Antonio Gaudi: Structure and Form

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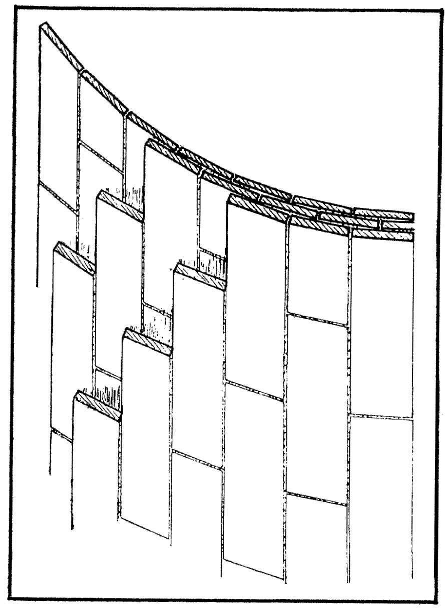
1 *Bóveda tabicada*—method of assembly



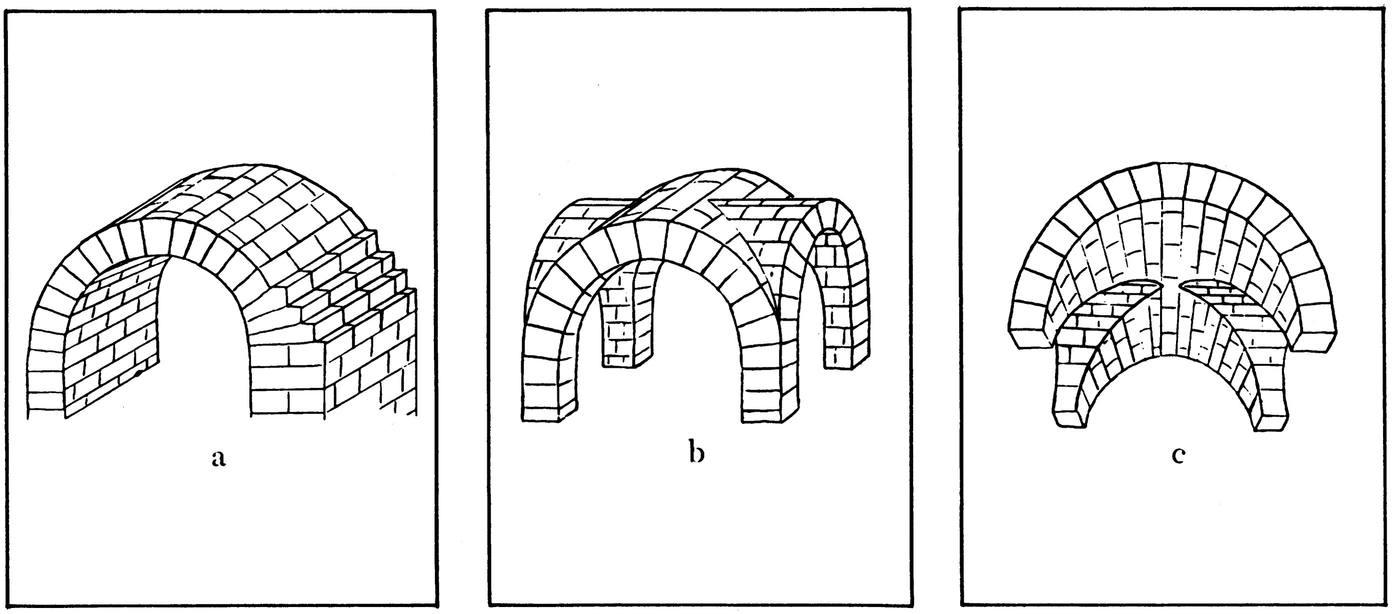
George R Collins
Antonio Gaudí: Structure and Form

Contemporary interest in the architecture of Gaudí has arisen in part from a realization that the unusual structures and shapes that he employed have something in common with our own remarkable shell-vaulted forms of today. However, the precise nature of this connection has never been stated. We have not, on the one hand, had available to us a clear and comprehensive exposition of Gaudí's structural theory and practice, nor have architectural historians taken sufficient notice as yet of those changes in modern ideas about structure which underlie the very buildings that most 'resemble' Gaudí's.

The matter is not entirely confined to the single architect Gaudí: it has its roots in a resurgence of methods of building in late nineteenth-century Catalonia that were simultaneously ancient and prophetic—methods that actually spread from Valencia and Barcelona to our own doorstep, in the form of the vaults of Pennsylvania Station, the Boston Public Library, the New York subways, a score of cathedrals, and hundreds of other edifices. The structural aspect of these American buildings has never received serious historical study.* However, the particular fascination of Gaudi for us lies in the fact that his buildings, drawing upon the same Catalan traditions, did not resemble Pennsylvania Station or the Cathedral of St. John the Divine, but look more like the buildings of today.

In order to understand the structural component of Gaudí's architecture, we must familiarize ourselves with the traditional Catalan building methods which he inherited and furthered. These were quite sim-

2 Normal voussoir vaulting



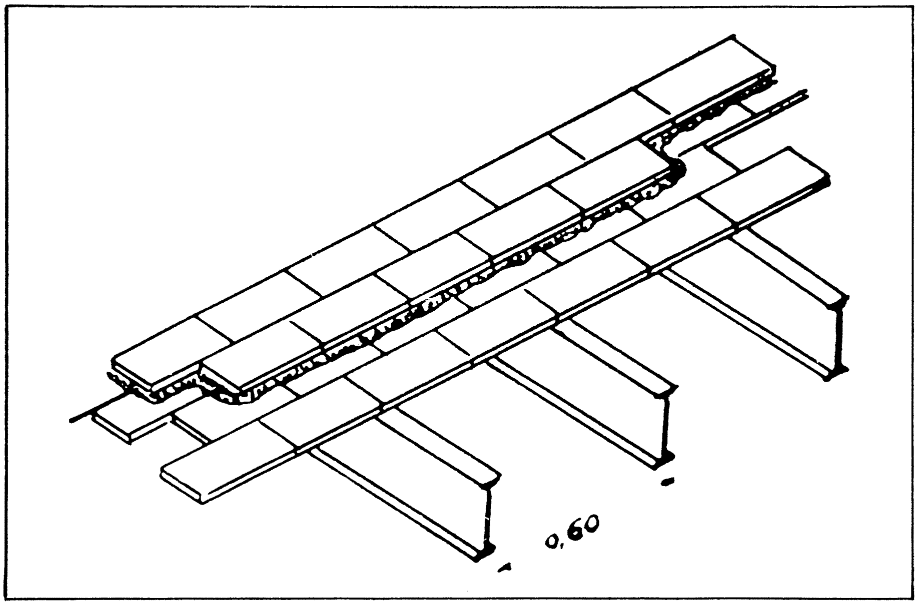
ple and very reasonable, but as they seem to flaunt our usual ideas about structural function, it would be useful to indicate here certain of their basic—and unique—aspects.

The Catalan procedures with which we are concerned are all based on the use of a specially resistant, broad, flat tile, about an inch thick and 6 by 12 inches in area. It is laid flat—that is to say, with narrow edge to narrow edge (Figs 1, 9), rather than with the broad sides against each other in 'voussoir' fashion (Fig 2). These tile courses are usually laminated in sufficient layers to resist the moment of stress at any particular point; homogeneity is achieved by breaking joints, often doubly in a herringbone pattern such as one sees in Widener Library or the United States War College. Part of the efficiency of this masonry derives from the excellence of the tiles, which are frequently stronger than stone and of such hardness that they ring when struck with a trowel. The Spaniards employ a variety of types of tile, bearing different names according to their thickness; they may or may not be hollow.

However, the character of the mortar employed is fully as crucial. It is quite thick, occupying up to 50 per cent of the depth of the masonry. Except in the first layer, where plaster of Paris is used in order to achieve an immediate 'set,' the cement mortars employed in modern times have been so strong that the masonry usually breaks or pulls apart across the tiles (not at their joints) as would occur with plywood or wood stuck together by joiner's glue. In fact, a simple way to distinguish Catalan from other brick or tile masonry construction is that in Catalan work the fragments of a wrecked building cannot be used over again, whereas ordinarily bricks can be cleared of adhering mortar and largely reused for the next structure.

A final characteristic of Catalan methods is the dramatic manner in which the masonry takes shape in the hands of a skilled artisan. Templates may be used when the surfaces are of complicated geometrical form, and scaffolding is sometimes needed for the workers, but the setting of the first, plaster-of-Paris layer is so quick that ordinarily no centering is necessary in the erection of vaults. The cement in the upper layers is so excellent that vaults can be walked upon within 24 hours; thus masons can work 'overhand,' supporting themselves, as work continues, on the previous day's masonry. If we add to this the fact

3 A *solera* laid on I-beams to form a floor



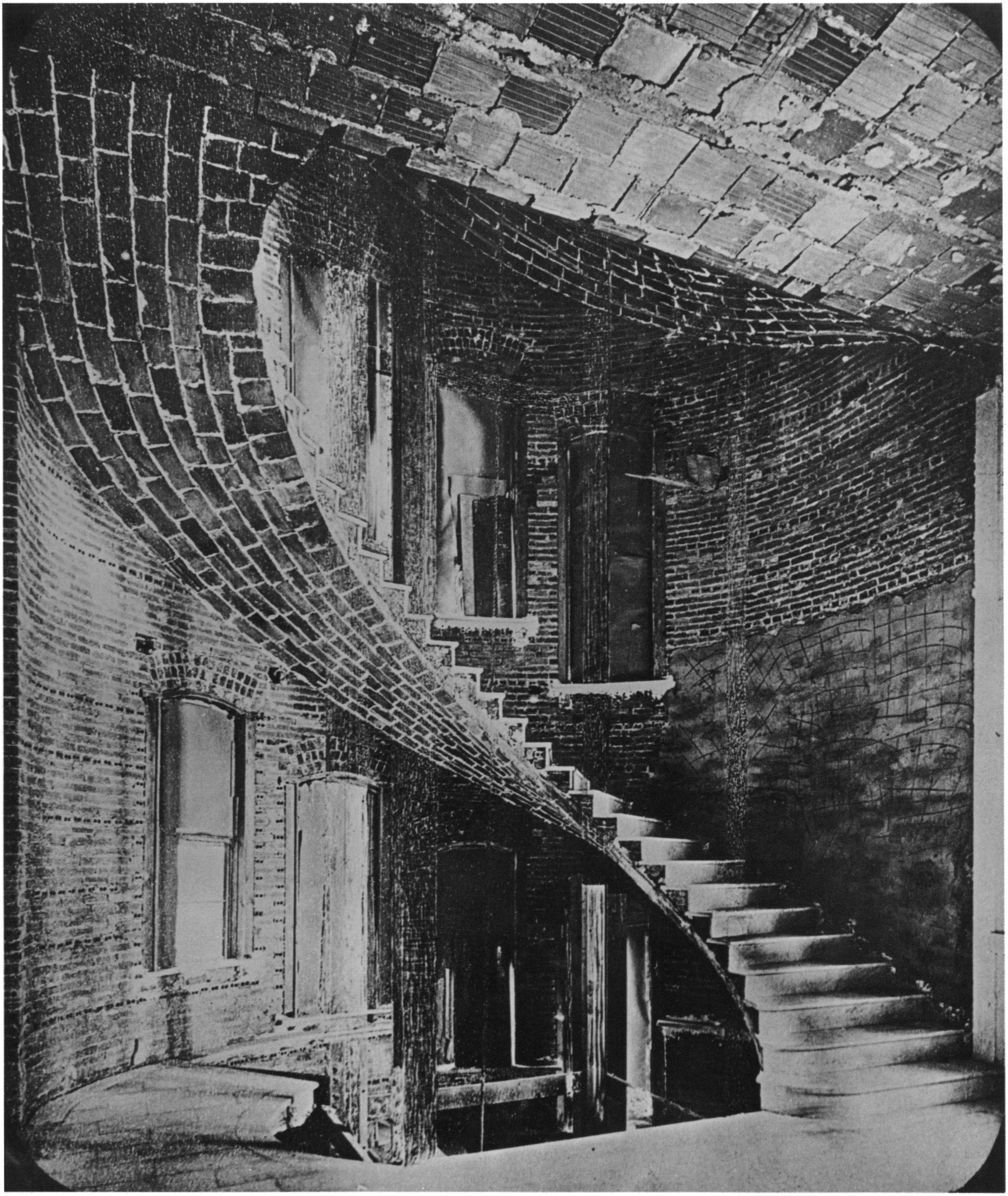
that Catalan masons tend to proceed from experience, following a simple gesture from their foreman rather than blueprints, and the fact that the resulting vaults possess the appearance and many of the gravity-defying properties of our modern thin-shell vaults, it then becomes clear why Catalan masons have been thought to be the magicians of the building trades, and why they have been exported in gangs to many lands to erect their famous vaults and stairs.

Simplest of their devices is the *solera,* or 'deck' surface, laid directly upon beams or on diaphragm arches to serve as a floor, a ceiling, or a roof (Fig 3). This may be flat or it may undulate, thereby deriving additional strength from its doubly-curved surface. As observable in the diagram, the span between supports does not exceed two tile-lengths, so that an appreciable number of the tiles actually lie athwart the beams. However, to visualize the device properly, one must think of it as possessing the cohesive homogeneity of a piece of thick cardboard and not as being made up of a series of tiles, any one of which might fall out if released by its neighbors.

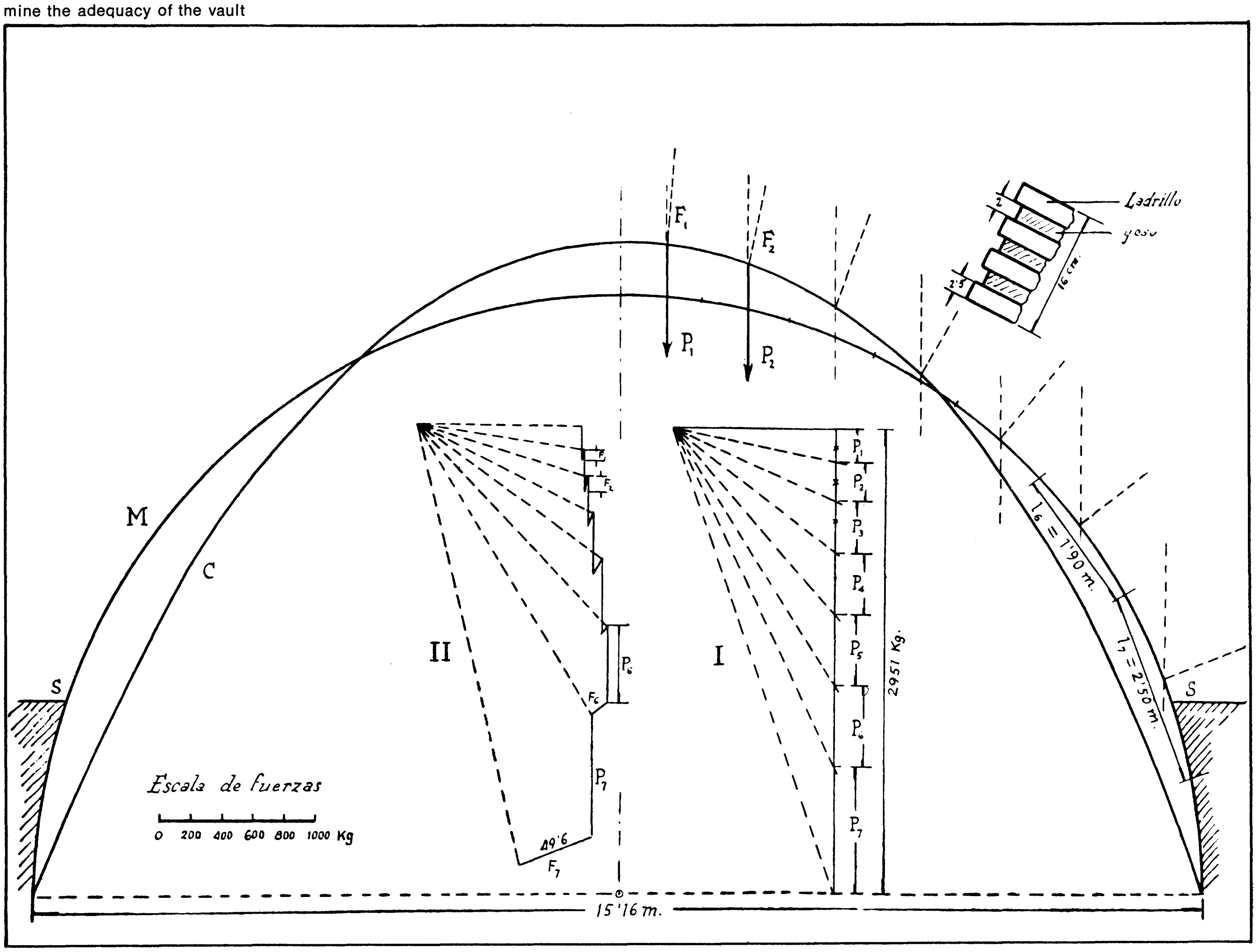
A second element is the *tabique de panderete,* a thin wall of tiles laid edge to edge, one tile thick. Although this is customarily employed in a flat, non-bearing capacity as a partition wall, Gaudí used it in exceptional fashion: undulating so as to take on greater rigidity (Fig 17) and as a supporting diaphragm arch (Fig 14). The word *panderete* (tambourine) gives a clear sense of the structural refinement and tautness of this device. *(Tabique* means partition.)

Most typical element of the Catalan structural vocabulary is the *bóveda tabicada,* or 'broad vault,' i.e. a vault of the thickness and properties of a bent or molded board (Fig 1). Its curvature is usually slight, only about one foot in ten, so that the vault does indeed seem flat and boardlike. It is composed of laminated layers of tiles running concentrically to its line of pressures, instead of perdendicular as in a voussoir arch. It is in connection with these vaults, which he called *bóvedas de panderete* (timbrel or tambourine vaults), that Rafael Guastavino made the interesting distinction between what he called gravity and cohesive types of construction. Gravity construction is any structure, trabeated or arcuated, in which the individual parts are held together primarily by the force of gravity; it is of no consequence whether

4 Elliptical spiral stairway in First National Bank, Paterson, N.J., c. 1890. Guastavino system



5 Parochial church of St. Augustine, Barcelona. Catalan tile vaulting has resisted solution by theories of elasticity, plates, etc., and has generally been handled by simple empirical formulae. Gaudí treated such vaults as stone arches: he laid out a catenary (C) of equal length and span as the vault M. The polygon of forces I corresponds to this funicular C, its strings being parallel to the midpoints of the vertical divisions of the funicular. The strings of polygon II have the same relation to the semi-circular vault M. The F forces are those that would be necessary to make the funicular pass through the vault; the critical one, F_7, is checked mathematically against the resistance of unit l_7 at the haunch of the vault in order to determine the adequacy of the vault

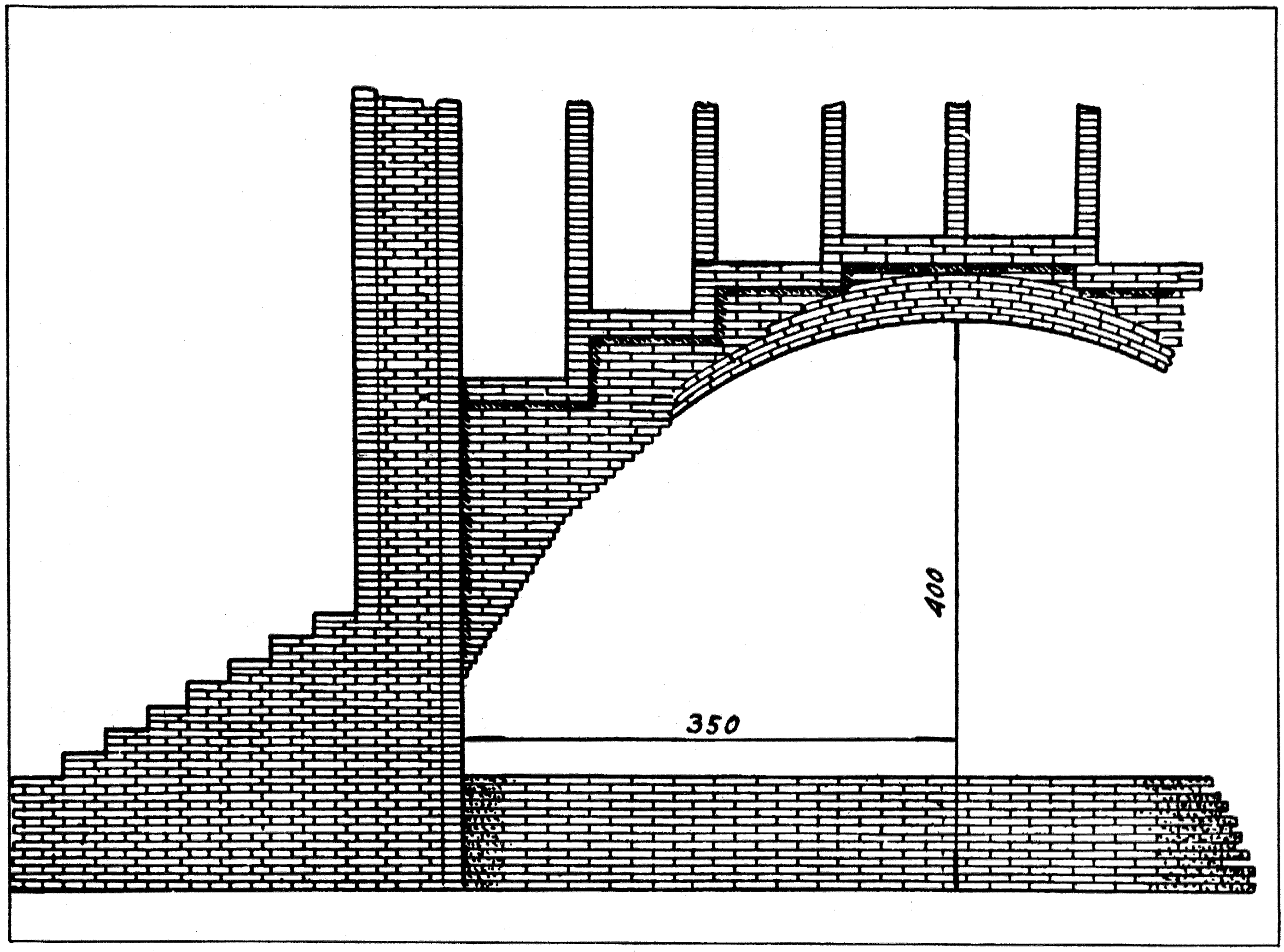


the part be supported by a post or block between itself and the ground, or if it be a voussoir supported by the friction of its own surfaces against the surfaces of its neighbors. In either case, whether or not mortar is employed as a cushion, the parts obtain their stability chiefly from the force of gravity. Cohesive construction, on the other hand, consists of a stuck-together mass, whose elements have lost their independence and adhere to each other, even in defiance of gravitational pull. Needless to say, our histories of architecture have until now restricted themselves almost exclusively to the development of gravity systems, except for certain discussions of concrete. The cohesive aspects of Sassanian, Byzantine, Moslem, Turkish and medieval brick vaults have received almost as short shrift as has the Catalan tradition with which we are concerned here. John Fitchen's recent book on vaulting is an exception.

The *bóveda tabicada* may assume almost any shape and, like modern thin shells, it derives its strength from the properties of its particular geometric form rather than from the thickness of its fabric, which should be minimal. While it may be employed as a single cylindrical vault, it is more efficient in surfaces of double curvature. A favorite is the *bóveda vaída tabicada,* a domical vault that is actually a spherical segment and, like most Catalan vaults, has a very low rise. Gaudí is remarkable for the variety of forms he imparted to the *bóveda tabicada.* He observed, 'The *bóveda tabicada* is the most precious element of our construction; it permits us to execute with simplicity and rapidity the most complex forms, it does not require centering, and it has great resistance in comparison with its lightness and the simplicity of its components.' It is not merely a covering surface, but can carry great loads, as witnessed by the approaches to the Queensborough Bridge in New York City.

There are two special applications of the *bóveda tabicada* that deserve mention here. One is the *bovedilla,* a little vault set in between metal I-beams or into metal frames. This is a standard way to construct the floors of a multi-storied building. If these vaults are flat enough so that their rise does not exceed the distance between upper and lower flanges of the I-beams, they will nestle neatly into the metal floor-framework and, because of the very slight vertical component in their thrust, they will

6 Cascade in the garden of the Casa Vicens, Barcelona, 1878-80 (After Bergós.)

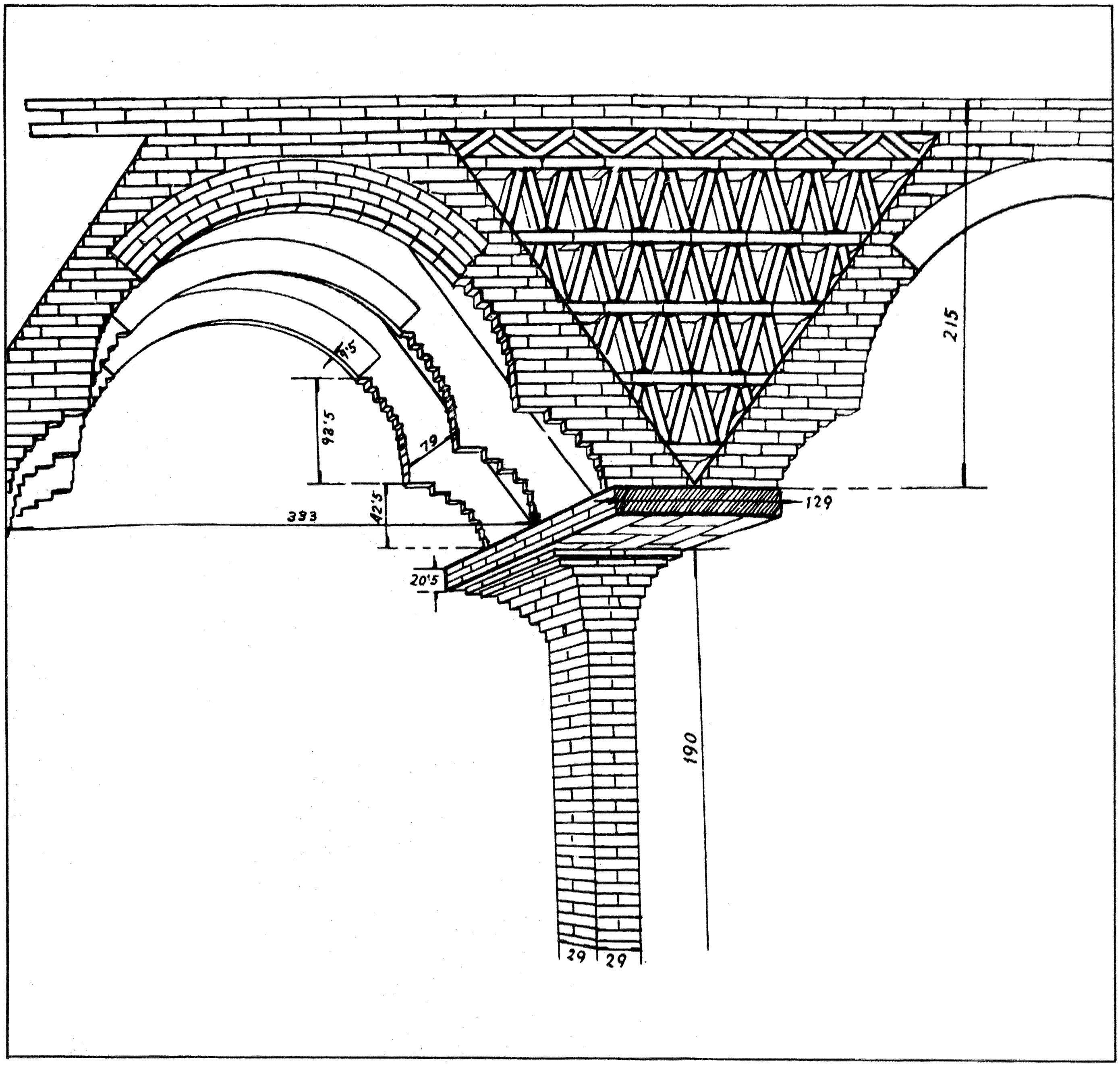


not, after completion of the entire floor, depend on the framework of metal beams for their support. Hence the floor becomes a flat canopy of low vaults supported by the piers at their corners, anticipating somewhat Maillart's pier-and-slab method of construction. If these piers be well protected, the result is an almost entirely cohesive and fireproof structural-system for modern office and industrial buildings. It is also common to support the *bovedillas* or even wide *bóvedas vaídas* on sturdy multi-ply arches of the *tabicada* type, thus eliminating the use of metal except, perhaps, for hidden tie-rods; this was a favorite Guastavino device as seen in the Taunton Court House basement, the Columbia University Chapel crypt and numerous other buildings.

Last, the most unbelievable and most famous element in the Catalan repertory is the *volta d'escala,* or 'Catalan stair.' This is, essentially, a series of narrow and vertically ascending *bóvedas tabicadas.* It may be of continuous helical form (Fig 4) or it may leap up daringly in a succession of ascending parabolas around the sides of a rectangular stair-well. In either case our experience with voussoir arches makes the inner rim seem to be entirely without support; in the latter case each successive rise appears to take off from the unsupported edge of the previous one, and, when the stair-well is open on one side, that unit seems to be carried on thin air. The fact is that the stair vault is set well into a skewback in the wall, or otherwise maintains its shape by shear forces along its edges and so functions as a rigid longitudinal beam or shell.

One is naturally curious about the historical origin of these techniques. Although the Spanish-speaking world has always considered them to be unmistakably Catalan, and the Catalans are themselves proud of this uniquely vernacular tradition of building, they have never claimed the original invention of it for themselves. As historical and archaeological research on the matter is almost completely lacking, it is impossible at this point to trace the development back through history; we can do no more than relay the opinions, largely intuitive, of some of the more informed practitioners of the methods, such as the Guastavinos. And we restrict ourselves to only a few salient characteristics of the tradition, namely: the laying of the vault elements tangent *(de plano)* rather than perpendicular *(de canto)* to the curve of

7 Roof structure of Bellesguard, Barcelona, 1900-02 (After Bergós.)



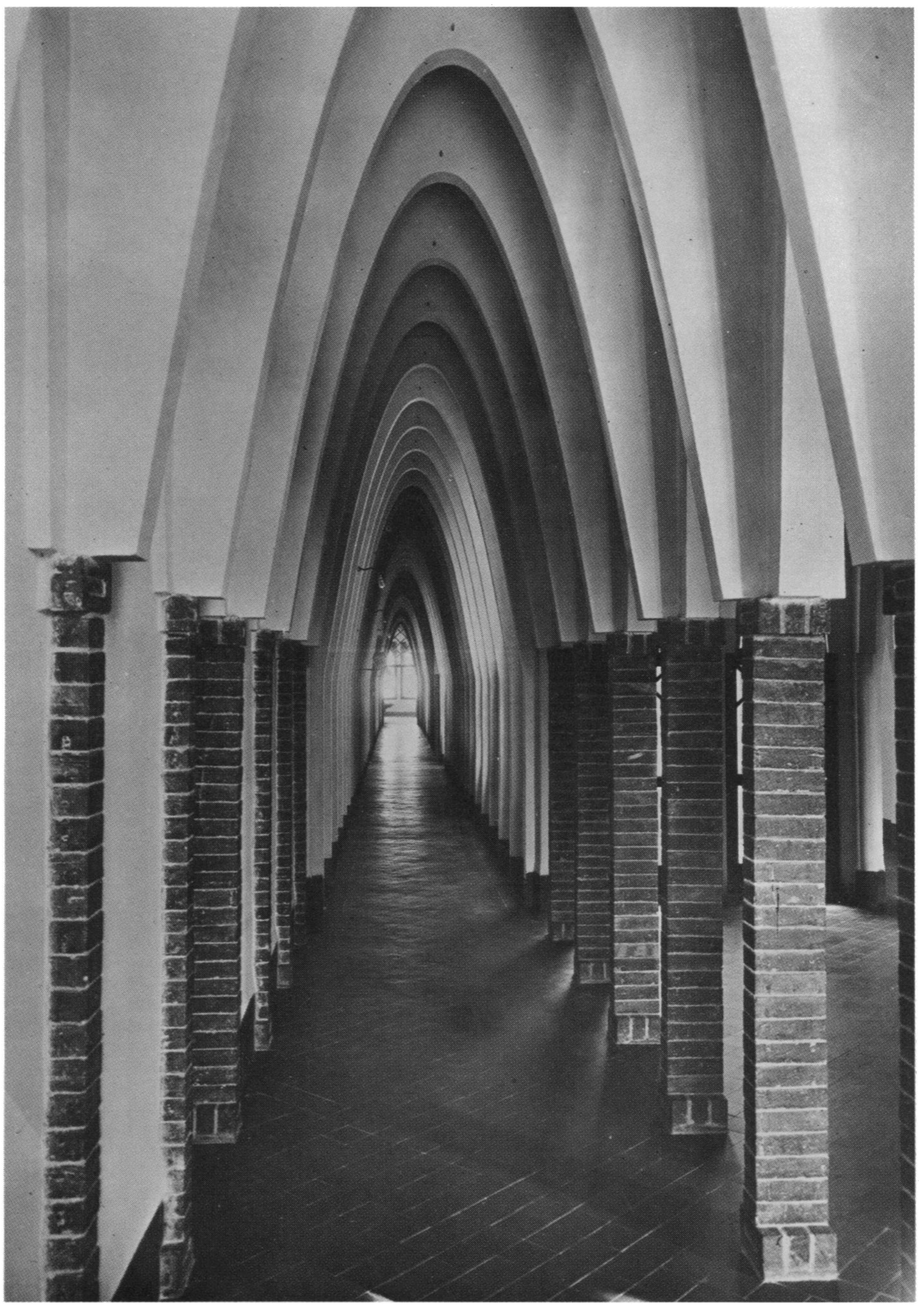
the vault; dependence on monolithic cohesion rather than on voussoir action; and the erection of vaults overhand without centering.

The Catalans presumed that their techniques went back to the cohesive brick vaults of Mesopotamia and Egypt (the Ramesseum), which were constructed without the use of centering by corbelling out the springing and then slanting back the first courses of each arc so that they stuck to their predecessors. This tradition was later taken up by the Sassanians (c. third century AD). The drawings that appeared in engineering and archaeological publications of the 1880s reporting the Persian expeditions must have fascinated Catalans, although the tiles are not, of course, laid *de plano* in their manner. A closer approximation to the Catalan system was to be seen in the Roman use of laminated tile vaulting as a permanent centering for their great concrete vaults of Imperial times, e.g. in the Baths of Caracalla. Although these tile layers did not constitute an independent structure but only the under-surface of the concrete mass, it is the opinion of some individuals (such as Choisy) that the procedure persisted on its own after concrete technology had lapsed and was therefore the ultimate origin of our method. There is no question that the major use of tile-vaults has always been in areas of strong Roman antecedents: Italy, Southern France, and Catalonia.

It was thought by many Spaniards that the later middle ages inherited these techniques via the Byzantines and Moslems. Although both these cultures employed cohesive masonry of brick and rubble, it is not clear how common the thin *de plano* brick vaults were among them. But from wherever they sprang, Gothic instances of thin tile-vaulting (as thin as 1½ inches) abound in Catalonia. Renaissance and Baroque examples seem to be plentiful along the Mediterranean littoral from Italy to Valencia; Blondel described their use in southern France in his *Cours* of 1777.

There seems to be no question that the method had been very prevalent in Italy, perhaps since Roman times. It has been suggested that the Catalans took up the old tradition with renewed vigor in the Renaissance, owing to a new importation of the method from Italy for large church naves; it came with a certain authority, having apparently been used in the Sistine Chapel and other Roman buildings. To

8 An upper floor in Teresan school, Barcelona

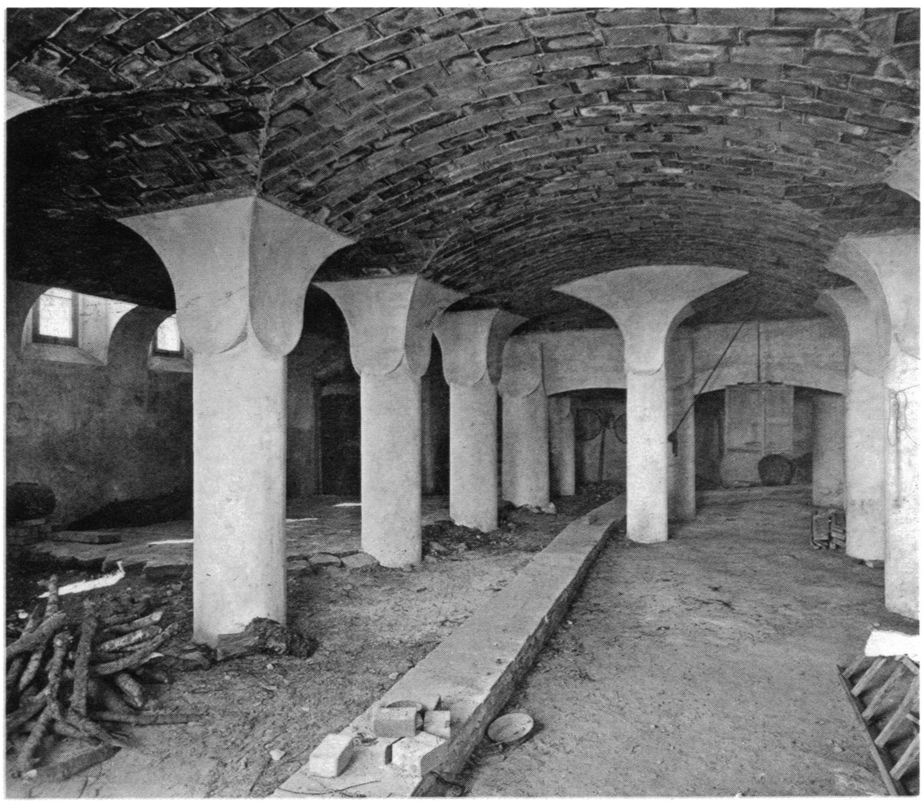


mention only two Spanish examples: the famous church of the Desamparados of Valencia and the parochial church of St. Augustine in Barcelona (Fig 5) of which we illustrate a graphic analysis of forces by Gaudí's method.

This proto-thin-shell system of building was then revived, intensified, and industrialized in late 19th-century Catalonia. The elder Guastavino, who played such a pivotal role in this process, ascribed it to the burgeoning textile industry in Catalonia, which, modeling itself in so many ways on the machinery and methods of contemporary England, also sought to fireproof its new plants. Desiring a less expensive system than the English one of heavy brick arches, the Catalan industrialists fell back upon their own tradition of *bóvedas tabicadas* and *tabiques de panderete.* Hence the stimulus to find new, quick, waterproof mortars — i.e. Portland cement. Guastavino's first important commission was a spinning mill, the vast plant of Batlló Hnos., a structure that was much studied by the students of the Barcelona School of Architecture when Gaudí was in attendance there.

There was, however, a totally different and generally unappreciated aspect of modern Spanish culture which contributed to this development. That was the precocious state of Spanish mathematical science. (Eduardo Torroja comes from a family of mathematicians.) Histories of technology, engineering, and architecture, concerned as they have been with the industrial use of iron and concrete in the Western world, have largely bypassed Spanish science. There existed, however, a lineage of

9 Basement of Bellesguard, Barcelona



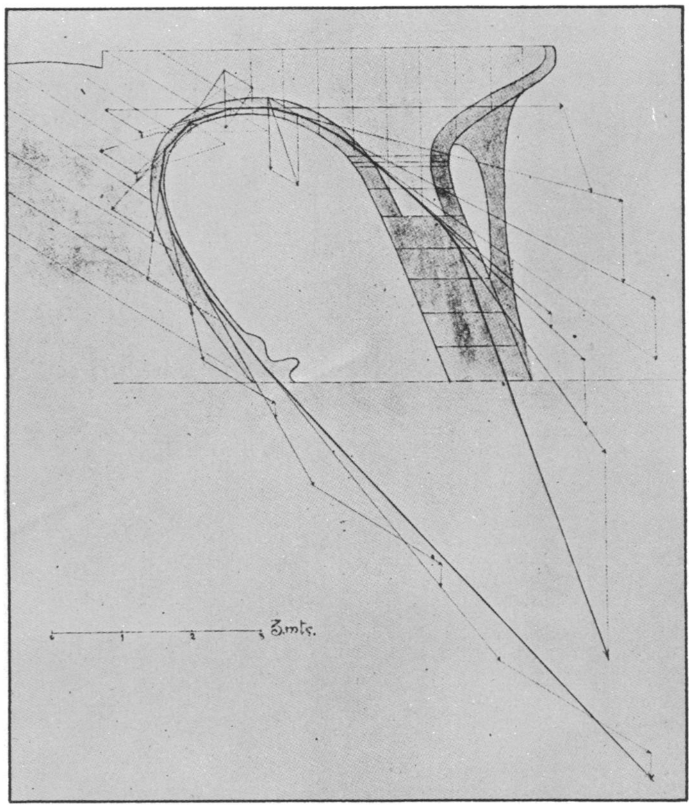
Spanish engineers and architects whose mathematical genius was not appreciated abroad, perhaps because of their tendency to associate the beauties of that science with those of nature or with religious symbolism (as Ramón Lull had done), instead of with the machine or with rationalized mechanical processes.

For instance, the Spanish engineer Juan Torras ('the Spanish Eiffel,' 1828-1910) remarked: 'The architect of the future will construct by imitating nature, because it is the most rational, durable, and economic method.' The elder Guastavino observed on entering a great subterranean cavern that 'all this colossal space was covered by a single piece... no centering or scaffolding... without heavy girders... all being made of particles set one over the other as nature had laid them. From that time I became convinced that there was much to be learned from the immense book called Nature.' The admiration of Gaudí for both natural process and divine symbolism is well known, although it is not so generally understood that he had recourse more to the *laws* of nature than to its actual appearance in evolving his architectural forms.

The history of the Catalans' theoretical speculations concerning the functioning of their vaulting methods is too intricate to go into here, but it might be mentioned that such studies have persisted down to the present, and it is not inconceivable that in countries where handwork is not prohibitively expensive, the Catalan method of tile vaulting still today offers some competition to reinforced-concrete shells. Today some Spanish architects

10 Underneath a viaduct of the Park Güell, Barcelona, c. 1900-03

11 Graphic analysis by Gaudí of the viaduct in Figure 10. He divided this problem into three units. The left half is treated as a retaining wall, so the divisions are made diagonally at an angle of 32° representing the angle of sliding of the earth fill. The upper part of the right half of the main arch is divided vertically, as is usual for a masonry arch. The horizontal divisions of the right side are conventional for an inclined wall or pier. One can follow his determination of the heavily-drawn line of pressures of the structure by starting at the crest-polygon and working either to right or left. For a clear explanation of the methods of graphic statics as used in his day see L. de Coppet Berg, *Safe Building* (various editions from 1886)



claim that it is unnecessary to laminate the tiles in *bóvedas tabicadas,* that single-ply vaults are more efficient and easier to calculate because they more closely approximate modern shell theory; such single-ply vaults must, however, be spherical segments (vaídas). These modern Spanish vaults are, pound for pound, far stronger than metalbeam flooring.

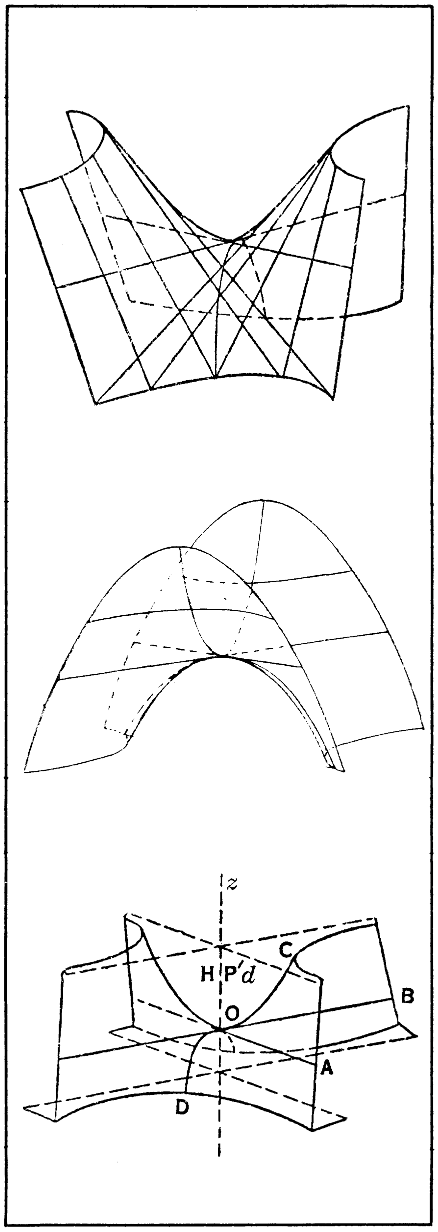
Turning now to Gaudí, for whom the matters we have discussed were standard practice, it is proper to inquire what special use he made of these building traditions of his region.

We find that, although some of his most important buildings were constructed in stone masonry rather than in brick and tile, Gaudí thought instinctively in terms of the 'cohesiveness' of the Catalan tradition, and he actually anticipated a number of our own mid-twentieth-century conceptions of 'continuity' in structure. In so doing, he broke very early with such traditional Western structural metaphors as the 'Orders,' designing instead in terms of the elemental forms and elementary laws or forces of nature. His buildings tend to be monumental representations either of diagrams of graphic statics (by which the forces of nature were visualized in his time) or of surfaces of higher mathematics (which exemplify nature's efficiency for us today).

His most characteristic structural devices seem to issue from a desire to eliminate horizontal thrusts in his structures and to keep all forces within the safe center-section of the material employed.

1 He preferred not to span voids by voussoir arches but by a corbelling outward of courses of brick within a monolithic, laminated system. In the cascade vault of the Casa Vicens (Fig. 6) this corbelling extended out precariously, to be joined by means of a short laminated Catalan arch of low rise to its mate, which counterbalanced it. Under somewhat similar circumstances, in the Teresan school he was forced to use a voussoir arch at the crest, because the span was too short and the curve too acute to allow the bricks to be placed *de plano*. A nicely orchestrated example is the attic ceiling of Bellesguard (Fig 7). Here a slate-covered *solera* of tiles rests partly on lobed, corbelled arches such as we have seen in the Vicens cascade and partly on openwork spandrels. These supporting diaphragm arches are set in turn on remarkably resistant *soleras,*

12 The hyperbolic paraboloid seen in three different ways:
I as generated by a parabola of one sign moving along a parabola of opposite sign;
II as a form of which horizontal sections are hyperbolas (except at 0);
III as a ruled surface of 'saddle shape'



which transmit the load through mushroom capitals to square piers of very small cross-section.

2 Such simple piers, of a minimum cross-section, prevented from buckling by the excellent grip of their mortar, and funneling the load to within their core by means of 'mushroom' capitals, are very characteristic of Gaudí's work. The arcades upstairs in the Teresan school are an almost diagrammatic reduction of this concept to its fundamentals (Fig 8). The subterranean piers of the Palacio Güell (Fig 30) or of Bellesguard (Fig 9) are much more robust versions of this, but are equally elegant as they express their structural function of supporting the heavy floor vaults with a minimum of material and effort. Figure 8 suggests the floating, suspended effects of Byzantine or Moslem architecture, but the

13 Attic interior of Casa Batlló

cellar vaults seem to find a parallel only in the ferro-concrete imagery of our own day.

3 It follows quite naturally from what we have just observed that Gaudí should have taken the entirely unprecedented step of inclining his piers out of the vertical wherever they carried a superstructure with unresolved diagonal thrusts. These inclined piers (Figs 10, 11) absorbed within themselves such resultants, making quite unnecessary the use of buttresses (which he called the 'crutches' of the Gothic) or exposed metal tie-bars (which were popular among his Catalan contemporaries).

4 A simple corollary of this was his well-known employment of arches and vaults of parabolic profile, by which he found that he could most easily approximate the catenary of the line of pressures or of the 'true' arch, viz., an arch without moment or thrust. To this end he experimented extensively in order to determine whether the ellipse, 2nd-degree parabola, cubic parabola, or hyperbola (all easy to calculate) came closest in profile to the catenary curve (difficult to design). It is interesting that he found Sassanian and High Gothic arch forms to have approximated as close as any in history to the theoretical catenary arch.

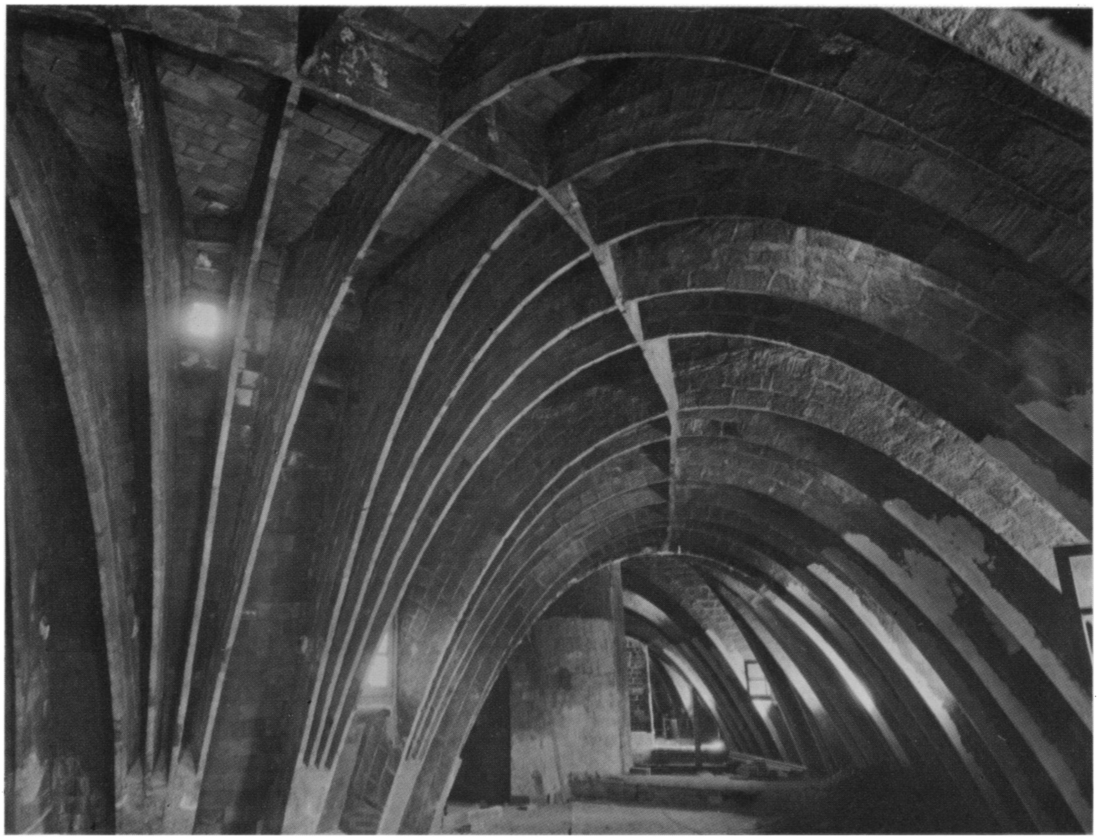
What Gaudí was doing, essentially, with the devices illustrated so far, was to reduce vaulted structures to virtually a post-and-lintel or post-and-canopy function. This might possibly explain why he so often castigated the Gothic style and claimed that he was himself a Greek.

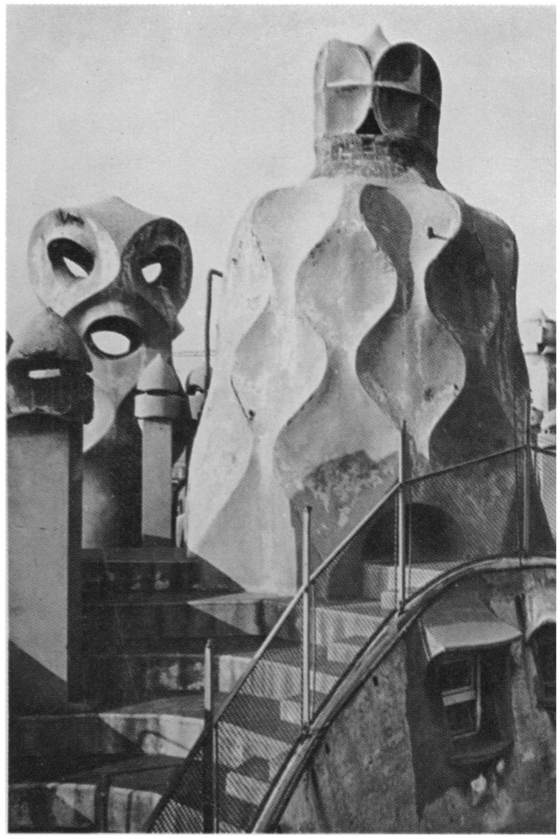
5 Today, it seems quite logical to us that his search for vaulted forms in which the line of pressures automatically falls within the form, and in which bending stresses are at a minimum, would, in the end, lead him to study the architectural possibilities of surfaces of double curvature—such surfaces being as easily obtainable in Catalan laminated-tile masonry as in modern ferro-concrete. Furthermore, he favored the same classes of surfaces that we do today: conoids, paraboloids, hyperboloids.

The fascination of these ruled surfaces derives not only from the fact that they can be erected with ease on straight timber (i.e. ruled) forms, but also from the great range of shapes that can be achieved by varying the value of the variables in their equations and the quite different ways in which they can be described or visualized.

14 Attic interior of Casa Milá, 1905-10

15 Casa Milá, Barcelona

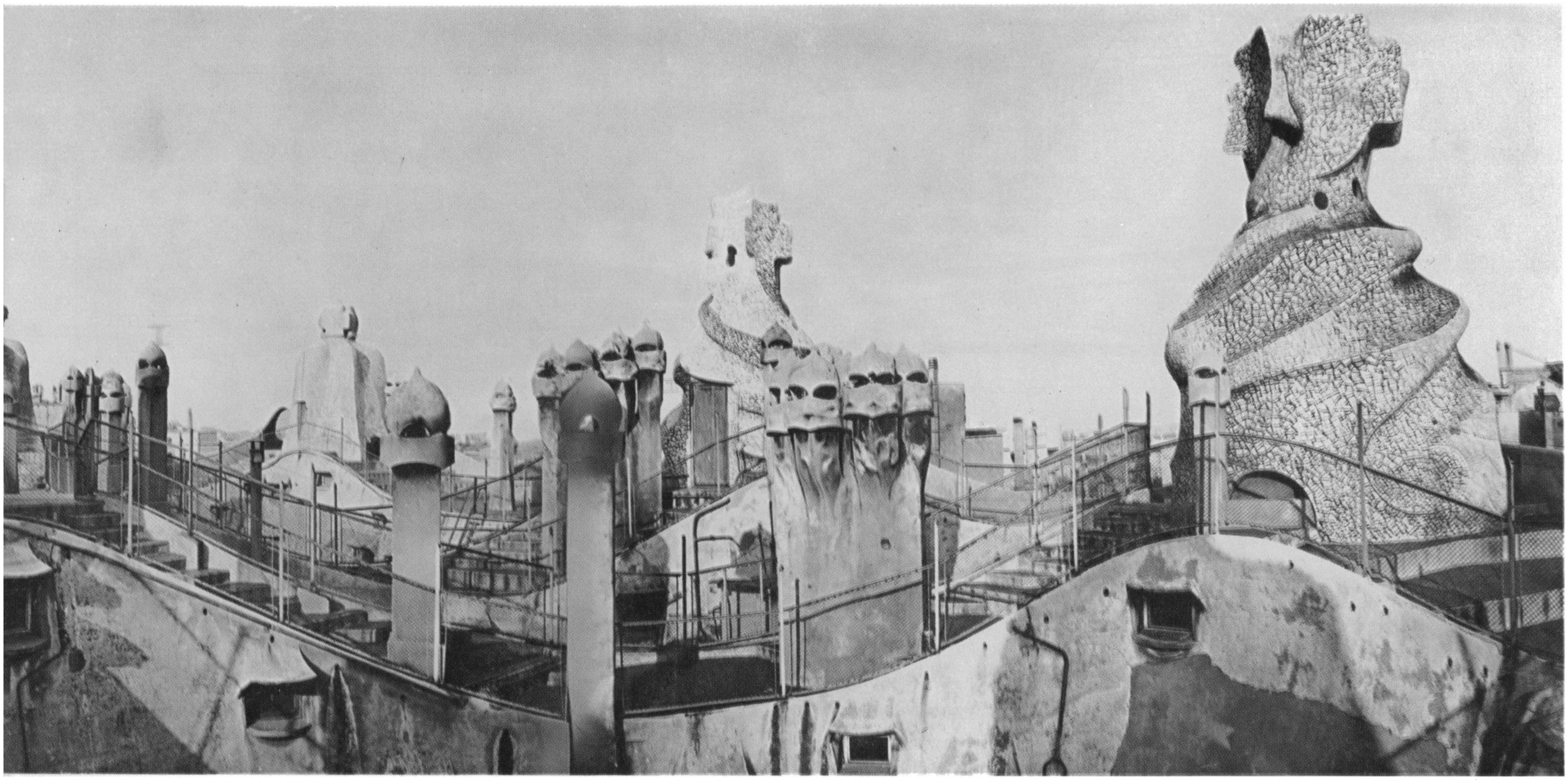




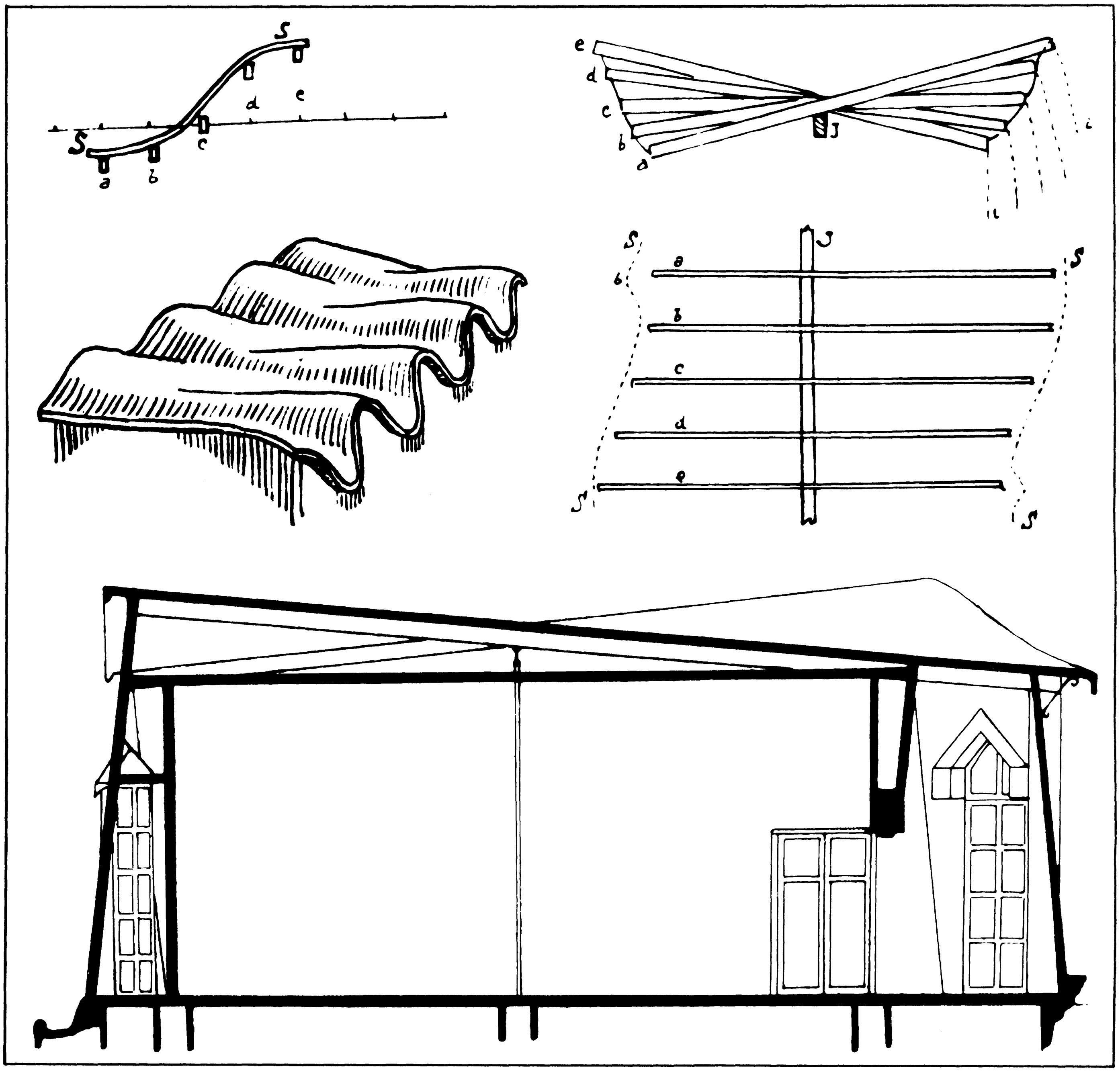
We illustrate here for instance three different ways of visualizing the hyperbolic paraboloid (Fig 12). But Gaudí preferred still another definition — in terms of sets of straight lines. This principle can easily be demonstrated by laying down two thin dowels parallel to each other at a distance, crossing them at right angles and equidistantly with a set of similar dowels, securing all intersections with elastic bands, and suspending the whole framework from diagonally opposite corners so that it sags between its supports. The hyperbolic paraboloid surface that results is obviously generated by one straight line (the set) moving over the other two (which, when suspended, are no longer in the same plane). Gaudí claimed that the latter two represent the Father and the Son, the moving line (the set) being the Holy Spirit which establishes communication between Father and Son.

The roof of the Casa Batlló consists of hyperbolic paraboloids carried on parabolic arches (Fig 13); the roof of the Casa Milá is produced by an equivalent method. The parabolic arches of the latter are of identical profile (Fig 14), but they span a *solera* of varying width (which rests on I-beams that tie the arches), so that their crests rise and fall in a curve that could determine a series of paraboloids. However, in this case he made the roof (also a *solera*) in discrete stepped levels so that it would be usable on top (Fig 15); in fact, he introduced intermediate steps to help walk about.

When faced with the problem of producing



16 Structural diagrams of the Sagrada Familia school building. (After Bergós)



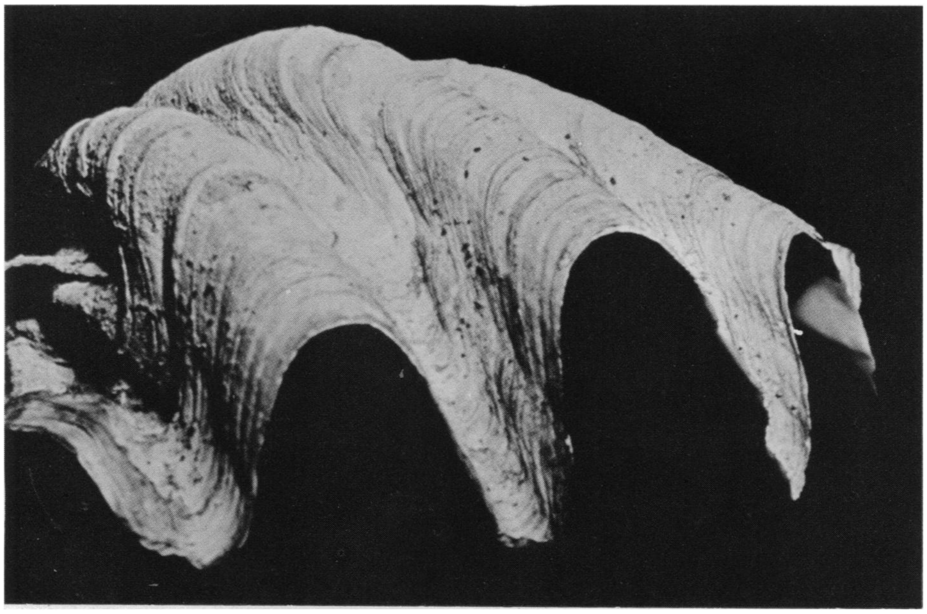
an inexpensive 'flat' *solera*-type roof that would shed water easily (Figs 16, 17) Gaudí hit upon the idea of a conoidal surface, whose supporting rafters (a, b, c. . .) follow sine curves (S-S) with their extremities, while teetering on a longitudinal metal I-beam (J). Since the walls *(tabiques de panderete)* are almost perpendicular to the roof at all points, they undergo a complementary undulation. At the low edges he extended the roof in a lip to throw water free of the wall below. There is an unmistakable likeness of this geometrically-derived surface to the Tridacna shell (Fig 18)—an object with which he was well acquainted, having used it for the holy-water stoup in both his churches. It should be noted, however, that his roof does not *copy* the natural shell, but rather both shell and roof partake of the same underlying geometrical derivation.

The architectural projects by Gaudí that hold the greatest interest for us structurally are his two unfinished churches: the Colonia Güell chapel (1898, 1908-15) and the Church of the Sagrada Familia, on which he worked from 1884 until his death in 1926. If we disregard the earlier neo-Gothic phases of the latter building, it will be seen that these two projects summarize for us the entire development of Gaudí's later attitudes toward form and structure, attitudes which are of the greatest concern to us today. Although only partially carried out, Gaudí's intentions with regard to both buildings are well known from his drawings, models, and photographs, so that we can actually study his structural theory and practice as though the two edifices had in fact been completed.

Of the two church projects, that of the Colonia Güell could be said to have been designed almost purely on the basis of *empirical* structural considerations. In this case both the over-all form of the building and the shape of its constituent parts were determined by structural necessity—that is to say, proceeding on the assumption that the most efficient structure in a masonry-vaulted building is attained by adhering as closely as possible to the funicular polygons (internal lines of force) of the vaults, arches, ribs, and walls when loaded.

Gaudí seems here, as always, to have accumulated most of his statical data by the direct testing of forms and materials. He made a table of available building materials, classified by their respective specific gravities and their resistance to his tests. The thrusts of his arches were determined

17 School of the Sagrada Familia, Barcelona, 1909 18 Tridacna shell



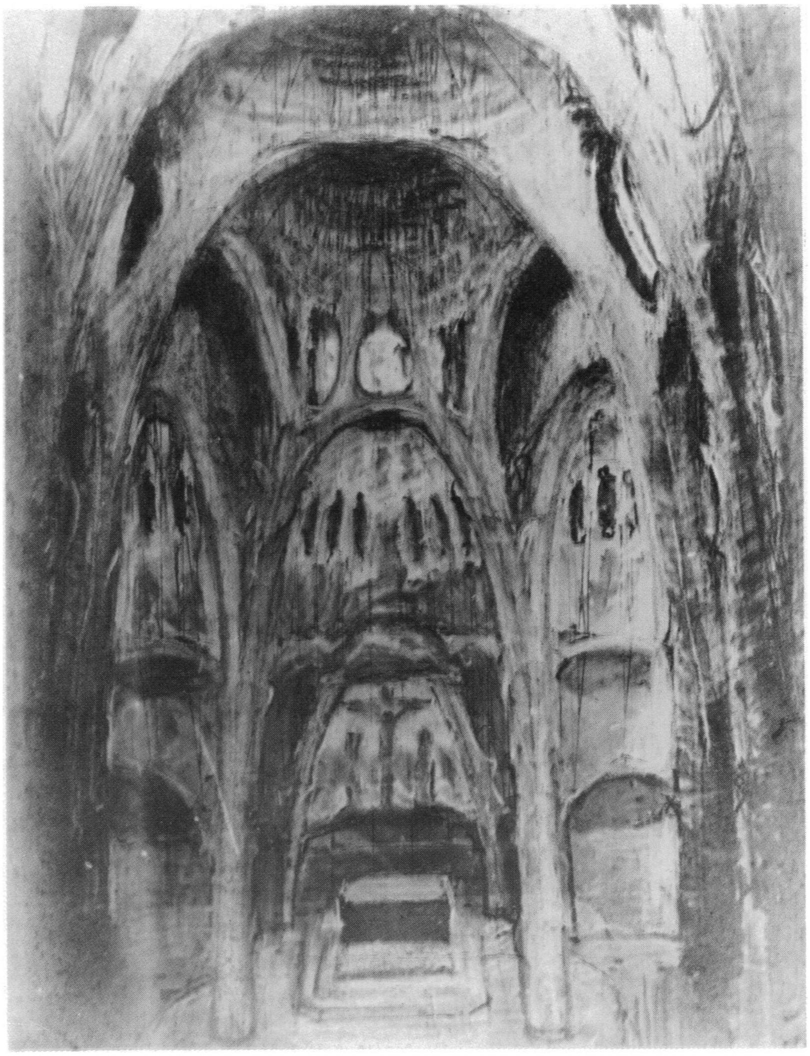
by hanging on a funicular that represented the arch a series of weighted sacks proportional to the loads that the arch would have to support in actuality; the tension recorded (by meter) at the points of suspension was then taken as being proportional to the resultant thrusts of the arch.

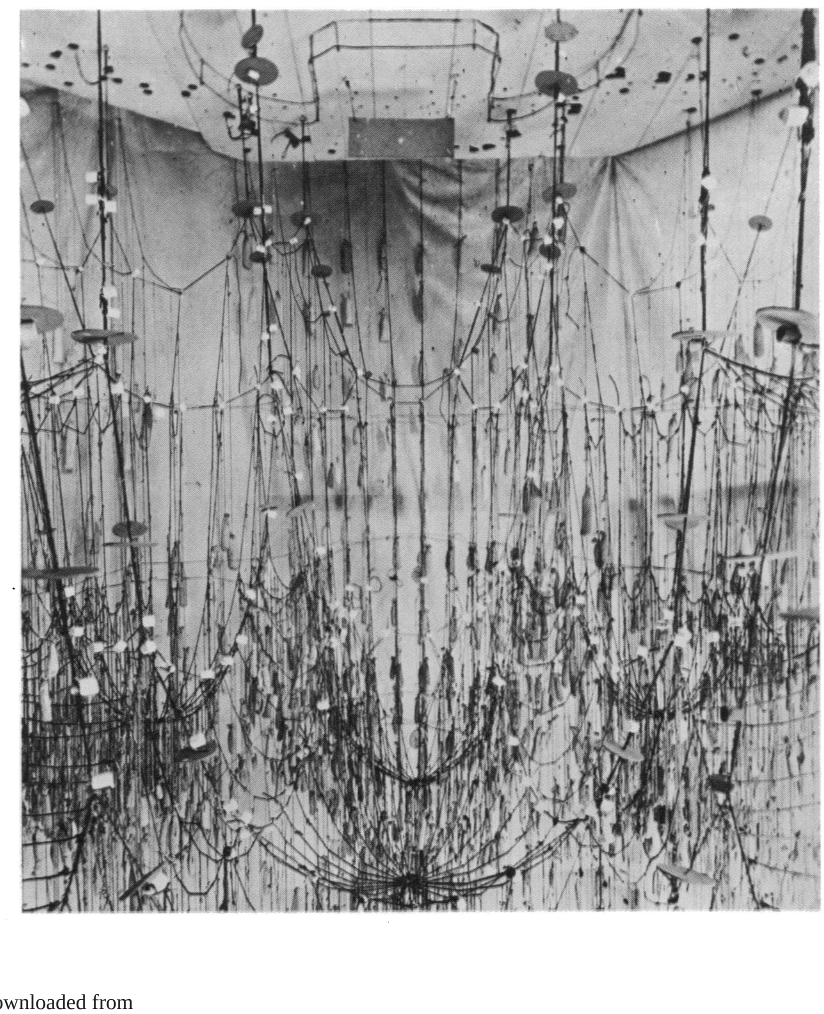
Rather than dealing with this data by the science of graphic statics as was his custom, on this occasion Gaudí, because of the complicated three-dimensional forms involved, made a scale model in order to determine the final building shapes of the chapel. To calculate it on paper by graphic statics would have required the use of projective geometry, which would have produced diagrams of great difficulty to visualize. Instead, he constructed a funicular model—that is to say, a suspended network of catenaries that represented the 'true' arches in inverted position and that were hung with weighted sacks to represent, upside down, the loads actually in effect at various points (Figs 20, 22). With such a device he not only obtained the forms of his architectural design (Figs 19, 21) but also a scale model which his workers could consult during the construction of the building.

Although the results (Fig 21) may seem quite wild, eccentric, and arbitrary, and although they have imparted ecstasy to a generation of surrealists, they are actually quite rational, functional, practical, and utilitarian. By a clever cohesive mixture of rubble and Catalan tile-vaulting Gaudí without the use of complex equations, has attained a network of paraboloid ceilings and walls, hyperboloid window-insets, and

19 Sketch of the projected interior of the Colonia Güell church—not of the finished crypt. It is clear from the wire-lines to be seen here that Gaudí drew this sketch directly on an inverted photograph of the interior of the model

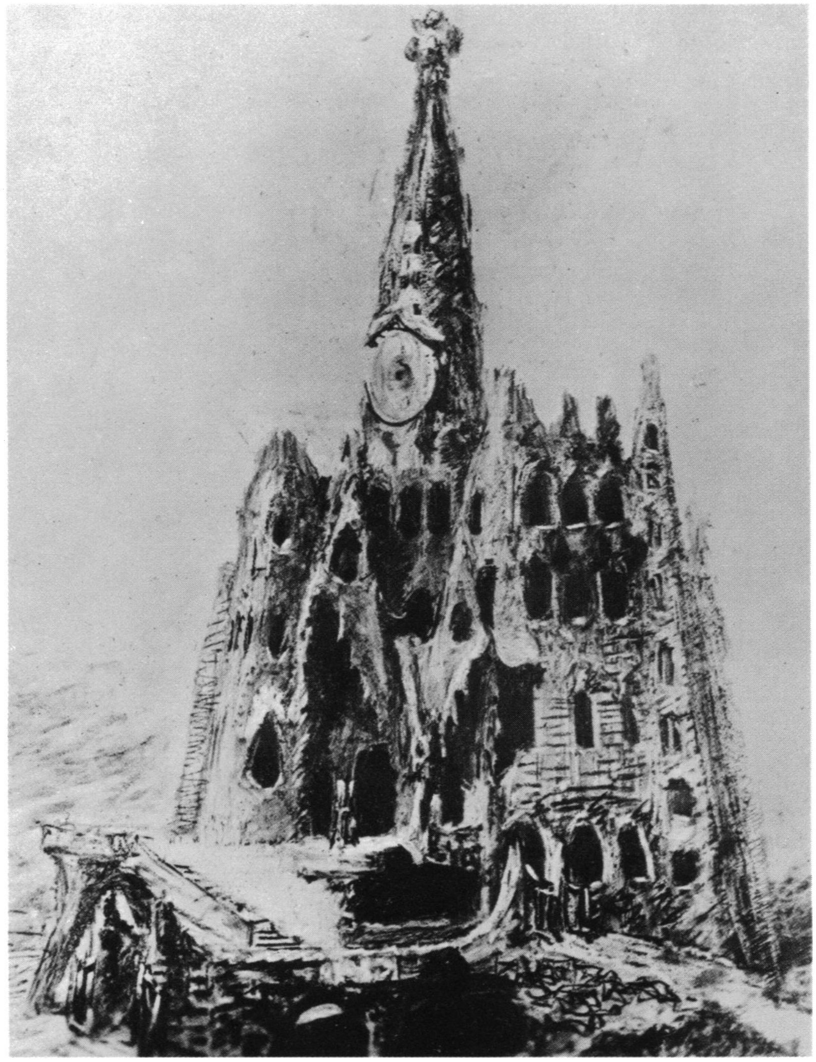
20 Interior view of same funicular model. It might be noted that at about this time Gaudí recommended the use of a hung roof for the new Barcelona railroad station, 600 feet in span and designed as a reticulated net

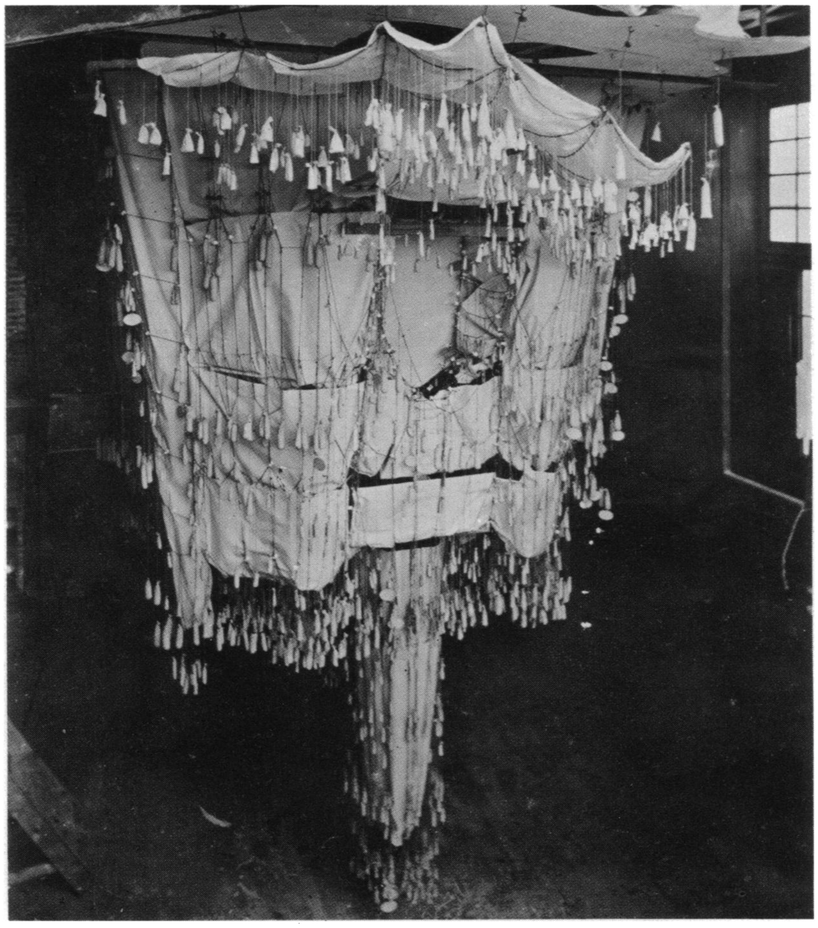




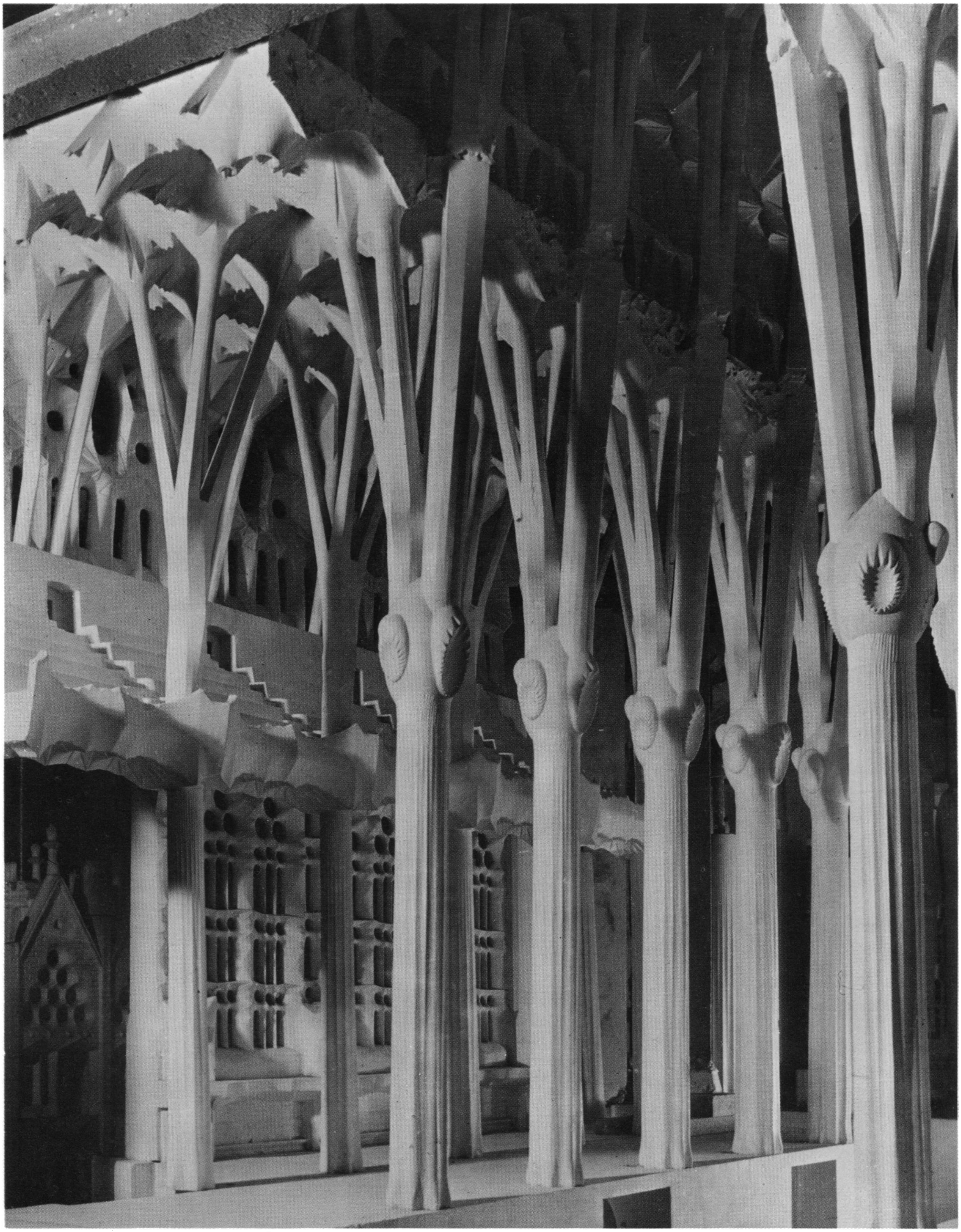
21 Sketch of projected exterior of the church made in the same way as Figure 19

22 Exterior of the complete funicular model for the Colonia Güell chapel near Barcelona (c. 1908). The employment of sheets, warped by cords and weights, gives a sense of the wall surfaces of the projected building

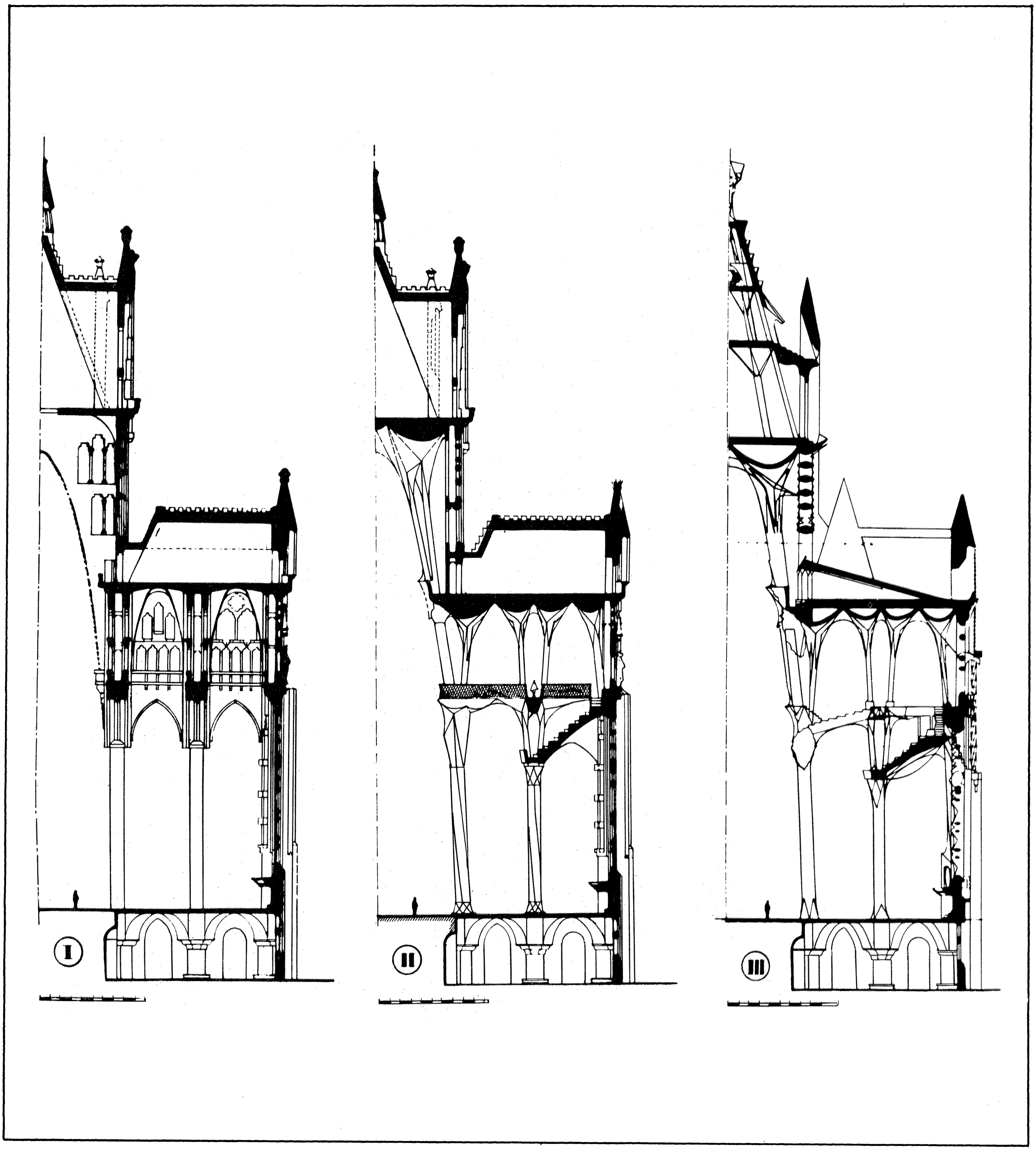




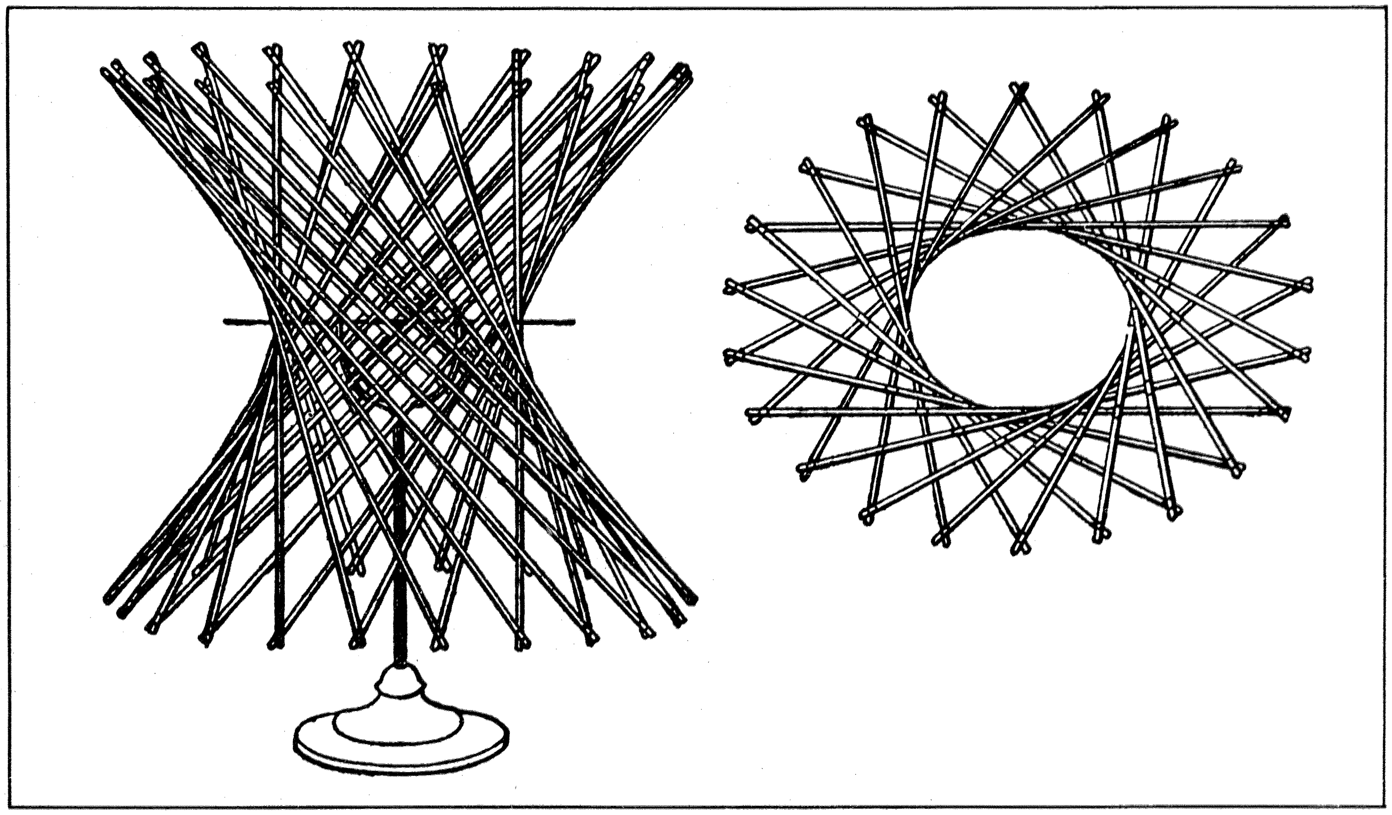
23 View into the interior of a model of the projected nave of the Sagrada Familia church. This is the latest version (c. 1925)



24 Three successive versions of the nave section of the Sagrada Familia church: I, c. 1898; II, c. 1915; III, c. 1918. These show the evolution of Gaudí's project from an essentially neo-Gothic edifice with certain parabolic features (I), to a parabolic design with piers of single helical revolution and paraboloid vaults like the Colonia Güell chapel (II), and then to a much more fluid, arborescent conception (III) with doubly-helical



25 Diagram of a hyperboloid of one sheet and a model demonstrating its character as a ruled surface



the like, that should be the delight of the contemporary engineer, as well as a resounding demonstration of the versatility and adaptability of such surfaces for structure and enclosure even with traditional building materials.

Gaudí conducted many similar tests of materials and structural types during the course of his more than forty years' association with the construction of the Sagrada Familia church, but his final determination of its architectural forms was more abstract and a priori—less empirical—than in the designing of the Colonia Güell chapel. His associates have always described the latter chapel as a laboratory device for his all-consuming project of the Church of the Sagrada Familia (Fig 23).

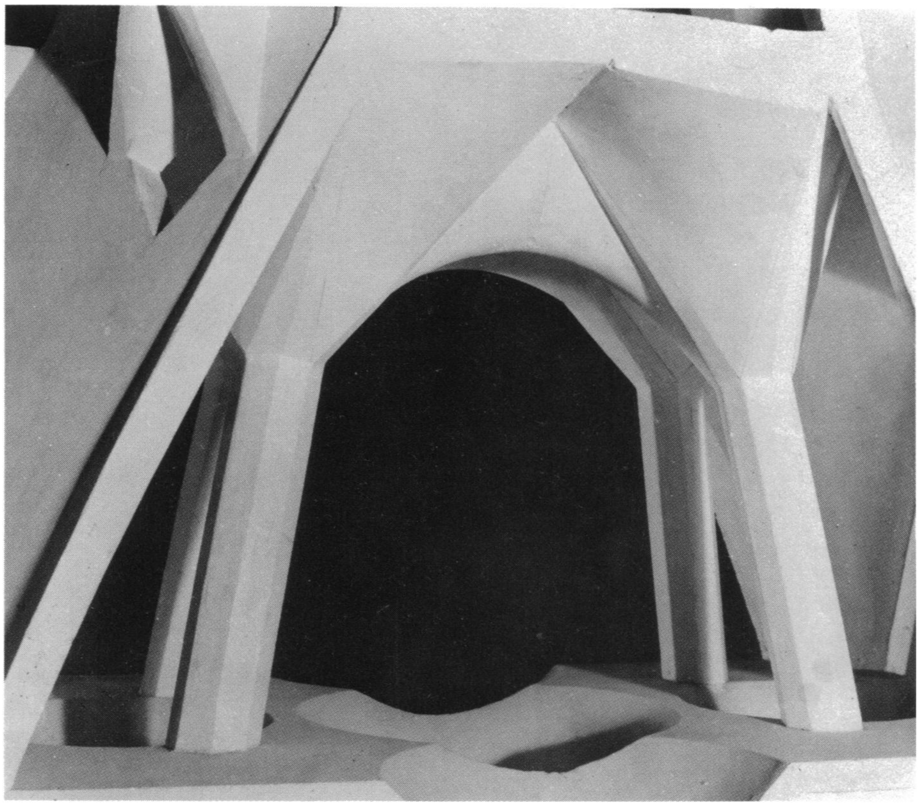
Such matters as the proper inclination of the piers and their branching superstructure, as well as certain calculations of thrusts, were probably worked out by means of funicular models and tensiometer readings as he had done with the Colonia Güell chapel, but for the most part he seems to have employed instead a combination of his customary graphic methods with the use of equations for the various geometrical forms: helicoids, paraboloids, and hyperboloids. In fact, his universal employment here of surfaces of double curvature probably made it possible for him to 'solve' certain of the structural problems through an intuitive choice of form rather than by laborious calculations—a procedure thoroughly in keeping with his usual elegance of method and form.

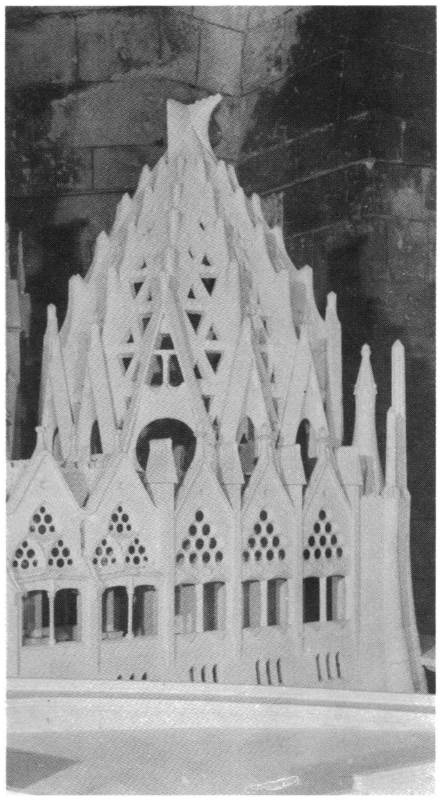
So the Sagrada Familia church became a more classic solution to structural problems, a fact that can be sensed by simple visual comparison of its crisply crystalline forms with the rather rough and almost brutal effects of the Colonia Güell crypt.

From the point of view of statics, his intentions may be summarized as the effort: 1) to get all lines of force within the centroid of supporting members; 2) to eliminate flying buttresses, wall buttresses, and all other supplementary contrivances; and 3) to attain a structural fabric composed of stable, independently functioning units. This last means, for instance, that each nave pier with its superimposed columns and colonettes and the portions of vaults and galleries that attach to them would be quite self-sufficient, like a tree or a parasol. Gaudí adopted this last principle in order to avoid the uncontrollable collapse

26 Model of the nave superstructure, showing hyperbolic paraboloid vaults above and pierced hyperboloid vaults below

27 Model of the Sagrada Familia sacristy





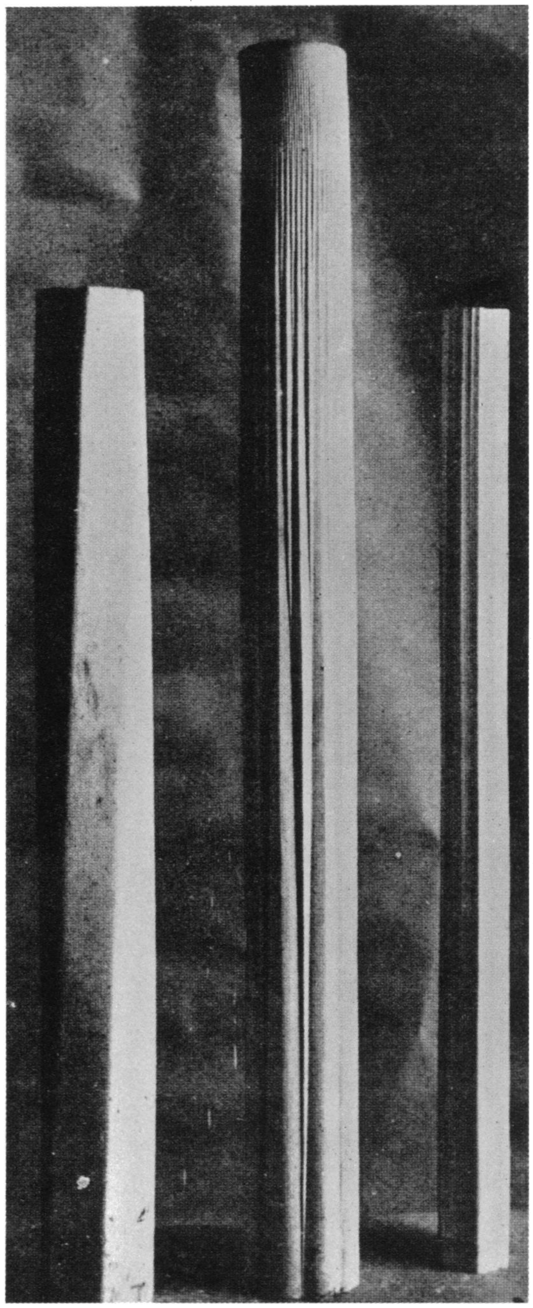
that occurred among vaulted churches as a result of the bombardments of World War I, and which he attributed to the intricate horizontal interdependence of their elements. The principle is that of Torroja's Quince Ojos viaduct.

The synthesis of these structural ideas came about slowly over a period of decades, as can be seen in Figure 24. His ultimate purposes were already clear, however, in stage II. It has been suggested that Gaudi's final designs represented a reversion to the more simple supporting-system of early basilicas.

More interesting to us today, perhaps, was his employment of complex warped surfaces which are arrived at by simple geometrical rules, as we have seen above, and can be shaped by workers employing rather elementary templates. From 1918 on, Gaudi's plans called for vaulting composed of hyperboloids of one sheet (Fig 25), which would cover all but the apex of the vault—at which point their gorges would allow illumination through from above (Fig 23). The walls were also to be formed of such hyperboloids, the gorges enlarged in this case to serve as windows. In the vaults, smaller hyperboloids shaped like egg cups were to be suspended in the gorges to diffuse the light. All these hyperboloids were to be translational surfaces, their directrices being serrated or starlike figures which imparted a pleated form to their surfaces. The capitals of the piers as they fan out to meet the vaults were also to be hyperboloids. It follows that the junctures of all such hyperboloid surfaces in vaults and walls are actually hyperbolic paraboloids, although this is not immediately perceptible. Owing to his concern over the World War I catastrophes we have mentioned, Gaudí decided to construct his vaults of reinforced concrete instead of masonry, inserting the reinforcements *as generating lines of these ruled surfaces*. Thus there are no ribs on or within the masonry, nor did he use his customary supporting diaphragm arches; any resemblance to the Gothic style of building here is purely coincidental.

Hyperbolic paraboloids, those handy roofing surfaces which he had intended to use to vault the nave in his earlier plans, were in the final design to be used only where a closed roof is necessary, as in the upper superstructure (Fig 26). A particularly tricky use of paraboloids was to be in the attached sacristy (Fig 27), whose gored

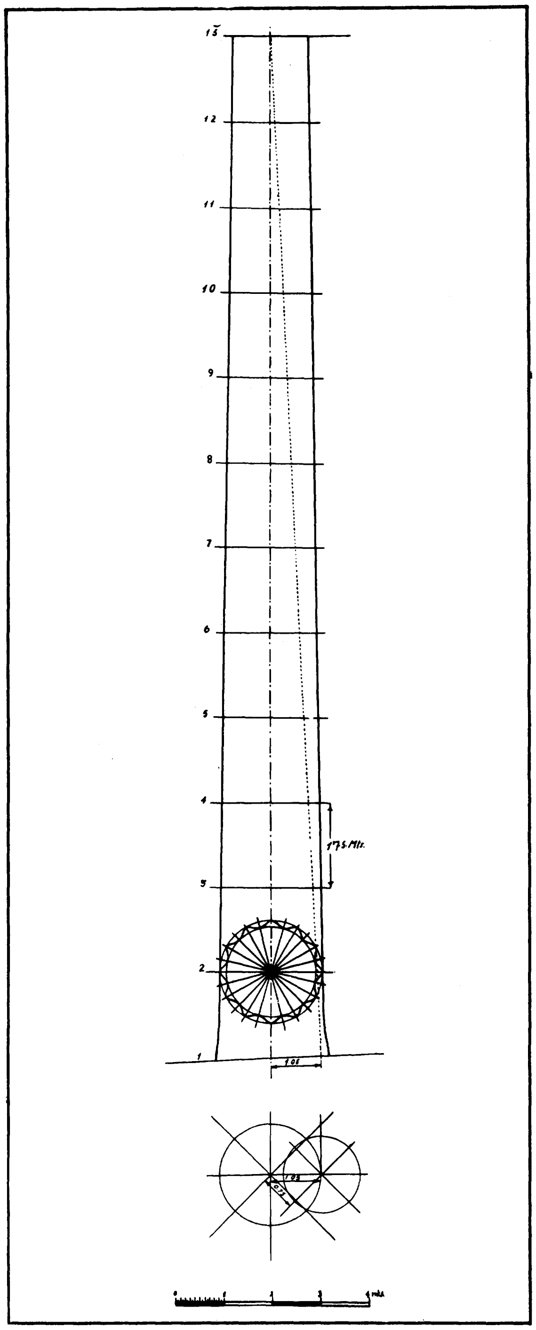
28 Experimental models of columns for the Sagrada Familia 'church. Left is of single helical revolution, the others of double revolution

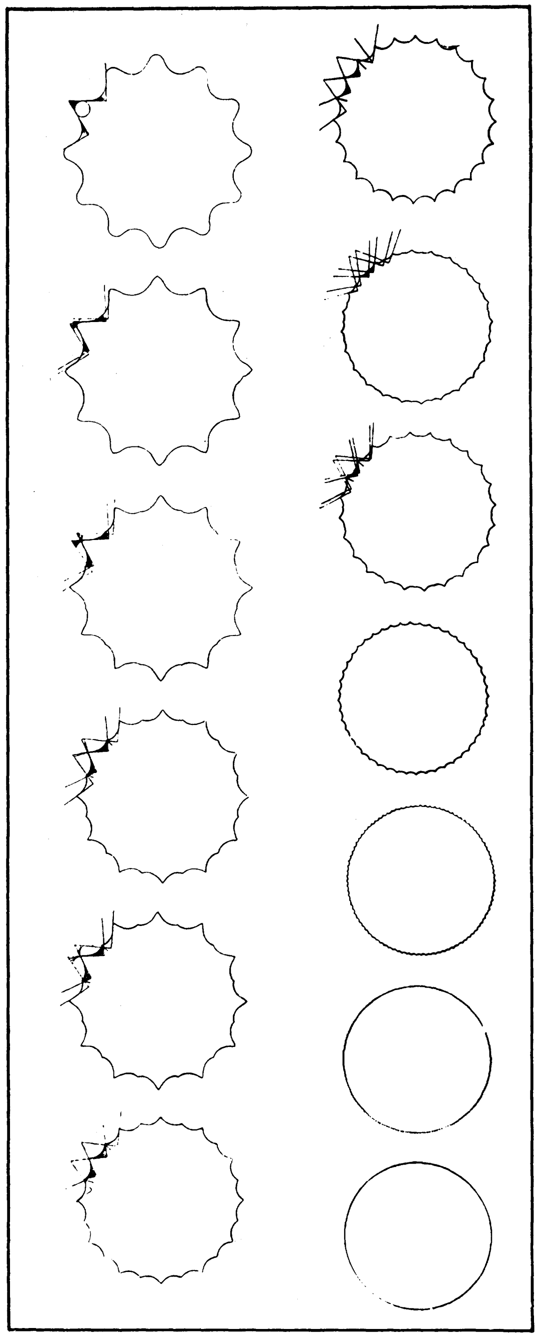


roof was to be constructed of them. Eduardo Catalano has suggested that Gaudí's are the first buildings ever to be designed of hyperbolic paraboloids, and has noted that this anticipated by many years the calculations on which our modern structural use of that surface depends.

The third class of higher geometrical forms which plays a crucial role in this building is that of the helicoids. The idea of helocoidal evolution found employment principally in the piers and columns. The way in which such a column can be formed by its base-shape making a partial helical revolution in one direction is seen in Figure 28 (left); these were to be used in some parts of the structure. But that the big, fluted, tapering piers of the nave are actually formed by the partial helical revolutions of their base-shape simultaneously

29 Elevation and horizontal sections of an inclined pier of the crossing of the Church of the Sagrada Familia (After Puig Boada)





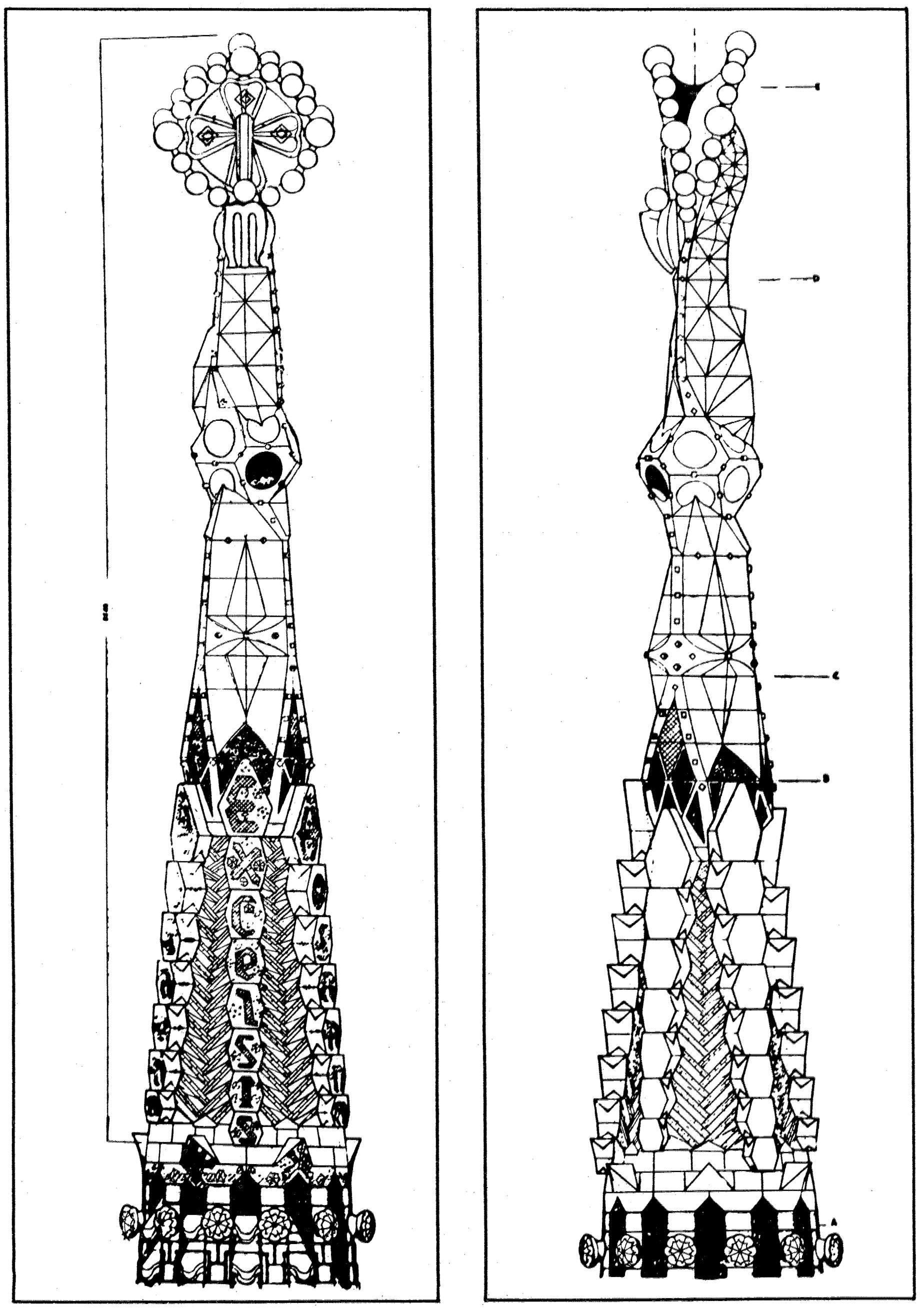
in opposite directions is a little harder to visualize. Figure 29 attempts to illustrate this process. Imagine two thin cardboard patterns of the serrated perimeter of the column-base laid on top of each other. If rotated very slightly in opposite directions, the combined silhouette of them both will undergo the following transformation: what was the arris will split and sink, becoming a valley between two peaks; what was the flute will rise slightly into a small peak; very soon there will be twice as many flutes and arrises, and the entire perimeter of the pattern will be slightly reduced. If a cardboard pattern identical to this is now laid on it and the process repeated, there will be another doubling of fluting and a further shrinkage in perimeter. Repeating it again, we end up with a very slightly serrated circle as the final pattern. If this counterrotation were to take place in vertical (right-helical) movements, there would be traced out the form of the other columns in Figure 28 in which there is a continual doubling of the quantity of arrises and a gentle upward taper—in underlying (modular) harmony with the other, twisted, columns of the nave that were arrived at by single helical revolution.

It is clear that we have now left predominantly structural considerations and are concerned with matters of architectural form. However, with Gaudí the interrelationship between these two factors was so intricate that there is scarcely ever a boundary to be found between them. For instance, he had throughout his career used cylindrical helices (the machine-bolt thread) and conical helices (the wood-screw thread) in a number of ways. The

30 Cellar of the Palacio Güell, Barcelona, 1885-89

31 Pier in the Teresan school, Barcelona, 1889-94

former are seen in the Palacio Güell structurally—the horse ramp (Fig 30)—and decoratively—the escutcheon on its facade. Is the Teresan school pier (Fig 31) structural or decorative? The Casa Batlló interior illustrates different usages of the conical helix, as do the snails sculptured on the Sagrada Familia church. The turret of the Park Güell gatehouse was formed by double revolution of a conical helix. The ventilator of the Casa Milá (Fig 15, left), by double (opposed) revolution of a cylindrical helix in which the crisscross helical lines are stressed instead of the arrises—a pattern that Gaudí also used in his grilles. Others of the Milá roof structures that appear to be the eccentric products of a pastry cook are actually compound helical revolutions in the same direction but of different points of origin, of varying angular direction, etc. If these seem to be somewhat complex, one has only to keep in mind Webster's definition of a helix, which tells us that it can be produced on any cylinder by a straight line on a plane (say, on a piece of paper) that is wrapped around the cylinder. Simple. A straight line or net of straight lines carefully drawn on a piece of paper of the right size could be handed to a workman for him to carry out by wrapping the paper around the object to be so executed. If instead of straight lines a sine curve is drawn on the paper, it will, when the paper is made into a cylinder, produce the curve that is followed by the roof edges of the Sagrada Familia school (Figs 16, 17) and the Casa Milá mansard (Fig 15). Thus the roof of the school is helicoidal as well as conoidal. A network of sine curves on the paper will result in the form of the left-hand ventilator in Figure 15. Gaudí and his circle of associates considered fully as important as the intricate structural character of the Sagrada Familia church the simple (and therefore for them divine and highly symbolic) derivation of the complex geometrical forms of the building. Complex, but harmonic and always rational! Gaudí's follower Juan Bergós commented, 'As elements of construction, Gaudí abhorred arbitrarily curved forms, the 'curves of sentiment' so much in vogue in the prevailing Art Nouveau. He found pure geometric forms to be superior to hybrid ones: ellipses more beautiful than basket-handle arches, parabolas more than ogees. He preferred, furthermore, curves which, while obeying a geometrical law, followed mechanical law as well—those which at the same time as being sculptural, resolved with elegance the exigencies of gravity.'



However, after acquainting ourselves somewhat with Gaudí's usage of warped surfaces of double curvature—ruled, translational, rotational, synclastic, anticlastic, etc.—we are entirely unprepared for the totally different geometric basis of his very last work, the finials of the Sagrada Familia church (Fig 32). Proceeding from top to bottom here, we find: round-cornered quadrilaterals bordered by spheres of varying size and leaning apart from each other; truncated pyramids from which other pyramids project sideways; pseudo-regular polyhedra formed by cutting off the corners of cubes or octahedra; triangular pyramids evolving from hexagonal pyramids, which sit in turn upon downward-projecting pyramids. Except for the paraboloid saddle at the top, there is not a flowing ruled-surface in the lot. They are instead an additive and interlocked series of crystalline forms looking for all the world like rock candy on a string—or an architectural synthetic-cubism.

There is no clearer proof than this of the fact that to the end of his career Gaudí's ideas were always changing, always in flux, and that he was constantly creating anew—not unlike his compatriot Picasso.

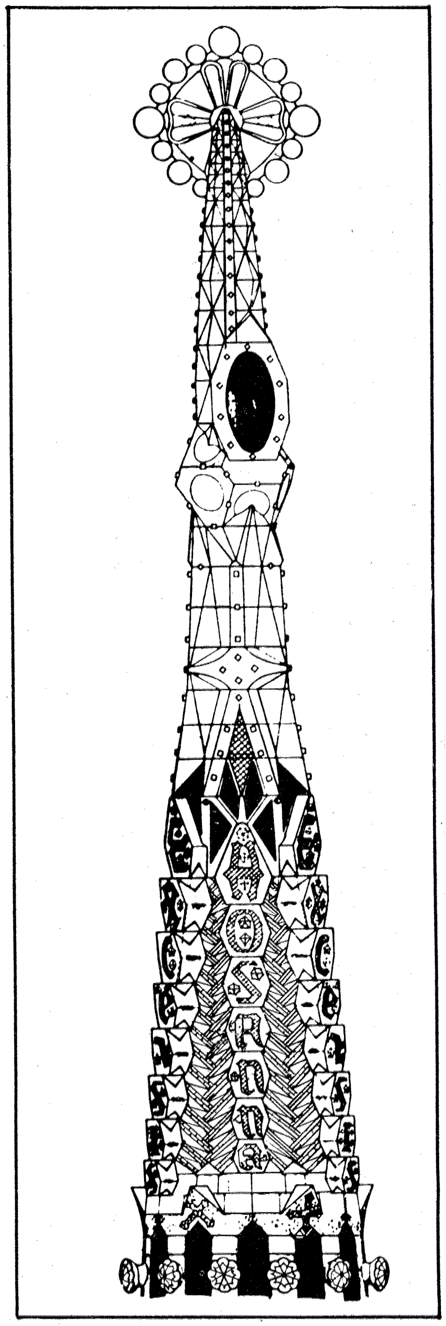
We are led, then, to three general conclusions:

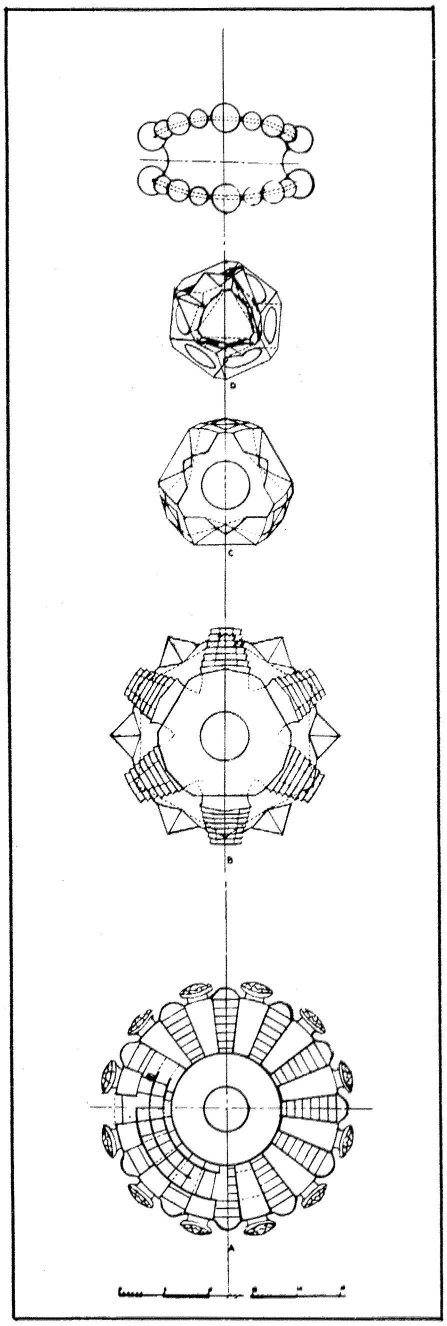
First, that in the work of Antonio Gaudí there is a near identity of structural design and architectural (viz., artistic) form—a phenomenon that is virtually unique in the history of architecture. Our suggestion is that this derives in part, at least, from his effort to be guided in his buildings by the forces of nature and by the underlying geometry of nature's own forms.

Second, that nothing in his work is really arbitrary: all is calculated, orderly, consistent within itself, and—to repeat—is in harmony with the geometrical and physical laws of nature, *not a copy after nature* as was so prevalent a practice in his day.

Finally, that much in the work and in the intuitive procedures of Gaudí is prophetic of what actually concerns us in architectural design today. The work of Catalan builders, and Gaudí in particular, is an antecedent of modern thin-shell construction—the most direct line of descent being, in this case, through Torroja and Candela and the forms and structures which Gaudí had envisaged are re-emerging today after a long hibernation during which the steel cage roamed at large and dominated our ideas about building.

32 Elevations and sections of a crowing spire of the Church of the Sagrada Familia (After Puig Boada)





*The American buildings that are mentioned in this article were vaulted in the Catalan manner by Rafael Guastavino (1842-1908) and his son, also Rafael, (1872-1950). Born in Valencia and active in Barcelona, the elder Guastavino contributed spectacularly to the vaulting traditions of his native Spain before emigrating to this country where he devised, perfected, and patented the 'Guastavino System' of fireproof construction. He published two fundamental books on the subject, *Cohesive Construction* (1892) and *The Function of Masonry* (1896-1904). His son was, in turn, responsible for many of the remarkable constructional feats of their company—such as the dome of St. John the Divine's. He developed their ceramic soffit tiles and, together with Professor Wallace C. Sabine of Harvard University, invented two different types of extremely effective masonry acoustical tiles.

The inventory of buildings with Guastavino vaults reads like an outline-history of American building from the 1880's down to the Depression and World War II when their popularity began gradually to wane in the face of rising labor costs, improved concrete technology, and, perhaps most important, a universal preference for flat ceilings. By that time the Guastavinos had accounted for about a thousand edifices throughout the United States and foreign countries, including blue-ribbon buildings by the best known American architectural firms of the era. Thus the reader may study Catalan vaults at firsthand here in this country in a variety of public and industrial installations, churches, banks, business and institutional structures, private residences, etc.

This article is a summary of lectures delivered at the Yale University School of Architecture in February of 1962 and at the New York Chapter of the Society of Architectural Historians in May of 1962. An exhibition of these materials was displayed at Columbia University during May, 1962. The writer is preparing a more detailed and annotated version of this study.

For further discussion of the matters treated here consult the publications listed in Notes 74 and 77, and in Bibliography D of the writer's book on Gaudí (Braziller, 1960). The materials used in this article have been drawn from the Catalan Archive of Art and Architecture ('Amigos de Gaudí—USA'), Columbia University.