becomes rubbery and is easily deformed by the application of weights that simulate the forces of dead weight and wind on the building. The deformations are locked in when the model is cooled and produce an interference pattern when it is viewed through crossed polarizing filters. The interference pattern can be interpreted as a contour map of stress and can thus reveal possible design flaws in the building.

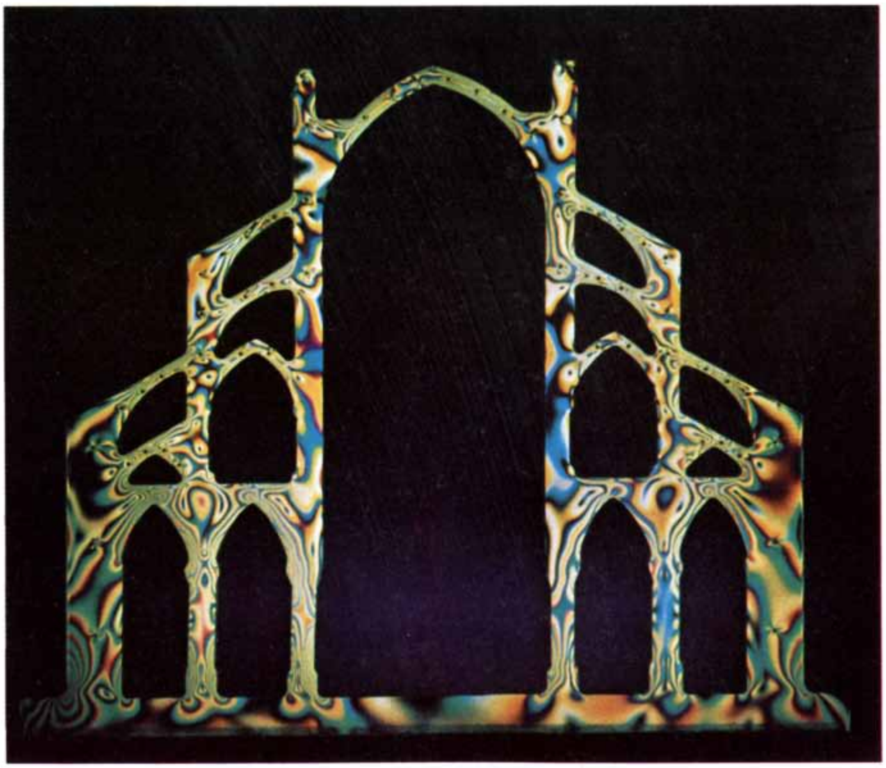
The study of Notre-Dame de Paris by these two approaches has led us to a new reconstruction of the original nave and of the first flying buttresses. The entire buttressing system was extensively rebuilt beginning in the 1220's, and massive restorations were also carried out in the mid-19th century. Archaeological evidence suggests that the original buttressing scheme was much simpler than has previously been thought. It included two separate tiers of flying buttresses: an upper tier above the gallery roof to brace the high clerestory wall and a lower tier to strengthen the outer gallery wall and to help resist the outward thrust transferred by the upper fliers.

The major evidence of this arrangement is a quadrant arch still preserved in the inner face of a wall buttress supporting the south transept [*see top illustration at right*]. Although it is embedded in the wall and has never been open in the manner of a true flying buttress, its curve almost certainly reflects that of the open flier arches that supported the clerestory of the adjacent nave. This means the original upper fliers must have abutted the main wall at a point about halfway up the original window opening. The lower, or gallery, rank of flying buttresses survived more or less intact until the 19th-century restorations, and so their configuration can be determined from drawings and early photographs made before that building campaign. Further architectural details are suggested by the contemporaneous church of Saint-Martin at Champeaux, which belonged to the bishop of Paris and whose flying buttresses are thought to reflect the original buttressing scheme of the Paris cathedral.

Beginning in the 1220's this scheme was changed dramatically: the upper flying buttresses were replaced by giant fliers that spanned both side aisles. (The original upper fliers had spanned only the inner side aisle, from the clerestory to the gallery wall.) What prompted this change in design?

Earlier investigators have argued that the change was part of an effort to allow more light into the cathedral. The Paris builders seem to have been unprepared for the decrease (compared with earlier buildings) in the amount of light reaching the floor of the church, an effect resulting from its significantly higher

TWELFTH-CENTURY WALL BUTTRESS above the gallery on the south transept at the cathedral has embedded in its inner face an arch that probably repeats the arc of the original upper fliers, which supported the adjacent nave clerestory. This archaeological evidence suggests that the first flying buttresses abutted the clerestory at a point about halfway up the original windows, well below the roof. In the 13th century the upper fliers were replaced by huge flying buttresses spanning both side aisles, and the clerestory windows were enlarged.



PHOTOELASTIC MODEL of the original nave of Notre Dame reveals the distribution of stresses induced by simulated wind loading and shows there probably were structural reasons for rebuilding the flying buttresses. The transparent plastic model is viewed with the aid of polarizing filters. The resulting interference pattern is a contour map of stress intensity in which each color corresponds to a different level of stress. Critical regions occur where the colored lines are closely spaced. Significant tension was found where the flying buttresses abut the clerestory and the gallery. Mortar cracking in these regions probably necessitated frequent repairs until the construction of the new buttresses in the 13th century eliminated the problem.

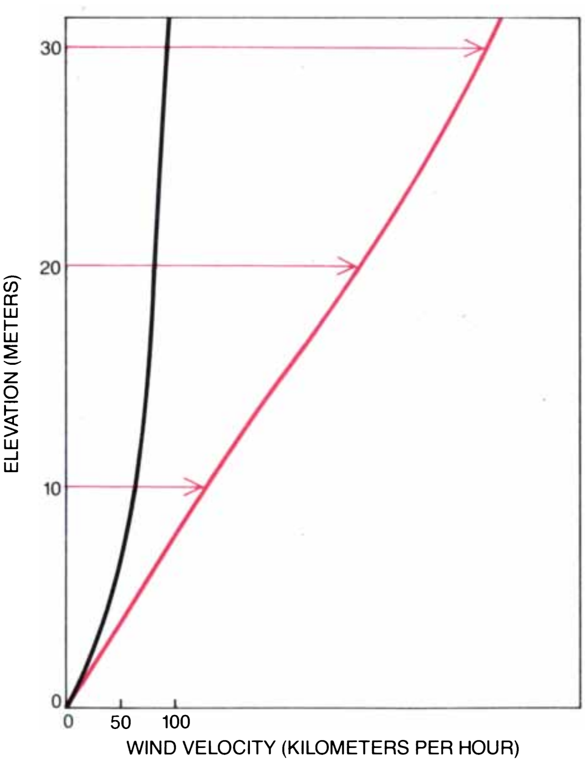
walls. The problem must have become apparent in the choir, however, because in the subsequent construction of the nave the builders raised the height of the gallery vaults and enlarged the gallery windows.

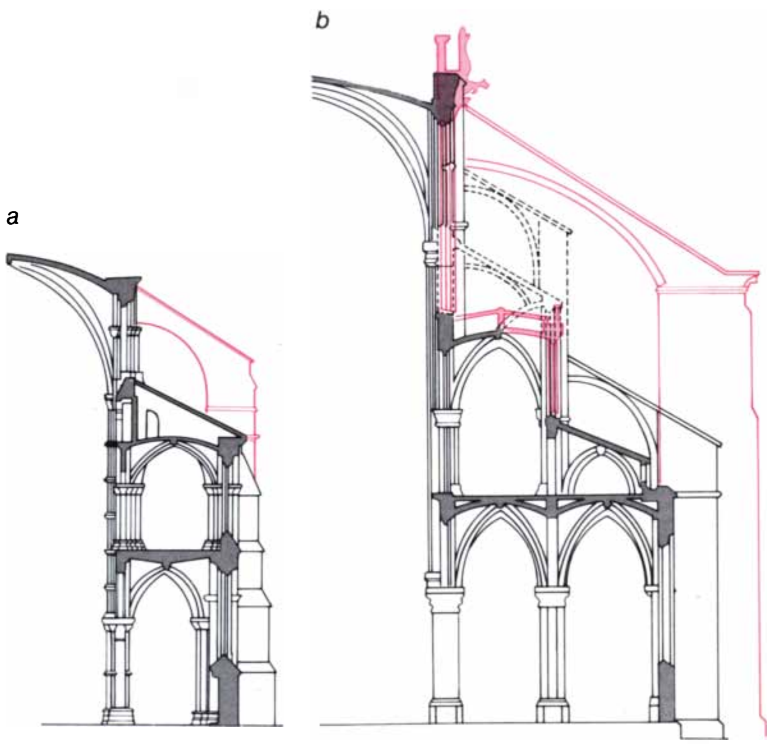
According to one argument, these changes were insufficient to dispel the darkness in the church, and this led directly to the decision in the early 13th century to enlarge the clerestory windows to their present size. To lower the base of the windows it was necessary to lower the roof and outer wall of the gallery; as a result the builders had to modify the flying buttresses, because they were structurally part of the gallery wall. In other words, according to this argument, the changes in structure were only a by-product of the need to change the window design.

Our structural analysis indicates, however, that the rebuilding of the first flying buttresses may actually have been a response to structural problems inherent in the original design. Initially undertaken to confirm the technical validity of the new archaeological reconstruction, photoelastic modeling revealed unanticipated critical levels of tensile stress in two regions of the windward buttressing: where the upper fliers abutted the clerestory and where the lower fliers joined the gallery wall. During particularly severe storms, which present-day meteorological records suggest would have struck Paris from time to time in the 40-to-50-year lifetime of the original buttresses, the wind-produced tension in these regions would have been from three to five times greater than the tensile strength of medieval mortar. Because of the highly localized nature of the tension, it is doubtful that major problems with the fabric would have arisen. The cracking would have been readily apparent, however, and repairs, including the pointing of the affected joints, would have had to be made promptly after every great storm to prevent general deterioration.

Such regular maintenance, however, would have been difficult because the regions in question were relatively inaccessible. This suggests it was more than a coincidence that the 13th-century rebuilding effort eliminated these regions of localized tension. The point of abutment of the new giant fliers with the clerestory was considerably higher, and they also significantly reduced the thrust in the gallery-level fliers.

In making the crucial structural changes, the builders probably seized the opportunity to try to raise the light level in the church by enlarging the clerestory windows. Whereas the structural problems of the original design were effectively solved, the benefits derived from the larger windows were at best slight; as anyone who has visited Notre-Dame de Paris will remember, it remains a dark building.





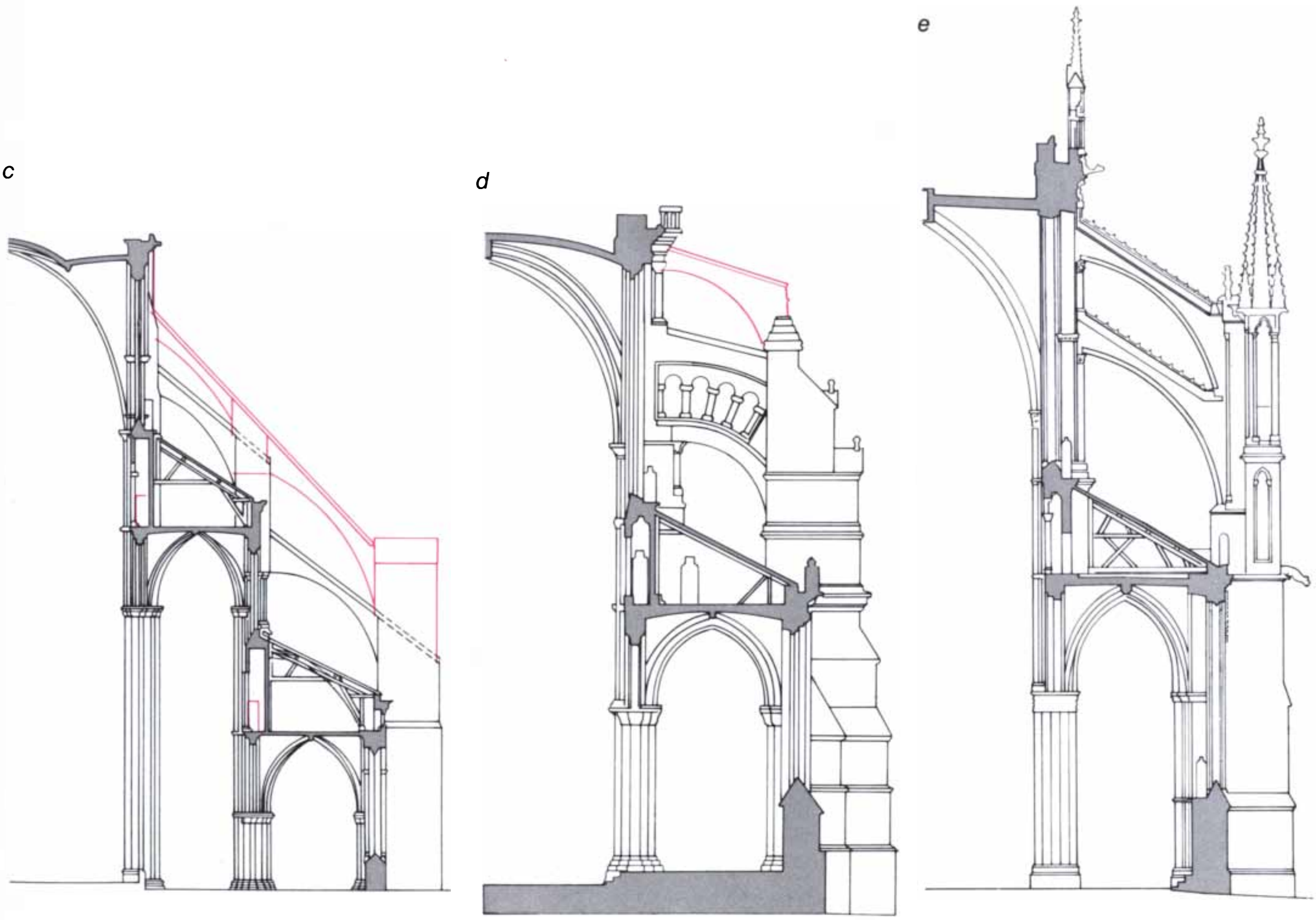
DEVELOPMENT OF GOTHIC BUTTRESSING reflects the recognition of structural problems associated with the original flying buttresses at Notre Dame. The evolution is depicted here by a sequence of building cross sections and a wind-velocity graph drawn to a common scale. Additions to the original design of each building are shown in color; elements that were eliminated are indicated by broken lines. Maximum wind velocity (*black curve*) increases with elevation, and wind pressure, which is proportional to the square of velocity (*colored curve*), increases dramatically. Because of its great height Notre Dame (*b*) was exposed to more severe wind stresses than previous Gothic churches were. The need to brace the nave wall against winds while allowing light into the church prompted the first

Even before Notre Dame was rebuilt the lessons learned there had been applied at other building sites. The choir of the cathedral of Bourges, constructed between 1195 and 1214, is a simple, light yet sound structure. Its elevation is unique: instead of achieving great height—36 meters from floor to keystone—by enlarging the clerestory, the builders dramatically elevated the inner side aisles. The resulting cross section is more triangular than the cross sections of classic High Gothic buildings such as Chartres and Reims, and the wide, stable base makes the walls less susceptible to lateral deformation. Furthermore, the buttressing system is unusually efficient. Because the fliers were steep, they transmitted the horizontal thrusts from vaulting and wind loading to the foundations more directly, and as a result the entire system of supports could be made lighter. Modeling has indicated that, in spite of its extreme lightness, maximum stresses in the Bourges choir are only one-half to two-thirds as great as those found in other large Gothic churches. In critical regions where tensile stresses tend to develop, such as at the ends of the flying buttresses, the Bourges choir outperforms any other large Gothic building we have analyzed.

How, at this early stage in the development of Gothic buttressing, did the Bourges master arrive at such an effective design? Bourges is often linked to Notre-Dame de Paris, because it has five aisles throughout and a similar ground plan. The late Robert Branner, author of the only modern monograph on Bourges, *La Cathédral de Bourges et sa place dans l'architecture Gothique* (Éditions Tardy, 1962), thought the unknown master had been trained not at Paris but to the northeast, in the Aisne River valley. A comparison of the cathedral's cross section with that of our reconstruction of the original Paris nave, however, reveals a striking similarity in spatial proportions. This similarity suggests that the design of Bourges may have been derived from Paris (and also provides additional corroboration of our Paris reconstruction).

The evidence that the original inspiration for the Bourges buttressing came directly from Paris is actually even stronger. From his archaeological analysis Branner concluded that the original design at Bourges called for only a single flight of fliers to support the choir clerestory, rather than the present double flight. Our own investigations suggest the same is true of the aisle buttressing system. The upper flight of aisle fliers visible today was probably not part of the original plan, and the great pier buttresses to which the fliers transferred outward thrusts were correspondingly shorter. When this scheme is compared with our reconstruction of the Paris nave, the buttressing patterns are seen to resemble each other closely.

At some point during construction the



use of the flying buttress in about 1180. The buttressing was rebuilt beginning in the 1220's in response to structural problems; the new scheme also enabled the builders to lower the gallery roof and enlarge the clerestory windows. Fliers were subsequently added to the cathedral of Laon (*a*), built at about the same time as Notre Dame, even though it was much smaller and probably did not need them. The original designs of the Bourges choir (*c*), completed in 1214, and of the Chartres nave (*d*), completed in 1221, were modified after cracking was observed at Paris. At both buildings upper fliers were added to reinforce the high walls against wind loading. In the Reims nave (*e*) the upper fliers were placed to resist wind loading on the clerestory and roof; the lower ones countered the outward thrust of the vaults.

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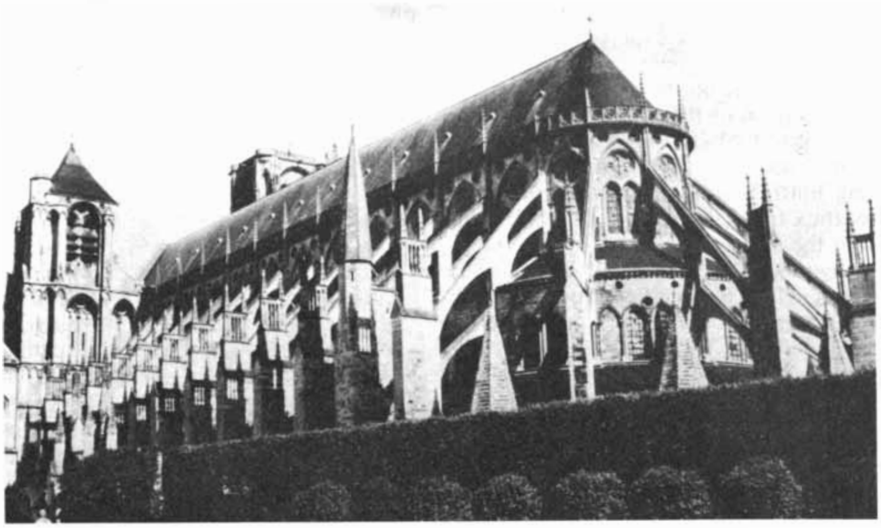
design at Bourges was changed to the one that is still visible. The exact date of this decision is not known, but it probably was made sometime between 1208 and 1214. By then most of the nave at Paris had been standing for perhaps two decades, and it is likely that mortar cracking due to inadequate wind bracing had already been observed. The decision at Paris to construct new flying buttresses abutting the clerestory at a higher level was probably being discussed by the second decade of the 13th century. The bifurcation of the main flying buttresses at Bourges and the raising of the point of abutment of the upper flier with the clerestory, as well as the addition of the second flight of aisle buttresses, can all be seen as precautionary measures taken by a master mason who had heard about the problems at Paris. As it turns out, the movement upward of the abutment of the clerestory fliers was particularly prudent. Photoelastic modeling has shown that the abutment region is the only one in the cathedral where critical tensile stresses tend to develop and that lower abutment would have worsened this problem.

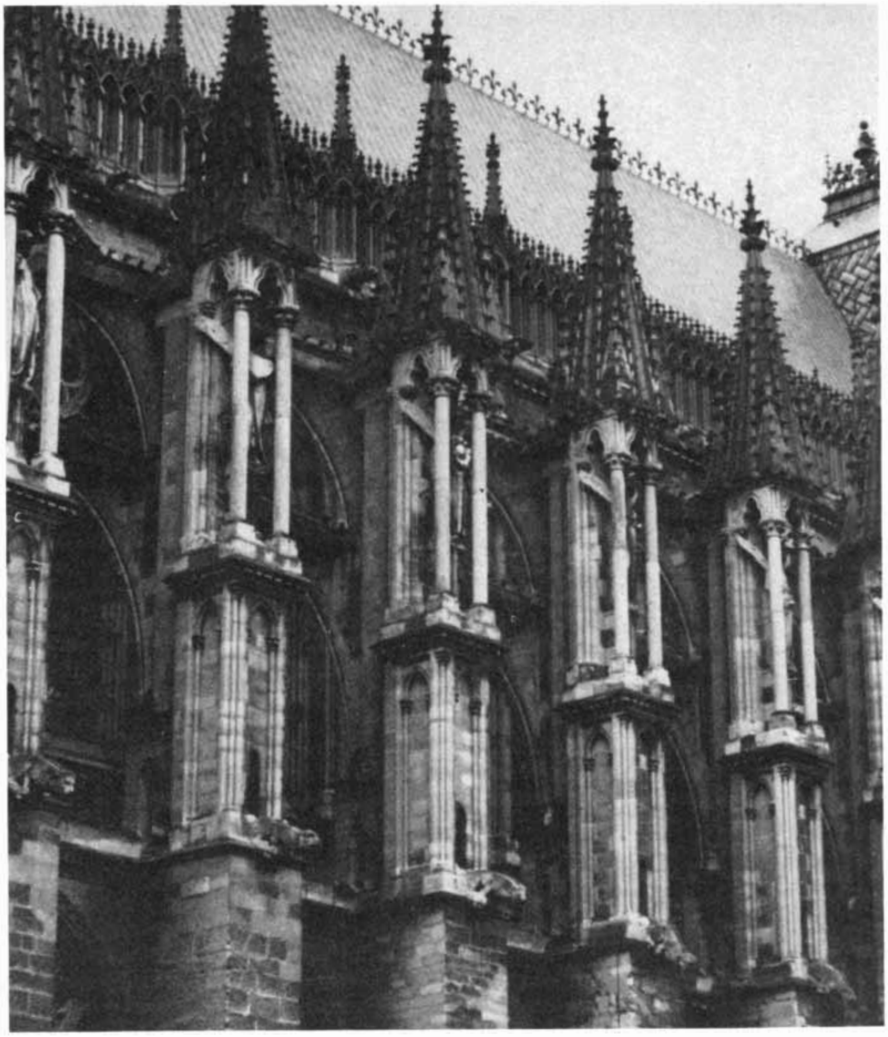
The steep, efficient flying buttresses at Bourges thus appear to be the result of increased awareness, based on the experience at Paris, of the effects of wind on tall buildings. In spite of their economy and their evident technical success, they were not adopted at other High Gothic churches. Perhaps the Bourges buttresses were seen in their time as too light and too daring, or perhaps they were considered a kind of "technical fix" inappropriate for "high" architecture. For whatever reason, the main line of Gothic buttress development passed instead through the cathedral of Chartres.

Begun almost simultaneously with Bourges, Chartres was built very rapidly; it was virtually completed by 1221. The principal design innovation at Chartres was the great enlargement of the clerestory windows. They drop well below the level at which the main vaults spring from the vertical piers. This achievement has generally been interpreted as deriving from a realization of the full potential of the flying buttress, but from a technical point of view the buttressing of the Chartres nave is relatively ponderous and even clumsy: it includes the equivalent of three separate flying buttresses, as well as an unnecessary spur wall under the side-aisle roof, perpendicular to the main wall.

The uppermost fliers are particularly remarkable. They spring awkwardly from the top of the pier buttress and cut through a projecting cornice at the top of the nave wall. No one doubts that they were not part of the original design, but when and why were they added? It was long thought they were a response



BUTTRESSING OF BOURGES CATHEDRAL is striking in its economy, particularly in the choir (*foreground*). Because the fliers are so steep, they convey the forces of wind and vaulting more directly and can therefore be far lighter than other High Gothic buttresses.



PINNACLES atop the pier buttresses at Reims are slotted and hollowed out, whereas their purely decorative counterparts along the west facade of the cathedral are solid. The combined weight of each buttress pinnacle and of the statue in the niche below is almost equal to the weight of the stone removed from the buttress to create the niche. This suggests the builder was concerned that the weight of solid pinnacles might have decreased the stability of the buttresses.

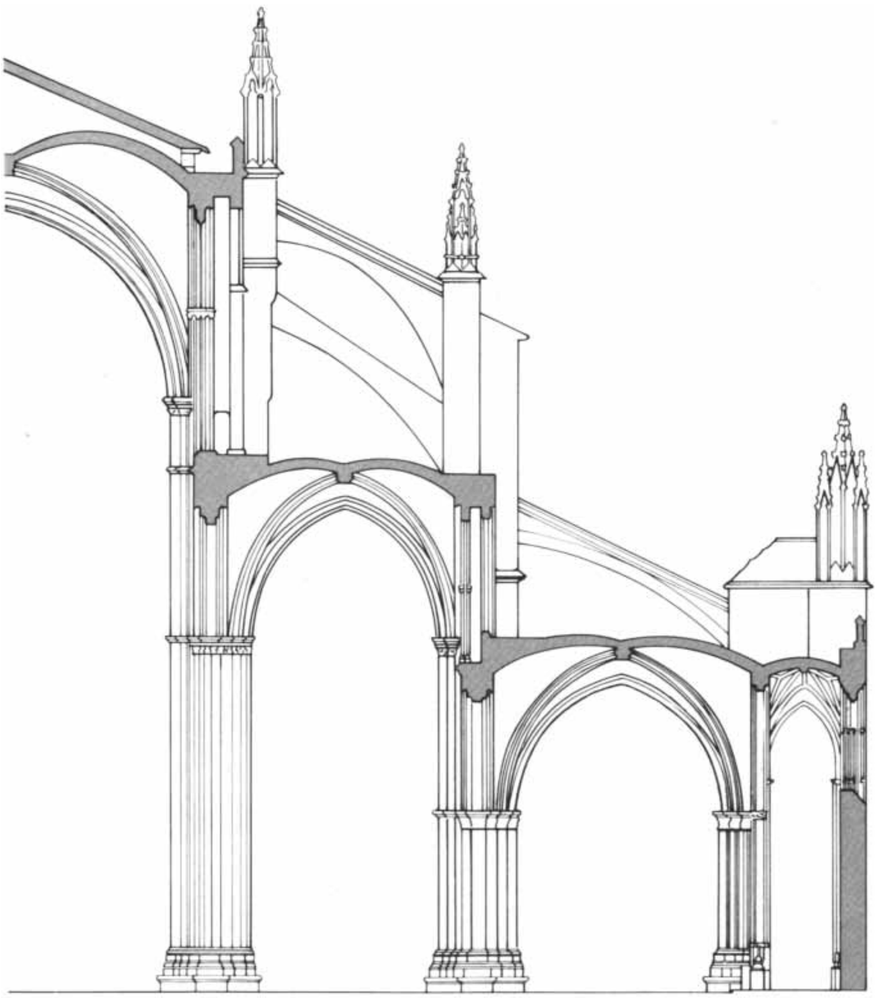
to the *Expertise* of 1316, a report by a group of Parisian experts recommending that the keepers of the cathedral "attend to the buttresses." Modern reinterpretation of the document indicates, however, that its vague injunction referred only to the need to repair existing buttresses. Furthermore, modeling of the Chartres nave both with and without the relatively light upper fliers has shown them to be not fully effective in reducing local tension caused by high winds. It is thus unlikely that they were intended as a corrective to an obvious design fault seen by the Paris experts.

Instead the upper fliers at Chartres were probably added at the end of the original building campaign. New archaeological evidence assembled by John James puts the date of their construction at about 1221. One reasonable interpretation is that the Chartres builder, like his counterpart at Bourges, added new fliers as a precaution against the possible effects of high winds on his structure. The likely source of such caution, both on the part of the builder and on the part of his clients who had to pay for the additional construction, was of course the experience at Paris earlier in the 13th century.

Although the upper fliers were not entirely effective at Chartres, they seem to have pointed the way to the judicious placement of flying buttresses in later High Gothic cathedrals. In these buildings a lower tier of fliers is positioned to resist the outward thrust of the nave vaults, and an upper tier braces the high clerestory wall and the tall timber roof against wind loading. The classic example of this design is the vast cathedral of Reims, begun in about 1210. The Reims buttressing is more refined than that of Chartres: the unnecessary spur wall below the side-aisle roof was eliminated, as was the third flier arch. Yet Reims is relatively conservative compared with the taller structures begun later in the century, such as the huge cathedrals of Amiens (1220), Beauvais (1225) and Cologne (1248).

The cautious approach at Reims, as at Chartres, may well be attributable to the influence of Notre-Dame de Paris. At Reims it extended even to minor details, for example to the design of the pinnacles that top the pier buttresses and lend a strong, unified visual impact to the cathedral exterior. Ordinarily a pinnacle placed near the outside edge of a buttress adds to the bending effect created by the outward thrust of the fliers and thereby diminishes the stability of the pier buttress. Because the pinnacle is relatively light compared with the great weight of the buttress, this effect is small, and at most churches it was ignored. At Reims, on the contrary, the builder appears to have taken some pains to lessen the effect of pinnacle loading. The central spire of each pinnacle is slotted and hollowed so that the weight of the pinnacle, combined with that of the statue in the niche below it, is estimated to be 52 tons—or only about two tons less than the estimated weight of the stone removed from the buttress to form the niche. The pinnacle therefore does not affect the overall stability of the buttress.

Such a sophisticated balancing of mass might seem to be beyond the ability of a prescientific builder. Yet in regions of the cathedral where the pinnacles have only a decorative rather than a structural role, such as along the west facade, they are solid and heavier than their counterparts on the pier buttresses. This supports our view that the hollowing out of the pier-buttress pinnacles was the premeditated act of a builder concerned about the stability of the buttressing. The structural conservatism was quite deliberate, and it probably was a response to the problems encountered at Paris.



TOLEDO CATHEDRAL section shows substantial upper flying buttresses that appear unnecessary for its structure. They were probably deployed in reaction to the observation, before building began at Toledo in about 1227, of wind-induced tensile cracking at Notre Dame.

Caution born of the experience gained at Notre Dame appears to have been a pervasive influence in Gothic architecture of the early 13th century, even affecting many smaller churches. One example is the cathedral at Laon, the construction of which was well advanced by the time the flying buttress was invented. There is no reason to believe fliers were necessary at Laon, which has an interior height of only 24 meters, but they were nonetheless incorporated, almost immediately after they appeared at Paris, into an otherwise unaltered structural scheme. An even clearer example of overbuilding is the Parisian abbey church of Saint-Germain-des-Prés. Flying buttresses were added to the already completed choir, even though its vaults are barely 14 meters high, significantly less than half the size of those of Notre Dame.

The influence of Notre Dame was not confined to France. In Spain, for example, a number of major Gothic churches were under construction in the third decade of the 13th century, just as renovations were being undertaken at Paris to address the problem of wind-produced tensile stress. The buttressing of the cathedral of Toledo resembles our reconstructions of the original buttressing of both Paris and Bourges. Compared with the French cathedrals, however, Toledo is relatively broad for its height (about 31 meters), and the roof is low-pitched, so that the maximum force of winds against the clerestory is relatively small. Nevertheless, the clerestory is buttressed by two tiers of fliers. The upper tier, which in the classic French churches resists wind loading on the roof, seems to have only a visual role at the cathedral of Toledo. It too was probably a response to the experience at Paris.

The modification of an entire series of Gothic cathedrals following the observation of structural flaws in an earlier building has a parallel in the present, one that also involves new experience gained from light construction on a large scale. When the 854-meter main span of the Tacoma Narrows suspension bridge opened in July, 1940, it was the third-longest in the world. Moreover, its weight per meter of roadway was by far the lightest of any long span. The Tacoma Narrows Bridge epitomized the early 20th-century trend toward lighter, almost ribbonlike roadway decks and slender towers. The depth of its plate-girder deck stiffening was only 1/350th of the span.

Four months after the bridge opened, a fairly steady 40-mile-per-hour morning wind produced severe twisting oscillations in the span; it collapsed catastrophically by midday. The only direct casualty was a dog abandoned in an automobile, but an indirect casualty was the "thin aesthetic" in American suspension bridges. Many of the suspension spans built during the period between the two world wars, including the Bronx-Whitestone Bridge in New York and the Golden Gate Bridge in San Francisco, were quickly stiffened, usually through the addition of heavy trusses to the roadway decks. The generation of bridges built after the disaster also incorporated such trusses.

Thus even in the scientific age architects and engineers must gain experience from completed structures, particularly from those that are much larger than earlier prototypes. And if the experience is to have a maximum benefit, it must be rapidly communicated to other building sites. From our studies of prescientific, Gothic structures we have concluded that similar, if a bit slower, communication occurred as early as the 12th century. With the establishment of such a network of communication the empirical approach to structural design proved surprisingly effective.