The Structural Analysis of Gothic Cathedrals

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The Structural Analysis of Gothic Cathedrals

Comparison of Chartres and Bourges by optical stress analysis relates the aesthetic achievement to structural imperatives and suggests that later Gothic cathedrals may have been patterned on the wrong building

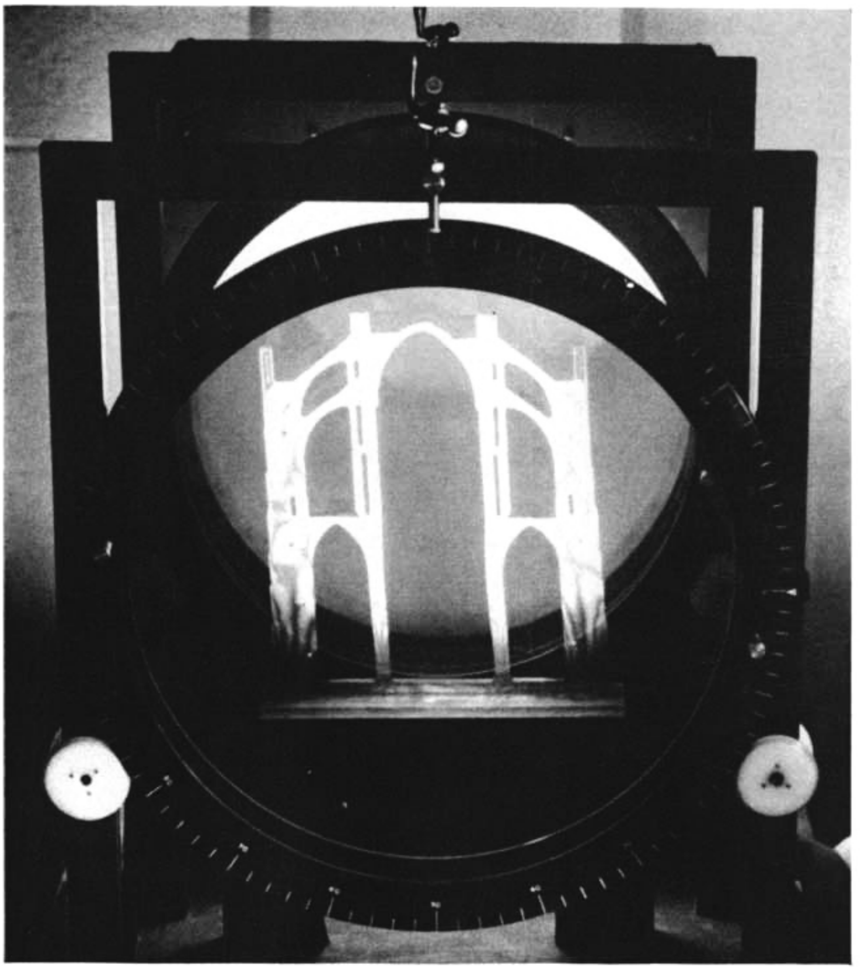
by Robert Mark

The 12th century was a time of prodigious change in the West. With the end of the First Crusade in 1099 the Mediterranean had again become a European sea; the reopening of trade routes and the creation of a powerful and affluent merchant class began to transform the entire fabric of medieval society. In the resulting context of increased wealth and expanded contact with the East a new form of architecture emerged: the Gothic.

Its primary characteristics were structure and light. Applied decoration was kept subservient to effects produced by the structure's own piers, ribs, vaults and buttresses. Even the achievement of interior "luminosity" was related to structure: it was attained by light admitted through stained glass in enlarged wall openings. By the end of the century this preoccupation with structure had taken visible form. Two immense Gothic cathedrals were under construction, one at Chartres and the other at Bourges. And it was during the first half of the next century, in the Île-de-France region, that Gothic architecture is generally considered to have flowered, with the completion of Chartres in 1221 and then of major portions of the cathedrals of Reims (begun in 1211) and Amiens (begun in 1220).

The principal structural features of what came to be called classical High (literally high) Gothic were established at Chartres and refined in the later buildings: thin, quadripartite, pointed ribbed vaults are supported at regular intervals on tall piers; the piers themselves are supported laterally at the level of the clerestory by flying buttresses that lead to pier buttresses, or high exterior towers, usually topped by pinnacles. Intervening load-bearing walls were not required, and so they were largely supplanted by window openings [*see illustration on page* 92]. The height of the central aisle of these cathedrals is striking: the distance from the floor to the bottom of the keystones of the vaults is 118 feet at Chartres, 123 feet at Reims and 137 feet at Amiens. And a peaked wooden roof above the vaults adds as much as 60 feet to the overall height of the building section.

The evolution over a relatively short time interval of new structural systems that made possible this substantially lighter and higher masonry construction



OPTICAL STRESS ANALYSIS of structure is carried out in a polariscope, in which a plastic model of a section of a cathedral (Amiens in this case) is viewed between polarizing filters (*see illustrations on page 96*). Regions of stress in the plastic produce interference patterns: different colors in white light, and dark and light bands in monochromatic light.

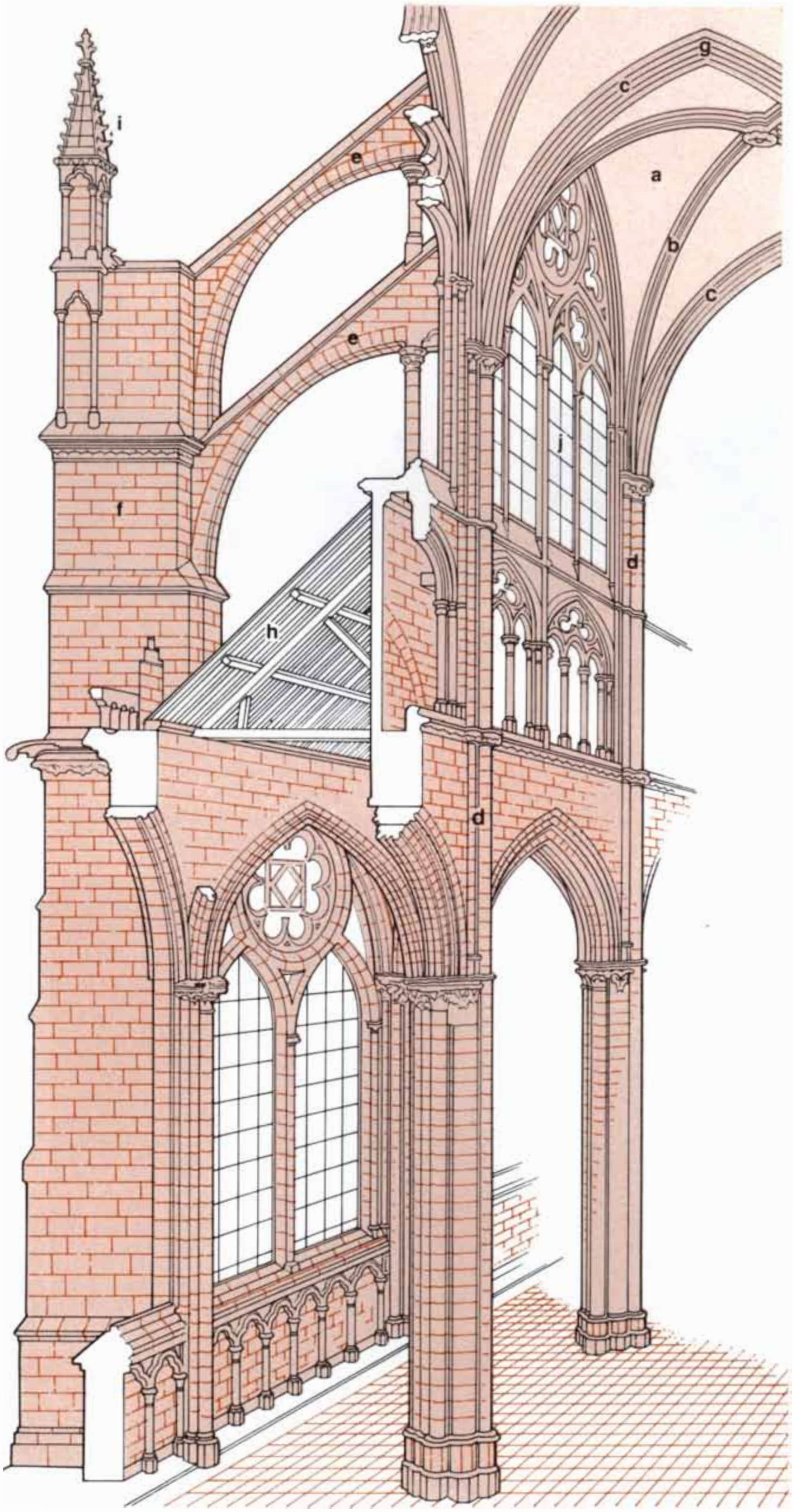
has never been fully explained. The stability of these great structures for some 700 years attests (in spite of a few spectacular failures) to the technical skill of their builders. How was this record of stability achieved? The cathedrals were designed without benefit of any mathematical structural theory; fragmentary evidence indicates, in fact, that the architects of the era worked only with roman numerals, so that they probably were unable even to multiply to calculate simple volumes. It has been suggested that they first built models to aid in planning, but in the absence of any numerical facility, let alone scaling theory, models would not have enabled them to predict the performance of the full-scale structures under load. My own hypothesis is that the design may have been successively modified on the basis of observation of the buildings during the course of construction. Corrections to eliminate the cracking of newly set mortar caused by either high winds or the removal of temporary construction supports could have been the source of structural innovation.

Far from understanding the cathedral builders' approach to the technical problems of design, architectural historians disagree even about the motivation that shaped their approach. For example, the influential 19th-century French restorer of cathedrals, Eugène Viollet-le-Duc, held that "every [Gothic] member was the result of structural necessity." At the other extreme, the contemporary architectural historian John Summerson has written that "reasons for the adoption [of the Gothic pointed arch] have been summarized in terms of statical expediency, but there is plenty of evidence to show that it was a matter of deliberate choice—a matter of taste.... Like almost everything else in Gothic architecture, [the ribbed vault] originated in aesthetic intention." These divergent opinions define a lively controversy that has developed between the "rationalists," who hail the cathedrals as triumphs of technical ingenuity, and the "illusionists," who reject the possibility that such great beauty could be derived from a technological approach.

In 1960 the noted medieval-art historian Paul Frankl, recognizing the difficulty of technical interpretation, urged his colleagues to consult with "the physicist." Modern physics had veered away from the study of applied mechanics, however, leaving it in the hands of research engineers, and in the past decade engineers have acquired

CHARTRES MODEL, stressed by simulated wind loading, is of a section across the nave of the cathedral. The pattern can be interpreted as a contour map of stress intensity; each color represents a different order of interference, which is related to intensity of stress. The stress is zero in black regions of the model and is highest where fringes are closely spaced.

BOURGES MODEL, a section across the choir, was photographed in the polariscope after being stressed by simulated dead-weight loading. Stress-intensity contours are quantified by analyzing the model illuminated by monochromatic light (*see illustrations on page 97*).



STRUCTURAL CHARACTERISTICS of High Gothic cathedrals are indicated in a drawing of the nave of Amiens Cathedral based on one made by Eugène Viollet-le-Duc. The pointed vaults (*a*) are constructed with a system of diagonal (*b*) and transverse (*c*) ribs on tall piers (*d*). The piers are supported by flying buttresses (*e*) that run to exterior pier buttresses (*f*). Other structural elements are the vault keystone (*g*), the side-aisle roof (*h*) and the pinnacle (*i*). The windowed wall area above the side-aisle roof is the clerestory (*j*).

new experimental and computer-based numerical modeling techniques that make it feasible to analyze the performance of complex structures. It was my students at Princeton University who about six years ago saw that the modern methods of analysis could be brought to bear on unanswered questions about the meaning of Gothic form.

At that time we were conducting research on the behavior of concrete thin-shell roof structures by studying small plastic models with optical stress-analysis techniques that had been developed primarily for studying specialized mechanical components. One goal of our research was to promote the wider application of these techniques for the structural design of complex buildings. We found that the model results could be reliably scaled to predict internal forces and deflections of reinforced concrete structures, even though concrete is an inhomogeneous mixture of materials and is subject to local microcracking. We realized that a masonry structure would also lend itself to this type of analysis provided that it was subjected to only moderate compressive forces. In effect this assumes complete cohesion, which may not actually exist in the full-scale masonry building, but the model does indicate the extent and location of any anomalous regions. If significant tension or compression stresses are found in a model, it can be altered locally, for example slit in tensile regions to represent cracking, and tested again to study the influence of such anomalies. It therefore seemed feasible to use model tests to study the actual structural behavior of the Gothic buildings and possibly also to surmise the intentions of the medieval architects regarding structure.

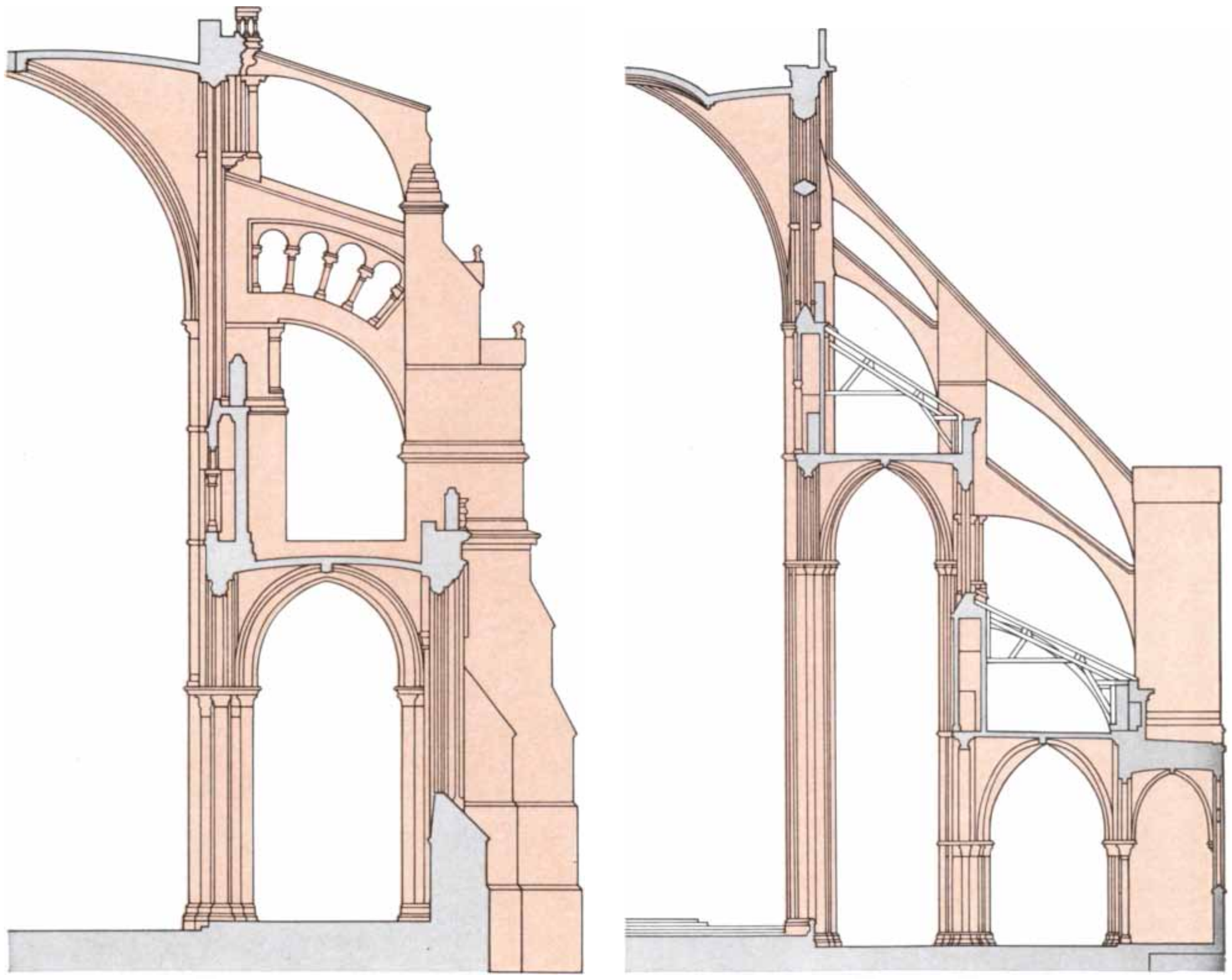
Our first tentative studies brought us in contact with interested colleagues in the humanities. A number of architectural historians, intrigued by the potential of engineering insights, provided the necessary guidance and criticism. Our early efforts included a study of the distribution of internal forces resulting from high wind and dead-weight loads on a section of the nave of the Amiens cathedral. One specific result was our finding that the pinnacles atop the outer edges of the pier buttresses helped to maintain the integrity of the buttresses by overcoming local tension. This analysis disposed of an illusionist argument that the pinnacles must be purely decorative because gross stability considerations would dictate their location at the inner edges of the buttresses rather than the outer edges. Another study, of the late

Gothic St. Ouen church in Rouen, indicated how structural ideas had evolved throughout the Gothic period. One particularly satisfying result of this investigation was our prediction that there might be some cracking in a certain region of the nave piers; the cracking was later confirmed by observation.

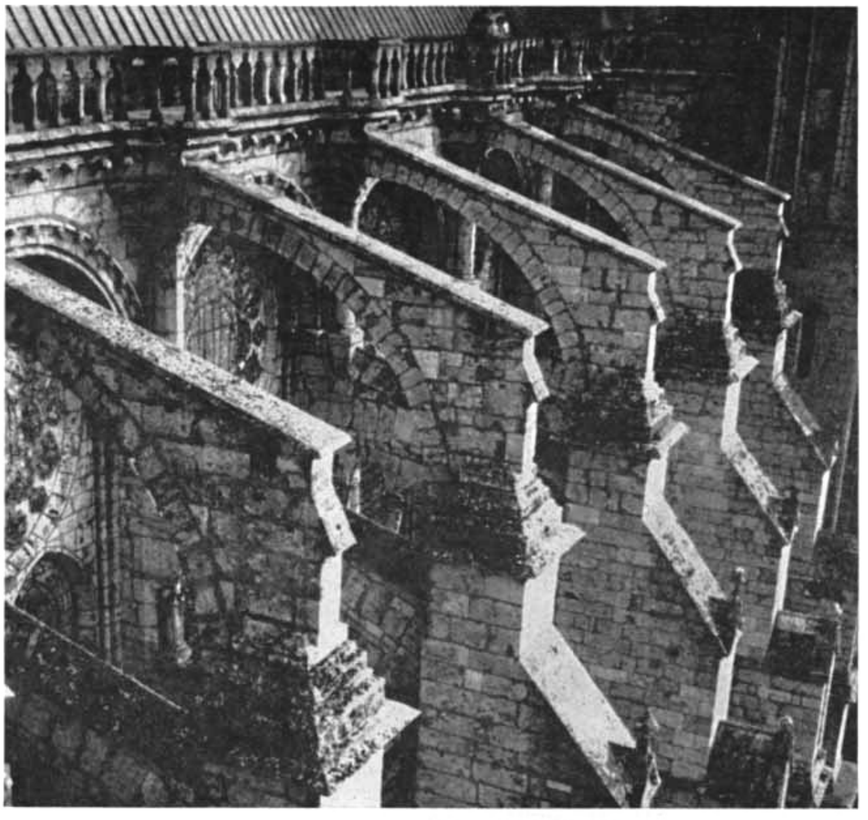
We have not clearly established whether the Gothic architect was motivated more by structural necessity or by "taste." By showing exactly how the structures perform, however, we have at least indicated how he responded to the actual structural needs, and so a beginning has been made in clarifying many of the questions posed by the historian. Probably the segment of our work that is most revealing about the development of High Gothic structure is a recent study comparing the early High Gothic cathedrals of Chartres and Bourges.

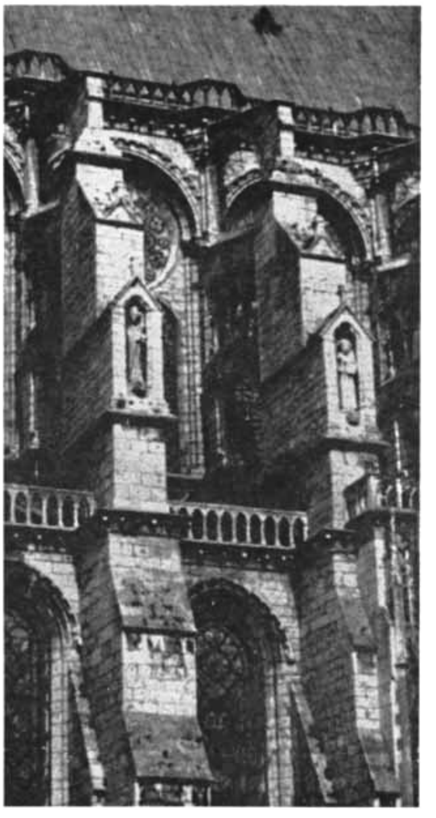
Construction of both buildings began in 1195. At Chartres the work apparently proceeded from west to east, beginning with the nave. At Bourges it proceeded from east to west, and the choir was completed in 1214 although other construction took almost a century to finish. The much more rapid pace of construction at Chartres brought work on the main vessel of the cathedral to a close in 1221. The dimensions of the two buildings are very similar: Bourges is slightly wider and higher and Chartres is longer. Chartres has three aisles and a crossing transept between the nave and the choir; Bourges has five continuous aisles and is without a transept.

Chartres is a very beautiful building, particularly in its details, and from the beginning it received a great deal of attention. After some initial resistance it was accepted as the standard, in effect ending the period of experimentation with Gothic building forms that characterized the 12th century. On the other hand, although Bourges has always been esteemed for its imposing size and beauty, it never attracted a similar architectural following. Even more important to the present study, the profile of its buttressing system was not duplicated in any other High Gothic cathedral. The importance of Chartres is implicit in the emphasis placed on it in the literature on the Gothic cathedral. Bourges, often mentioned as an interesting footnote, has been the subject of only one complete modern study, by Robert Branner of Columbia University. The main reason for the ascendancy of Chartres, according to Branner, is that it was imitable: its design could be reordered to suit almost any site, whereas the Bourges scheme could only be adopted whole. It might also be that Chartres's location, only 50 miles (a one-day journey on horseback) from Paris, allowed it to become far better known, to ecclesiastic patrons as well as to medieval architects, than Bourges,

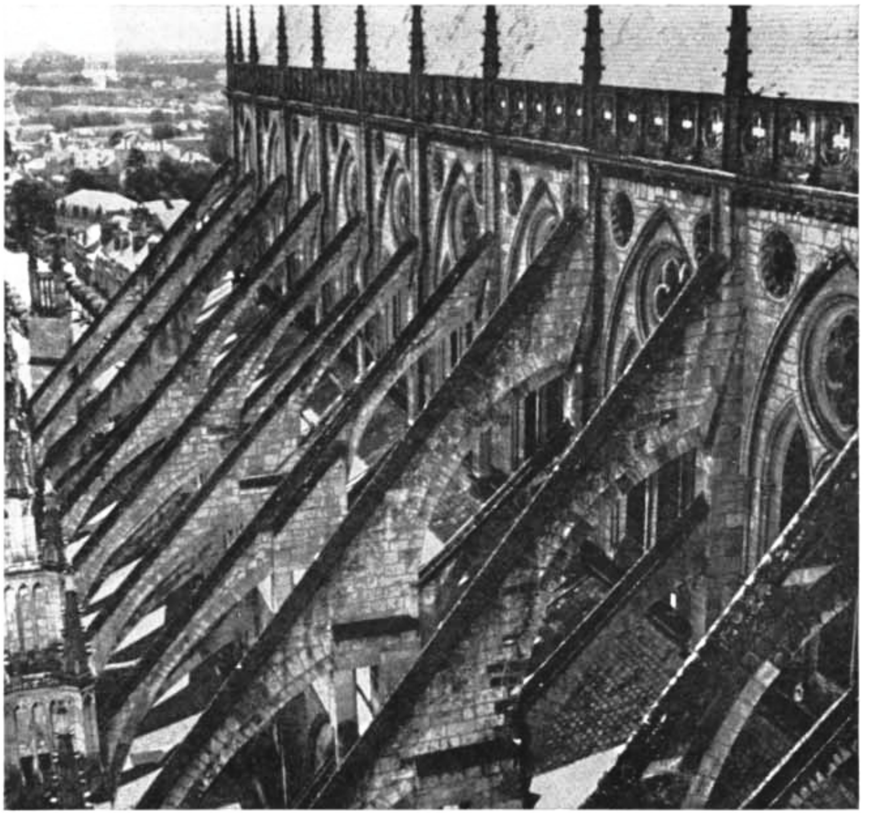


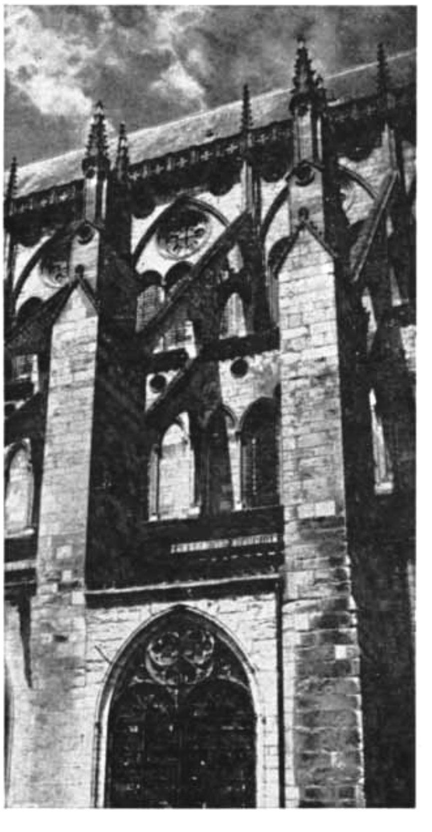
CHARTRES AND BOURGES sections are compared. The three-aisle layout of the Chartres nave (*left*) became the model for High Gothic cathedrals; the Bourges choir (*right*) has five continuous aisles. Flying buttresses carry the vault and roof loadings more directly to the foundations at Bourges than they do at Chartres. The Bourges section is based on a drawing made by Robert Branner.





UPPER FLYING BUTTRESSES of Chartres (*left*) are uncharacteristically light and were generally assumed to have been added during the 14th century in order to correct a fault in the original design. The author's analysis indicates that they were probably a part of the original design, however. As seen from the ground (*right*) heavy pier buttresses tend to obscure the flying buttresses.





FLYING BUTTRESSES of Bourges (*left*) were built at different times. Those supporting the choir (*background*) are lighter than those used for the nave, which was constructed later; the nave flying buttresses also come closer to the roof. The piers at the choir are seen to be reinforced, just above their intersection with the flying buttresses, by the parapet: the wall just below the roof (*right*).

which is more than twice as far from Paris.

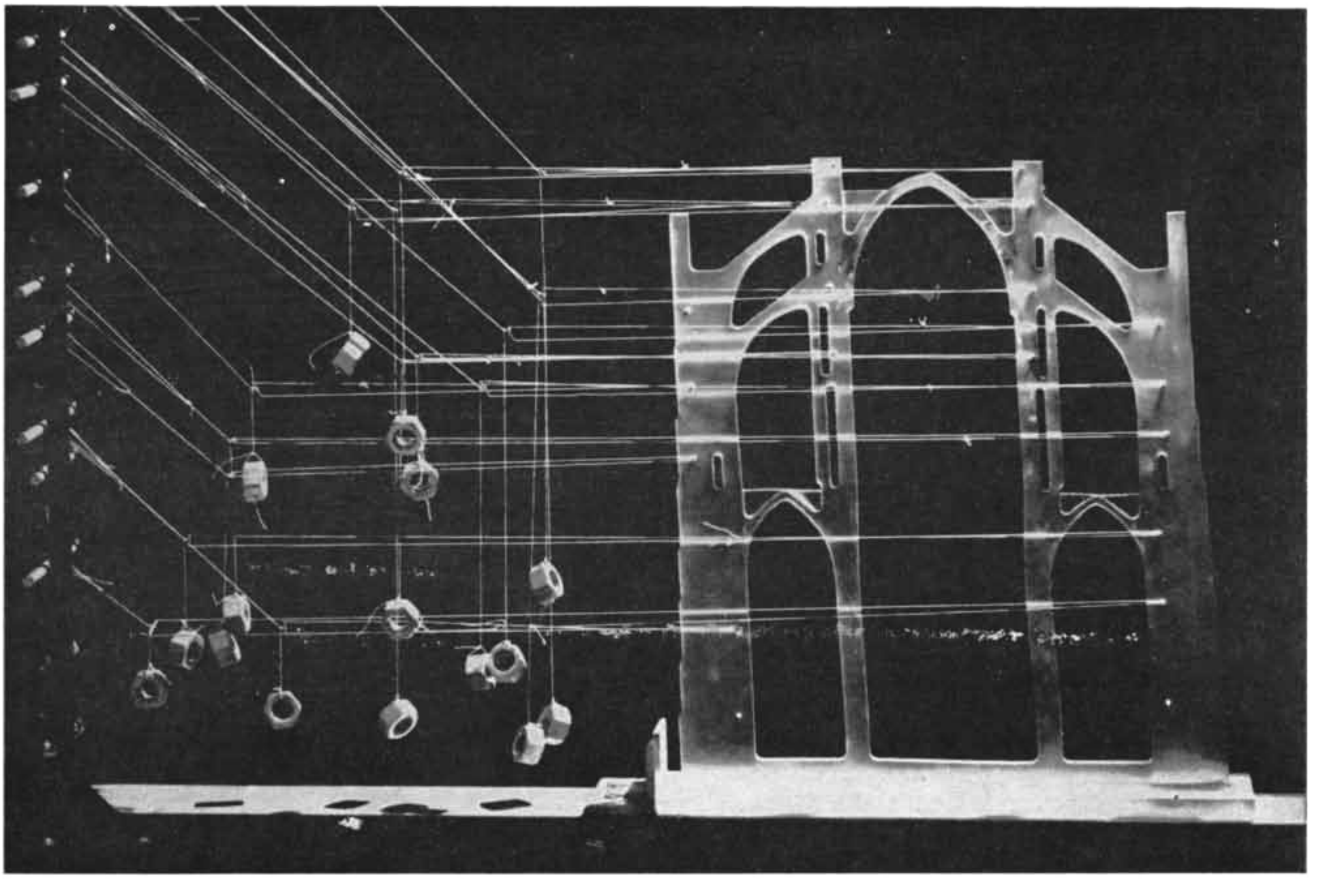
At the time the two cathedrals were planned, the exposed flying buttress was a relatively new device. It had been used first in the 1170's at Notre Dame in Paris, but its full significance in allowing a great reduction of clerestory structure was only realized at Chartres and at Bourges. The cross sections of the two buildings reveal that the two masters employed different forms of buttressing [*see illustration on page 93*]. At Chartres the entire system is very heavy except for the light upper fliers; each of the tall pier buttresses, exclusive of its foundation, weighs 1,000 tons. At Bourges, on the other hand, a series of fine, steeply sloped fliers is supported by a low pier buttress weighing only 400 tons.

As with every other feature of Chartres, much has been written of its structure. According to Frankl, "the master who rebuilt the cathedral at Chartres... was the first man to draw the logical consequences from the construction of flying buttresses." In the same vein Otto von Simson wrote that "the flying buttresses of Chartres are the first to have been conceived, not only structurally but also aesthetically, as integral parts of the overall design." Almost all the critics, however, have questioned the role of the light upper fliers at roof level. A 1316 document produced by a group of experts called to examine the fabric of the then century-old cathedral has been generally interpreted as calling for the construction of these additional fliers, but the various opinions as to their function serve only to demonstrate how little is actually understood about the technical behavior of Gothic structure and the medieval architect's conception of structural necessity. Some writers maintain that the fliers are purely decorative; others believe they function as structure, although there is disagreement about how they function.

My colleague Alan Borg reinterpreted the 1316 document and assembled art-historical evidence to indicate that the Chartres upper fliers had been part of the original construction, but the functional reason for their existence still had to be considered. Since medieval roof framing is tied between the piers supporting the roof by stout, pinned cross-members, the only lateral loads on the upper portion of the piers are those due to wind action. The argument that the upper flier was added after 1316 to correct a fault in the original configuration would be substantiated if it could be shown that the upper buttress significantly reduces local tensile stresses in the piers that are caused by wind loading on the high roof. In view of the fact that the strength of the ancient mortar in tension has been estimated to be only 30 pounds per square inch, whereas stone can resist almost 100 times that stress in compression, minimizing or completely eliminating tension in a stone and mortar structure was a critical design requirement.

To examine the pier response we applied engineering analysis methods developed for designing contemporary high-rise buildings and used in our previous cathedral studies. We began by obtaining local meteorological data for the Paris region in order to determine the maximum possible wind velocities over the life of the cathedral and defining from wind-tunnel data the maximum wind-pressure distributions related to the meteorological data, the terrain on

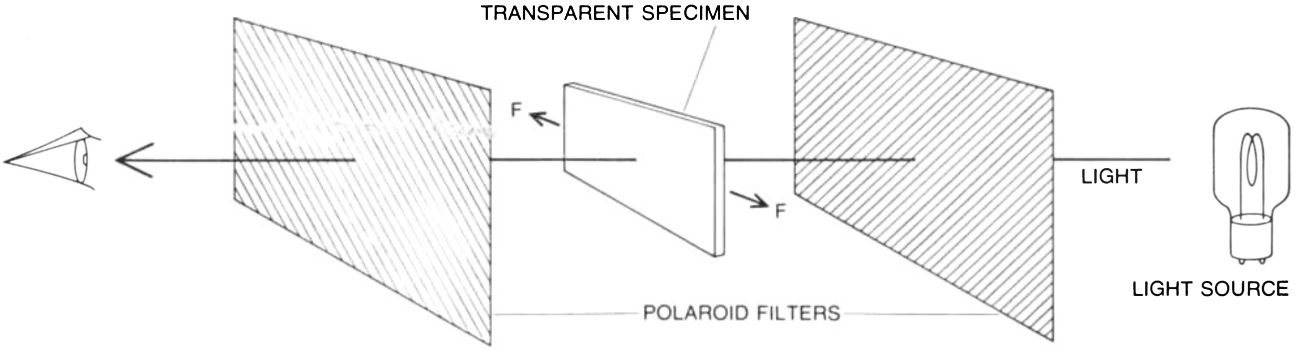
MAIN VAULTING of Bourges rises 120 feet above the floor. Whereas the vaulting of Chartres and almost all other High Gothic cathedrals is quadripartite (*see illustration on page 92*), Bourges's vaulting is sexpartite. Alternate piers meet one vault rib or three ribs.



MODEL OF AMIENS is weighted to simulate wind loading against the right side. (Dead-weight loading would be simulated by hanging the weights from the modeled ribs and buttresses.) When the model is heated to 150 degrees Celsius, the plastic becomes rubbery and is deformed; when the heat is reduced, the deformations remain frozen in and the model can be observed in the polariscope.

which the building is sited and the geometry of the building. A 1:180 scale model in epoxy plastic of a typical buttress section of Chartres was fabricated without the upper fliers and tested under loading that represented the actual distribution of wind pressure (and of suction on the lee side). Fortunately the systematically executed French cathedrals are susceptible to simple planar (two-dimensional) analysis, since the nave is generally divided into bays with similar dimensions, the piers, buttresses and transverse arches of the central and side aisles are all in the same plane and the loadings from the bays are entirely directed to these members. We assumed that the massive foundations give complete fixity to the piers and buttresses at ground level, that is, that they do not allow any deflections at the base. Cross sections of the structural members were not fully modeled. (For example, fluted piers are represented by rectangular sections.) The analysis for the full-scale structure therefore contains discrepancies, but they are not significant.

Epoxy plastic undergoes a phase change to a rubbery state when it is heated to about 150 degrees Celsius. Lowering its temperature back to normal locks in any deformations due to loadings that are present during the high-tem-



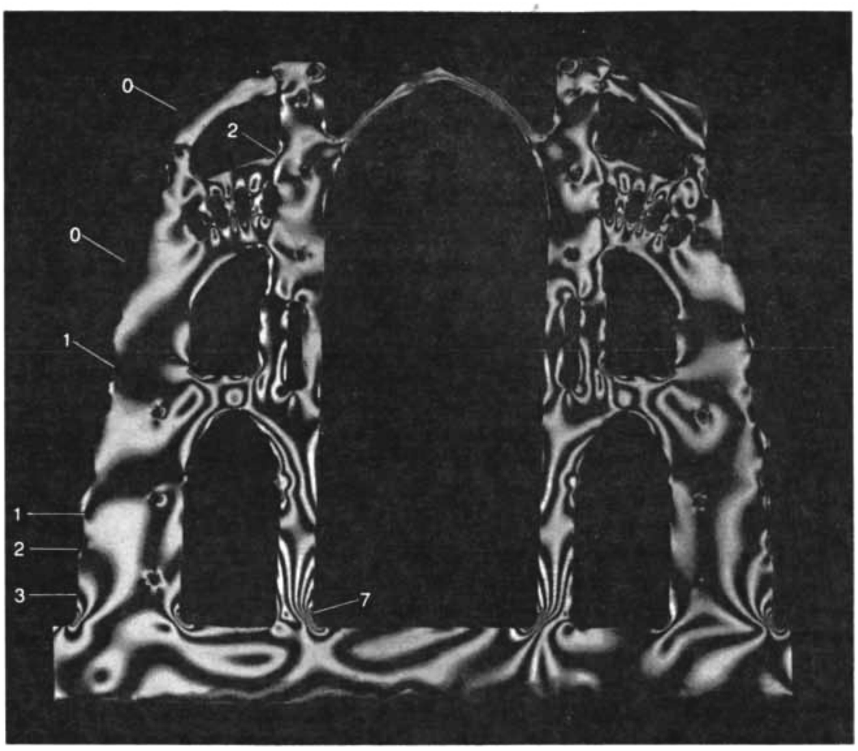
PHOTOELASTIC PRINCIPLE underlying stress analysis is illustrated. Crossed-axis polarizing filters cut off the light. An unstressed transparent specimen has no effect on the polarization and so the field remains dark, but when forces (F) are applied, the specimen is deformed. As a result the polarization of light leaving the specimen is altered depending on the magnitude of the forces, the material and geometry of the specimen and the wavelength of the light. This altered polarization is seen as an interference pattern.

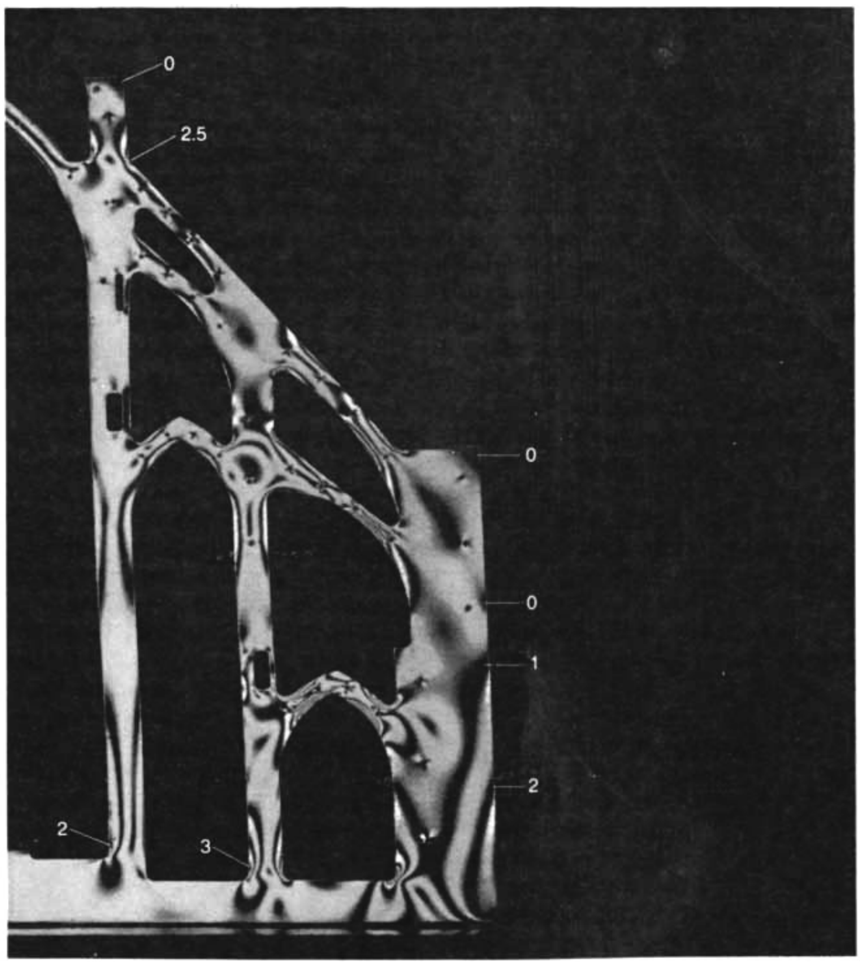
perature phase. This process is called "stress freezing" because the loading can be removed after cooling without disturbing the deformations that occurred at high temperatures, and the model can be examined and photographed conveniently.

The internal force distributions in the deformed model were determined from photoelastic observation, in which the polarized-light interference pattern produced by the model in a polariscope is read as a contour map showing stresses [*see illustrations on page 91 and at right*]. Under white-light illumination each line in the pattern is characterized by a distinctive color indicating a specific order of interference. The intensity of stress at any point is found by multiplying the order of interference by a calibration factor obtained from a specimen of the model material. Scaling laws can then be used to predict full-scale behavior under actual conditions.

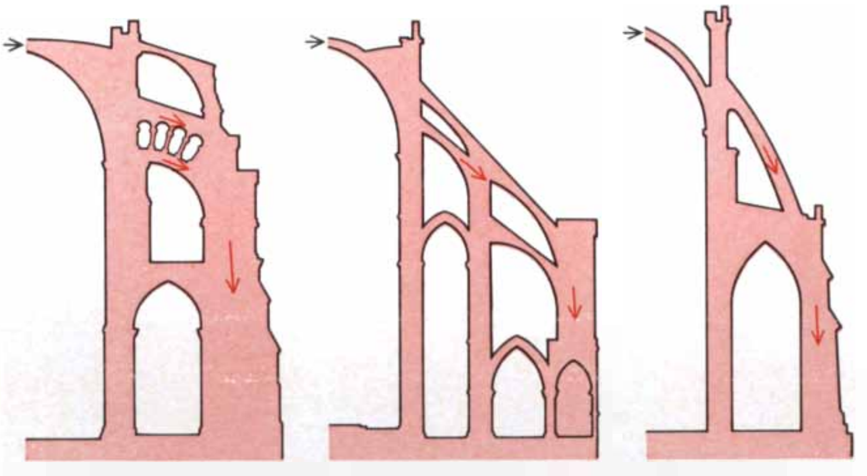
Following the first test we annealed the model by heating to restore it to its undeformed condition and then attached the scaled upper fliers with high-temperature epoxy cement and made a second test with the same simulated wind loading. In the final phase of the analysis the stress in the piers caused by the dead-weight loading of the roof and its framing, the weight of the piers above the critical sections and the weight of the heavy longitudinal arches above the clerestory windows were calculated. Combining this dead-weight effect with the stresses arising from the extreme wind forces gave the maximum stresses that could be expected in the structure.

All the compression values in the buttress region were much less than stresses at the pier bases, and they required no further consideration. Low tensile stresses were also indicated at the windward edges of the windward piers just above the main vault-supporting flying buttresses. The onset of this pier tension in the unbuttressed configuration was found to correspond to gusts with a mean velocity at rooftop level of 45 miles per hour, compared with 55 m.p.h. for the buttressed pier. Under the most extreme gust conditions, with mean velocities of 65 m.p.h. near ground level and 85 m.p.h. at the rooftop, there could be a maximum tensile stress of 60 pounds per square inch in the unbuttressed pier and 30 pounds per square inch in the buttressed pier. In other words, a region of local tensile activity is indicated in the upper piers under extreme winds. If there had been no upper flying buttresses, this condition would have been present with somewhat lower wind velocities and the





PHOTOELASTIC PATTERNS in wind-loaded Chartres (*top*) and Bourges (*bottom*) models appear as dark and light lines in monochromatic light. Successive dark lines represent different orders of stress intensity, indicated by numbers; intermediate orders are found by interpolation. By calibration with a known specimen, one can derive quantitative stresses in the model, which are scaled to indicate the behavior of the actual cathedral structure.



PROGRESSION to lighter and more simplified construction is indicated by a comparison of vault thrusts (*black arrows*) and resulting structural forces (*colored arrows*) in Chartres (*left*), Bourges (*center*) and a hypothetical modern design for a Gothic cathedral: a redesign, by the French critic Julien Guadet in 1902, of the cathedral of St. Ouen (*right*). Guadet substituted steeply inclined arches for the classical buttressing system. Analysis in the author's laboratory showed that the Guadet design is feasible and reduces structural forces.

probability of pier distress would certainly have been greater, but the upper flier does not entirely eliminate the problem; it is too light a structure to have been a deliberate addition intended to rectify an obvious structural flaw.

While it is not possible to draw absolutely firm conclusions from either analyses of the models or art-historical observations, both sources of evidence point to the conclusion that the upper flier was part of the original construction. The analysis has shown that this flier has only small effect on the heavy pier section, and so it becomes difficult to believe that the experts of 1316 would have suggested its addition. By that time the architects had had considerable practical experience with buttressing, and they would hardly have proposed the difficult and expensive addition of extra fliers unless these members were absolutely essential.

The significance of this analysis goes beyond the apparently minor issue of the date and purpose of the upper buttress itself, since our conclusions indicate that the Chartres architect was uncertain about buttressing. Considering the state of the art at the time of construction, that is hardly surprising. Yet an entirely different picture emerges when we examine the contemporaneous Bourges choir, whose light, open buttresses invite comparison with the heavy (in contrast even ponderous) Chartres system.

In planning the model test for Bourges it was necessary to account for its sexpartite vaulting. Unlike the quadripartite vaults of Chartres, which distribute equal loads to all the interior piers, the Bourges vaults transmit alternating high and low loads to correspondingly sized main piers along the interior aisle. A typical "strong" pier section, subjected to the higher vault loads, was modeled in epoxy plastic at a scale of 1:107 and was tested as in the Chartres study, first under dead-weight loading and then under simulated wind loads.

The best meteorological data applicable to Bourges were for Châteauroux, some 35 miles southwest of Bourges, and for a recent 10-year period rather than for 100 years, as at Chartres. The data indicated that Bourges is in a more sheltered area than Chartres. The maximum mean-wind velocity at the elevation of the cathedral roof was taken as being 65 m.p.h. Since wind forces on a building are produced as the square of the wind velocity, this reduction from the 85-m.p.h. velocity at the Chartres roof lowered the calculated maximum total force acting on each cathedral bay from the Chartres value of 110 tons to 60 tons for Bourges.

Under the action of combined dead-weight loading and wind loading, the stress levels throughout the section were found to be quite low. The highest compression stress, at the base of the main piers, was scaled to be 300 pounds per square inch, or about two-thirds of the maximum levels found in several other High Gothic buildings. Part of this reduction is attributable to the lower ambient wind speeds and part to the broader profile of the building section.

Since the Bourges choir does not employ an upper flier at roof level, we were particularly interested in scrutinizing the relatively slender unsupported upper main pier. We found that the vault thrust is entirely carried by the lower of the two flying buttresses that support each pier. The higher one must then have been placed to provide support against roof and parapet wind loading. Why was it not brought up close to the roof as at Chartres, or for that matter as in the seven nave piers of Bourges that were constructed in a later building campaign (after 1232)? The answer can be seen at the choir clerestory if one examines the intersection of the higher flying buttress with the pier. At this point of greatest bending moment the pier is reinforced by the lower part of the parapet to form a stout *T* section [*see bottom illustration on page 94*]. The tests revealed that the onset of tensile stress, which occurs in the windward upper pier, corresponds to gusts with a mean wind velocity at rooftop level of 57 m.p.h.; tension here is less than 10 pounds per square inch under the highest wind condition. The light choir structure of Bourges, then, provides stability to the high roof that is fully comparable to that afforded by the much heavier Chartres buttress configuration. One can speculate that a second Bourges architect, who clearly attempted to maintain the visual pattern of the choir buttresses when he designed the nave, was familiar with Chartres and probably was uneasy over his predecessor's daring. He modified the original design by deepening the flying buttresses and raising the point of abutment of the higher buttress against the pier.

Our analysis also indicated that without its pinnacles the low pier buttress would not be subjected to tension; the existing pinnacles have no structural role, as they do for example on the Amiens pier buttresses. This observation is entirely consistent with the fact that the Bourges pinnacles have been shown to be a 19th-century addition.

Additional light is shed on the achievement of the Bourges architect by a critique of the late Gothic St. Ouen church at Rouen that was published in 1902 by the French architectural authority Julien Guadet. He questioned the unique necessity of the classical structure: massive pier buttresses resisting vault forces through flying buttresses. He proposed a hypothetical alternative design in which the original interior configuration is unaltered but the buttressing system is considerably lightened by the substitution of steeply inclined arches. Besides requiring less material the alternative design implies a simpler construction process.

Guadet published a graphical force analysis to substantiate his design, but it was a limitation of the current method of analysis that the interaction of the structural members could not be taken into account. For example, in the actual structure any deflection of the pier at its intersection with the arch must be accompanied by a corresponding deflection of the end of the arch. Considerable forces can be set up by these interactions and their effect should not be neglected. We accounted for these forces in a model test of the Guadet design. Although some further modifications might be necessary if wind forces were to be considered, the test showed that Guadet's design was reasonable for the deadweight loadings he applied. Hence we can consider the alternative St. Ouen design to represent a more advanced, theoretical Gothic form.

Juxtaposing the sections of the three similarly sized buildings reveals an obvious structural hierarchy [*see illustration on opposite page*]. The quantity of stone in the buttressing systems is progressively reduced from Chartres to Bourges to Guadet's St. Ouen. This reduction is achieved by carrying the vault and roof forces more directly to the foundations by raising the angle of the flying buttresses and consequently lowering the height of the pier buttresses. With only primitive machinery available for cutting the huge building stones and lifting them into place, the 60 percent reduction in weight of the Bourges pier buttresses compared with those of Chartres must have represented a tremendous economy in construction.

The final irony of Chartres is that instead of treating the flying buttresses as "integral parts of the overall design" the architect may actually have been attempting to conceal them behind the extremely heavy pier buttresses. It is a fact that the flying buttresses cannot be easily seen unless the viewer is quite close to the nave wall [*see top illustration on page 94*].

Clearly architecture can be misinterpreted if its technical aspects are not well understood. The problem is more acute when the scale of the project is large and the underlying technology assumes a more vital role in the design. The major contribution of Chartres was aesthetic; it provided the model for the great High Gothic buildings to follow. Yet technically Chartres was far less revolutionary than has been claimed. On the other hand, the structural solution adopted at Bourges was truly unique. It may, in fact, have been too far ahead of its time.

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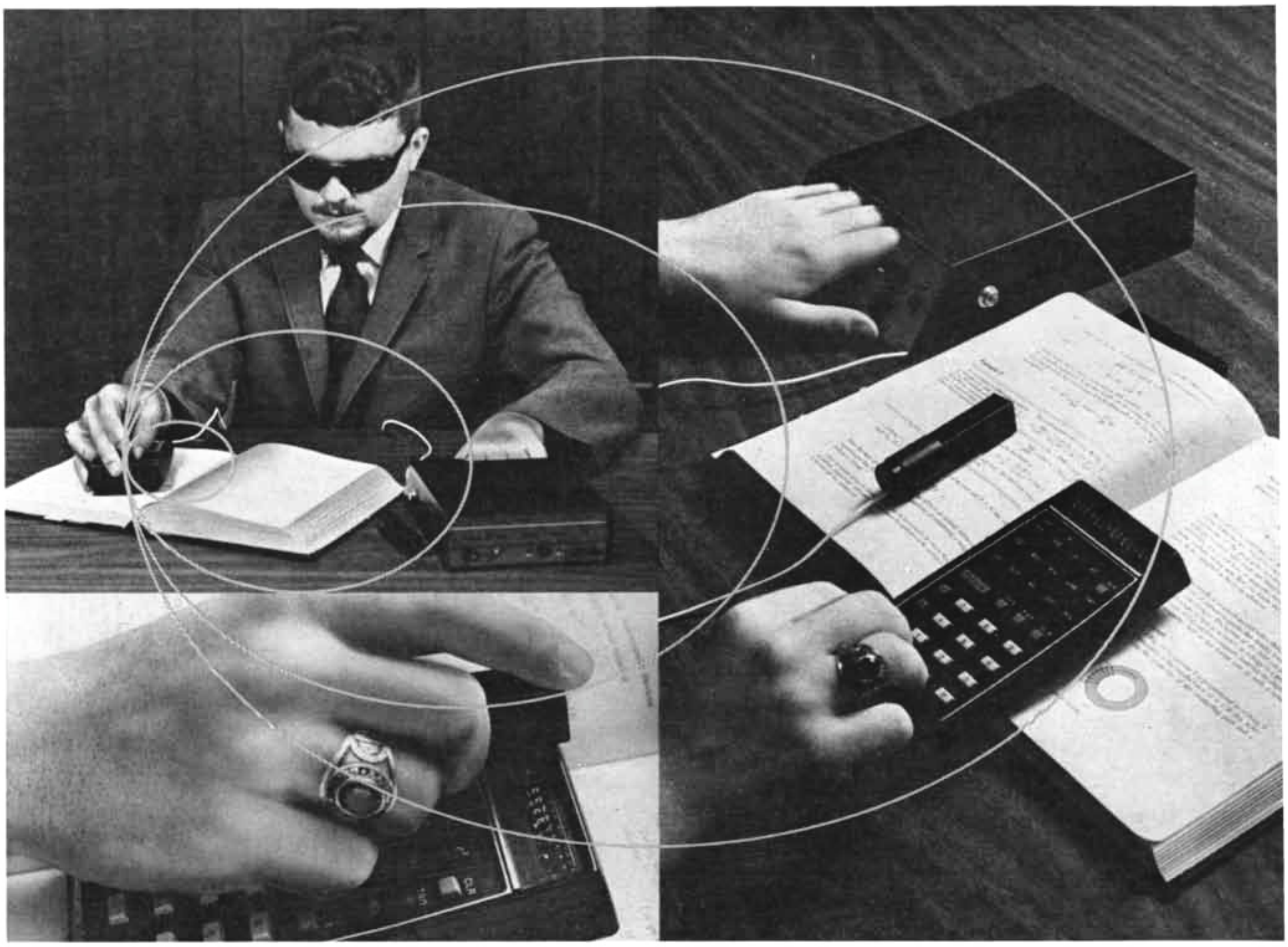

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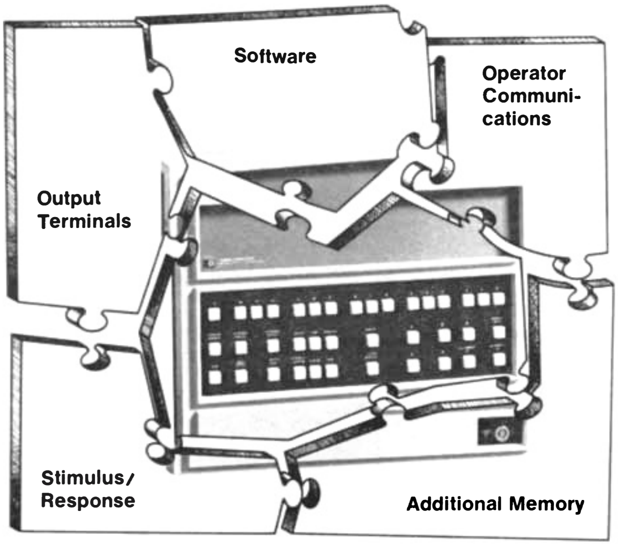
The HP-35 is also proving a boon to many thousands of sighted scientists and engineers who are using it in the lab and on the road. Here are some additional reasons why: ten-digit accuracy between 10^{-99} and 10^{99}, automatic decimal point positioning with floating point or scientific notation, operational stack of four registers plus storage register, blanking of insignificant zeroes, battery or AC operation, nine-ounce portability and advanced computational capability. All for a price, in the U.S., of $395 (plus tax).

We'll be glad to send you a full description of the HP-35 and forward your request for information on the Optacon to its manufacturer, Telesensory Systems, Inc.



Making the computer fit your problems.

The problem with many computer systems is that you have to make too many trade-offs between what the system can do and what you want to have done.

We believe you should have freedom to tackle problems *your* way, and not be forced to accept someone else's methodology. So Hewlett-Packard computers and systems are designed to help you be the master of how they're configured and used.

With HP's versatile 2100 computer, you can assemble a system that's right for your job. You determine how much and what kind of memory it should have, how you want to talk to it, and how you want it to provide your answers. The software to focus all this capability on your problem is equally flexible.

Want to hook up instruments? You choose from more than 75 standard HP stimulus/response instruments that plug directly into our computer.

But most important of all, we begin by giving you the training you need to understand and run what you have. If you need special assistance, systems analysts in our Data Centers are available for consultation.

Finally, every element of an HP computer system is fully supported from 172 sales and service offices in 65 countries. After the warranty, we can continue to maintain your system under a customer service agreement, or show you how to do it yourself.

Basically, it's all up to you. And most of our customers wouldn't have it any other way. Information on the HP 2100 will be sent upon request.

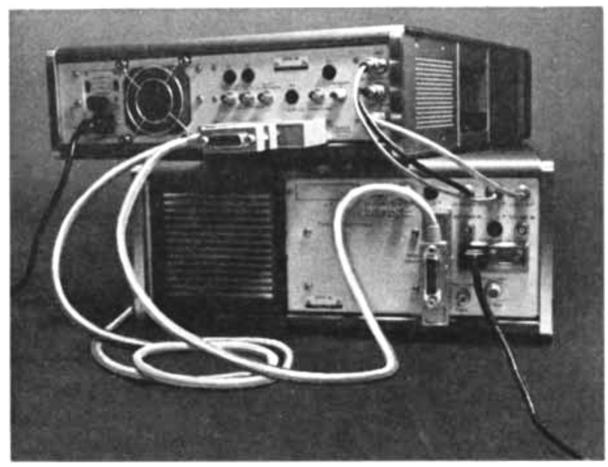
The new non-instrument that's making measurements easier.

Automated measurements have long been seen as a way to improve productivity, both in scientific research and in industry. But establishing local centralized control of measuring instruments hasn't been easy. Although some progress has been made over the years, each instrument typically has its own provision for external control. Assembling several instruments into an automated system often takes a system expert and a lot of costly interface equipment in addition to the instruments themselves.

This picture is now changing fast. Engineers throughout Hewlett-Packard have agreed to design their products using a consistent interface system, so that all instruments, no matter what their function, can be controlled by connecting them to a common interconnecting cable. Thanks to low-cost integrated circuits, even inexpensive instruments can have the new interface, and the cost of an automatic system need be little more than the sum of the costs of the instrument in it.

Instruments interconnected through the new interface communicate on a "take turn" basis: (one talks while the others listen). The benefits:

- Low-cost systems can be assembled with no special interface equipment.
- System management can range from simply one instrument controlling another, up through control by calculators and computers.
- System operation is simplified since control can be passed from one device to another.
- The system is flexible in speed, language, and size. Messages and data can be transmitted at up to one megabyte rates.



Now one common cable system is all that is required to interconnect instruments digitally.

This interface is going to enhance the usability of many of our new products and substantially reduce the rigors of making complex measurements. To obtain a more complete description write for the October 1972 issue of the Hewlett-Packard Journal.

For more information on the products described in these pages, fill out the coupon or write to: Hewlett-Packard, 1502 Page Mill Road, Palo Alto, California 94304; Europe: P.O. Box 85, CH-1217 Meyrin 2, Geneva, Switzerland; Japan: Yokogawa—Hewlett-Packard, 1-59-1,Yoyogi, Shibuya-Ku, Tokyo, 151.

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Please send me information on the following:
( ) HP-35 Calculator
( ) Optacon
( ) HP 2100 Computer
( ) Interface System

Name__________

Title__________

Company__________

Address__________

City__________ State__________ Zip__________