

THE NEED TO STEP BEYOND CONVENTIONAL ARCHITECTURAL SOFTWARE

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ABSTRACT

The Sagrada Família Church has appointed two groups of consultants to assist the translation of Gaudí's 1:10 scaled models of the nave into coherent information from which to build. One team has been undertaking the static analysis of the nave roof vault structure and the other the study of the complexities of Gaudí's composition in order to provide full-scale production templates and models for the walls. Both teams had begun using the same basic CAD package and both have had to move onto high-end and very expensive solid-modelling software normally used by mechanical engineers and vehicle designers.

Both groups are collaborating together with different accents despite an improbable geographical separation. The original problem, one of intersecting ruled-surfaces accurately to reflect the geometries of the surviving fragments of the original models, has led to surprising possibilities which were not anticipated at the outset. Currently the potential of *parametric variation* and *associative geometries* are being investigated as a mirror for some of the intuitive design process and *finite element analysis* is being considered as a means of interactively analysing the structural implications for each study. The software being used also has a powerful ray-tracing module; rather than being simply a tool to produce eye-catching 'realistic' renderings it has proved to be invaluable in allowing the computer user to understand the spatial complexities of the components being studied.

This paper discusses the merits of an architecture so demanding (despite having been designed at the beginning of this century) that it requires the most costly equipment in today's market and it will consider the proposition that in ordinary circumstances, an architecture too complex to be described using basic CAD tools is an architecture beyond our reach. The interdisciplinary nature of the diverse and powerful modules within the software referred to will be used to contest this proposition using the presence of both teams in schools of architecture as evidence.

BACKGROUND

Gaudí qualified as an architect and entered the profession in 1878 and of his 48 years in practice he led the collaborative team at the Sagrada Família Church for 43. When he died in 1926 only the crypt beneath the apse, the apse and the eastern transept (Nativity Facade) had been completed. Work has continued on the building based on the material which survived the vandals' work during their occupation of the atelier (based on site) during the Spanish Civil War. Today, almost all the building work is dedicated to completing the main body of the nave by the end of the millennium. With the completion of the western transept in 1977 and the nave foundations and crypt in 1991, the built fabric is some 40% of the projected whole.

In 1906 Gaudí's assistant Rubió i Bellver produced the first definitive drawing showing the composition of the exterior of the whole building (fig 1). Gaudí never departed from this drawing during his remaining twenty years. Although he did not make any substantial changes to the overall *composition* of the building, he did propose fundamental changes in *detail* and it is the implication of these changes - the introduction of a geometrical rationale through the use of second order surfaces (ruled surfaces) - which is the subject of this paper.

While it is quite clear that parts of the building such as the central groups of towers and the main front are not resolved in detail, the nave itself was extensively modelled at a scale of 1:10 in gypsum plaster. Despite all the drawings being burnt during the church's occupation during the war and the precious models smashed, the fact that they were composed entirely of second order geometries has meant that their restoration, whilst onerous, was at least viable. It is the faithful interpretation of these models into coherent building information which may temper some of the earnest criticism of the Construction Committee's endeavours whose objective remains to complete the building commissioned from Gaudí as close to his stated design as possible. This is not the occasion to engage more fully with the polemical issues surrounding the current work; rather, it is the opportunity to discuss the mechanism which enables construction work to continue. [1]

THE BASIS FOR COLLABORATION

The principal operations for both the construction design and the building operations are based on site. The Technical office is staffed by a small team comprised of Coordinating Architect Director, Project Architect and draftspeople who work in tandem with a somewhat larger team of plaster model-makers. While a substantial part of the building work such as the major stone working and the prefabrication of the 'artificial stone' components is undertaken at a number of locations off-site, similar operations nevertheless continue on site alongside the sculptors, artists and general contracting. Despite the use of the most recent technological advances there is, in fact, no great difference in the production rationale behind this great building and its medieval forebears,

Just as a certain amount of the building work was contracted-out in order to increase efficiency so, too, has an element of the building design work. The involvement of two universities to aid the design work is not a denial of the Sagrada Família's technical team's abilities; rather, like the use of modern materials and methods in the building, the universities are seen as a more realistic way to explore opportunities using computing software otherwise untested for the peculiar problems presented by Gaudí's unorthodox design methodology.

The limitations imposed by this short paper also exclude any explanation as to why there are two consulting universities beyond the fact that the UPC has the expertise and understanding of the structural implications of non-planer surfaces (and the nave is composed almost entirely of such surfaces) and VUW has an expertise in dealing with the intersection of non-planer surfaces and other stereotomic concerns both graphically and through the use of sophisticated computing. Both universities had been working independently for a number of years in collaboration with the Technical Office at the Sagrada Família. By 1991 it was clear that both teams were pursuing parallel paths and, logically, it became necessary for both the UPC and VUW to pool their resources. A comfortable collaborative regime is in place and whilst neither party is dependant on the other, both teams have been able to address their focused concerns in a more holistic light with the Coordinating Architect Director appreciative of the triangular forum over which he presides. [2]

DESIGN ISSUES

The completion of 'La Pedrera' (Casa Milà) in 1912 [3] was not a happy occasion and coincided with the abandonment of both Colonia Güell Church as well as Park Güell. It was from this time the Gaudí dedicated himself to the Sagrada Família accepting no further commissions. The break between his time of greatest popularity as Modernista architect and the following twelve years of almost total withdrawal to the Sagrada Família also marked a radical change to the way he described the surfaces to his buildings. Whereas La Pedrera is a work characterised by its total plasticity, to achieve it stonemasons were required to work in the most inordinately tedious way. The surfaces were modeled at full scale in the basement in plaster and it is from these prototypes that the masons made their templates. Contemporary accounts reveal that often the pieces of stone were required to be raised and lowered up to four times before they registered exactly with each other giving the seamless facades that are so much admired. The implication of this laborious procedure was reflected in the cost; not only was the building not completed to Gaudí's design, he was forced to sue his client in order to recover his fee.

During his final twelve years at the Sagrada Família, Gaudí introduced a methodology which

represents a remarkable contrast to that which characterised the empirical investigations he used to generate the design and construction of La Pedrera, Park Güell and Colonia Güell. Although commented on for their aesthetic and formal qualities, the ruled-surfaces which Gaudí employed for the whole design of the nave are seldom, if ever referred to on the basis of their inherent rationality.

RULED-SURFACES AND THEIR INTERSECTION

The ruled-surfaces employed are the following:

- helicoids
- hyperbolic paraboloids
- hyperboloids of revolution of one sheet

The combination of these surfaces is articulated through their intersection and it is the position and treatment of such intersections that are the key to their success. They also represent, however, a problem from the point of view of the design process.

The feature that the combination of any or all three warped surfaces have in common, apart from an infinite range of possibilities both subtle and exaggerated, is their description through lines which, by definition, are straight.

The most simple is the helicoid with its description being a line, the *generatrix*, which both rotates and displaces about a central axis (fig 2). The second surface is the hyperbolic paraboloid (fig 3). Here the generatrix, which can vary in length, is guided by two non-coplanar lines, *directrices*, which can also be of different lengths. Clearly any section through the surface along a generatrix will be a line; a section through any other part of the surface will be a curve.

The third form is the hyperboloid of revolution of one sheet. In this case the generatrices go between two opposite circles which form the directrices. If the generatrices go between opposite points, the resulting form will be cylindrical. If they are slanted, for example, from 0° on one directrix to a position 60° around an axis on the other, the resulting form is a hyperboloid (fig 4). Cooling-towers from power stations are familiar examples. The size and separation of the directrices - which can also be elliptical - are variables. The degree of slant of the generatrices is also a variable between the limits of 0° with respect to each other (cylinder) and 180° where the result will be two opposing cones (figs 5 & 6). The hyperboloid with circular directrices (cooling tower) can also be produced through the rotation of a hyperbola about a central axis (fig 7).

The rationality of descriptive geometry, largely forgotten in today's building environment, has a distinct benefit for the mason whose task is to produce the individual pieces which have a complexity belied by the coherence of the whole. Because ruled-surfaces are composed entirely of notional (straight) lines which have points of origin and destination which can be templated, they inform the mason readily of where to work; simply by chiselling a series of from a to a', b to b', c to c' etc., the surface reveals itself without reference to any other resource.

Not only do these surfaces facilitate a stone working procedure which can be undertaken in a location quite remote from the stone's final location, the procedure provides an exactitude which allows for a single operation to be carried out with no need to refer each piece to its neighbours for fit before being fixed into place. The same descriptive advantages can be shown for mould-making and indeed the ruled-surfaces provide an extremely effective model-making procedure. With the contemporary use of artificial stone, full-size mould-making enjoys the same logistical benefits.

DESIGN PROCESS

Within the infinite variations in form, the common function of their description as ruled-surfaces, then, is the ease with which such surface description can allow their exploitation for construction advantage. Whereas a sculptor has complete personal control over their plastic medium, the problem of working with such liberal intentions for making a building as large as a cathedral is the

necessary involvement of so many different trades all dependent on a coherent translation of the designer's intentions to their each and separate tasks. The complexity of coordinating all the parties of such buildings is considerably reduced through rational description.

It is clear that from whatever basis Gaudí was influenced in his choice of such geometries, the decision was in greater part intuitive; there is no record of any explanation by him of how the models might be translated into full-size components nor how the laborious means of their production be facilitated more effectively. It would seem that the modelling technique was his principal design tool, reworked as a reiterative design procedure until he was satisfied with the outcome. Using such techniques the nave went through considerable detailed change until the definitive design was agreed some years before he died (fig 8).

The restoration of the models, too, has been aided by their ruled-surface composition and without this rationale, it is doubtful that models, if made with the 'irrational' plasticity of La Pedrera, for instance, and reduced to the same smashed state as those of the nave, could ever have been restored with the same complete confidence. Why, then, can they not be scaled-up to their full size using existing resources? The conundrum is the following: although the models are sufficiently accurate to provide reasonable representation of Gaudí's intention at 1/10th scale, the amplification of the inaccuracies that would be the consequence of scaling them up to full-size would result in templates that would deny the perfect finish only possible through the accurate use of this geometry. An approximate surface would require masons having to finish the work in situ which, apart from the danger to the mason, this represents a considerable extra expense.

It is only since the early seventies that a greater focus was given to the need to translate the nave models into coherent building documentation. Until that time, while the successors of Gaudí continued to collate, restore and investigate the nave design, their principal task had been the building of the second transept which was a virtual facsimile of the first [4]. With the nave, a technique had to be devised to reverse-engineer, as it were, the surviving models in order to rebuild them with an appropriate level of accuracy. Up until a satisfactory method was introduced to graphically plan the intersections between dissimilar adjacent non-planar surfaces, such work remained the model-maker's domain. The rigour and precision of this methodology means that rapid working in plaster is precluded. Graphical methods are a significant time-saving compared with modelling but are still too lengthy a refining process to afford the task of constant reiterative design testing almost certainly the predominant interest for Gaudí. It was only in the late 1980's that computer power had reached a level and cost apparently within the technical team's means [5].

COMPUTING RESOURCES

Both universities experimented with the same widely available drafting package and although there was the clear opportunity to advance significantly the speed with which graphical analyses could be undertaken, wire-frame geometry could not intersect adjacent interfering surfaces. Again, with the same package, the subsequent release of a solid-modelling extension in 1991, allowed a significant percentage of this work to be undertaken. That which could not be modelled, however, (all but circular hyperboloids) reduced the opportunity for its use which was handicapped, anyway, by the propensity for even the more powerful pc's of the day to fall over relatively small files. Initial enthusiasm for the solid-modelling extension and admiration for its price led to disappointment for its inadequacy for our particular task.

Turning away from the architect's traditional software resources, manufacturers of high-end solid-modelling software were lobbied (whose product was dedicated to a completely different end-user, principally the mechanical engineer) in an attempt to persuade them that the scope of their market might be wider than previously considered. Both teams now enjoy support and encouragement of Computervision using 'parametric' and 'explicit' versions of CADD5.

Apart from being eminently suited to the task described above, there are unexpected benefits not sought for at the outset but which now make a considerable impact on site operations at the Sagrada Família.

These are summarised as follows:

- solid sectioning
- volumetric and mass property analysis
- calculation of centroid
- finite element analysis
- realistic shade and material rendering
- parametric design
- numerically-controlled cutting and milling

The first of these is the capability of the *solid-model* to be rapidly and accurately sectioned (fig 9). Given the need for the building to meet the seismic design code with, as a consequence, the use of reinforced concrete within the dressed or artificial stone facing, regular sections through such curving facades and roof vaults help determine the location of reinforcement.

The second capability, and an intrinsic design feature of solid-modelling software, are the *volumetric and mass property evaluation* tools. With these, not only can the component be measured for volume, a mass can be determined ensuring that each piece is within crane lifting tolerances. Furthermore, the centroid can be determined with ease with the advantage that lifting points can be designed such that each complex shaped piece weighing up to 2 tonnes can be lifted orientated correctly for their final installation (fig 10).

A further advantage, but one which is still in its early stages, is the application of the *finite element analysis* module. Given the potential resolution of ruled-surfaces into lozenges, the interpretation of load paths in surfaces otherwise too complex to be investigated through conventional means represents a very powerful tool. Just as Gaudí developed empirical methods to pare structure to a minimum through his study of funicular model, it would seem that high-end computing resources will become a less rarefied means to allow otherwise impossible structural situations to be assessed by a wider group of people.

A corollary of the computer power required for the purposes of solid-modelling is the hand-in-hand opportunity to realistically render models so created. But beyond any 'artistic' concerns lies the practical need to be able to manipulate objects of such complexity on the screen with comprehension where view angle and, indeed, 'shape' is otherwise difficult to grasp. We are not yet at the stage of affordable real-time manipulation - not even in the industries for which such software is designed - but it is clear that we will not have to wait (too) long.

Perhaps the most exciting tool within this breed of software is the *parametric variation* facility using associative geometry. With such a tool there is a real possibility for reiterative design using computers which, thus far, seem to have been more disposed for the representation of ideas rather than the generation. Whilst we assume that the seed of an idea will not be derived from a machine, any process which allows reiterative testing of an idea as a way for moving it forward must be a welcome advance. For the analytical work in interpreting Gaudí's models, the ability to make continual adjustments to different related geometries testing the results without having to return to the beginning is a vital tool. But rather than allowing something to happen which would otherwise not happen, (and in the years up until the introduction of computing at the Sagrada Família Gaudí's models were interpreted adequately without such sophistication), this level of reiterative design applied to the models will be a far more effective way of removing the inaccuracies which Gaudí was not able to deal with entirely using his plaster modelling method. As a benchmark, CADD5 can model and realistically render in a day that for which a highly skilled group of craftspeople would require several weeks. (fig 11).

Finally, reference is made to the *numerical control* options which are also part of high-end solid-modelling packages (lower-end packages are also making an effective entrance into the field). Again, it is through their intended use in the manufacturing industry and its growing dependence on automated manufacture that has resulted in precise numerical control output from the software to

drive 5-axis milling. Although neither university is directly involved with the Sagrada Família's automated stone saw which cuts the granite, basalt and porphyry facing to counter-rotating doublehelical columns in the nave (fig 12), clearly there are possibilities regarding building component manufacture which will make an increasing impact on the building industry [6].

CONCLUSION

The advantages described above of a particular type of software tailored to the specific needs of manufacturing industry have an accent which is demonstrably as important for the atypical needs of the Sagrada Família. For both universities, the power of such a tool, especially after much lengthy and relatively ineffective work using conventional architectural software, is very welcome. The usefulness for our specific purposes is undisputed. It is when the opportunities are discussed for widening the scope of the architect's role in describing the building and effecting new conditions for its construction that doubts are encountered. What is good for one industry, where mass production factors-out the enormous capital cost of the equipment, may not be seen as relevant for the limited-run scale of the building industry. Worse, the potential of this equipment risks being described as the 'enfranchisement of the amateur'; the power and scope is manifest and the operation appears to be within the reach of the competent computer-user.

The relative ease with which the software appears to operate is, however, deceptive. It is not clear to what extent such equipment could impact undergraduate study given the many various pressures on the typical architecture student. Looking at the unusual circumstances of the Sagrada Família the introduction of such highly technological resources do not conflict necessarily with the way that Gaudí worked; the means, here, can be justified in the light of the end. Gaudí's design for the Sagrada Família is, in fact, stretching existing technological resources to their limits within the context of late twentieth century pace of life. If we try to extrapolate the opportunities provided by such tools to wider architectural discussion it is less clear to what extent parametric variation, for instance, will influence the way architects work or how soon it will make a significant impact. On the one hand it does allow much of the testing of design hypotheses to be undertaken and visualised more readily than by traditional methods; on the other hand, no matter how much prices drop and how easy, relatively speaking, 'intuitive' high-end packages become, their inherent complexity (simply through the three-dimensional intentions being dealt with by the machine) may always be more than the average designer will be inclined to address and therefore beyond the needs of undergraduate study.

Rather than Gaudí's design stratagem be used as a benchmark to demonstrate the power of contemporary computing technology, it would seem to be the other way round. The viability of such unorthodox computing within the building industry, even if it were only ever for prestige scaled projects, may, in fact, owe a posthumous debt to the way Gaudí worked during his final years; a methodology which could not be appreciated were it not for the efforts to continue the building rigorously informed by his design for the nave of the Sagrada Família.

[1] For a more detailed discussion of the actual situation with an historical background see the following:

Bonet Armengol, J., *Temple Sagrada Família*, Barcelona, 1992

Burry, M.C., *Expiatory Church of the Sagrada Família*, Phaidon Press Ltd, London 1993

[2] It is noted the Joan Margarit, Carles Buxadé and Josep Gómez Serrano (UPC) are also Architect Directors at the TSF

[3] This date varies between commentators and the one given is from Bassegoda, J., *El Gran Gaudí*, Barcelona 1989

[4] The western transept is higher and has an elliptical plan. (The eastern transept (Nativity Facade) is circular).

[5] It is noted that apart from the use of the algorithms for the various surfaces there has not been a concerted effort to analyse the models using applied mathematics. Building work during Gaudí's last twelve years was very slow and presumably Gaudí had the time to 'experiment' and revise his design in a way which would not be appropriate today. There is no record of Gaudí having used mathematics to plot the intersections.

[6] M Burry is collaborating with Dr K Whybrew at the school of Mechanical Engineering, Canterbury University, New Zealand with the investigation into automated large scale mould-making opportunities.

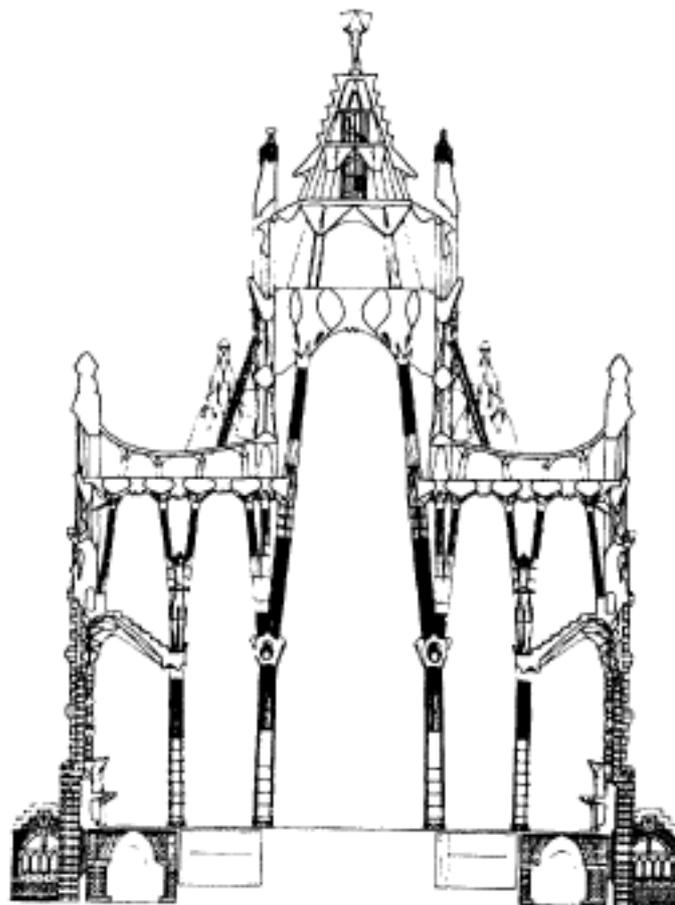
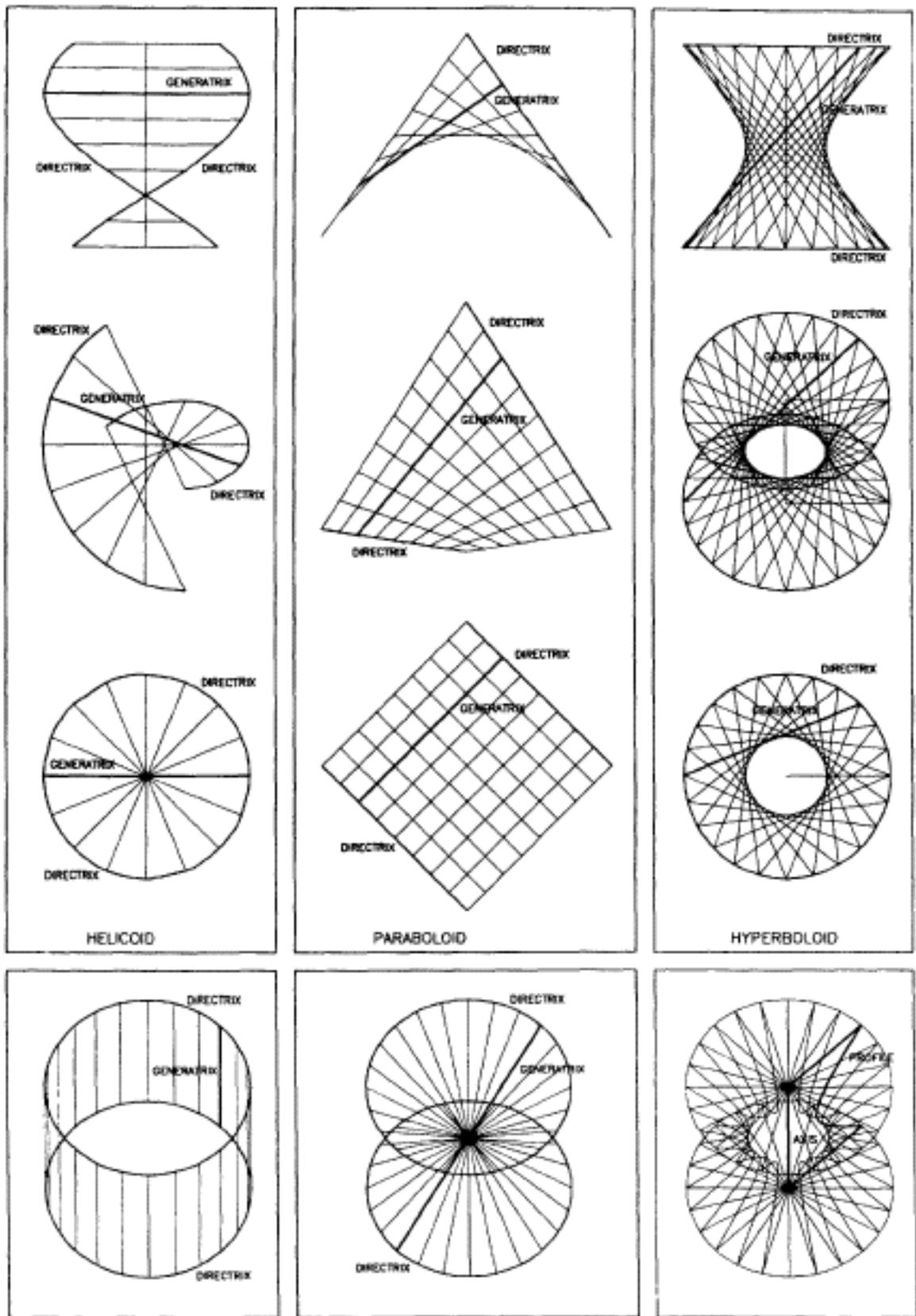


FIG 1: EAST ELEVATION OF SAGRADA FAMÍLIA CHURCH (1906) AND CROSS SECTION THROUGH THE NAVE



FIGS 2-7 RULED -SURFACES AND THEIR DESCRIPTION

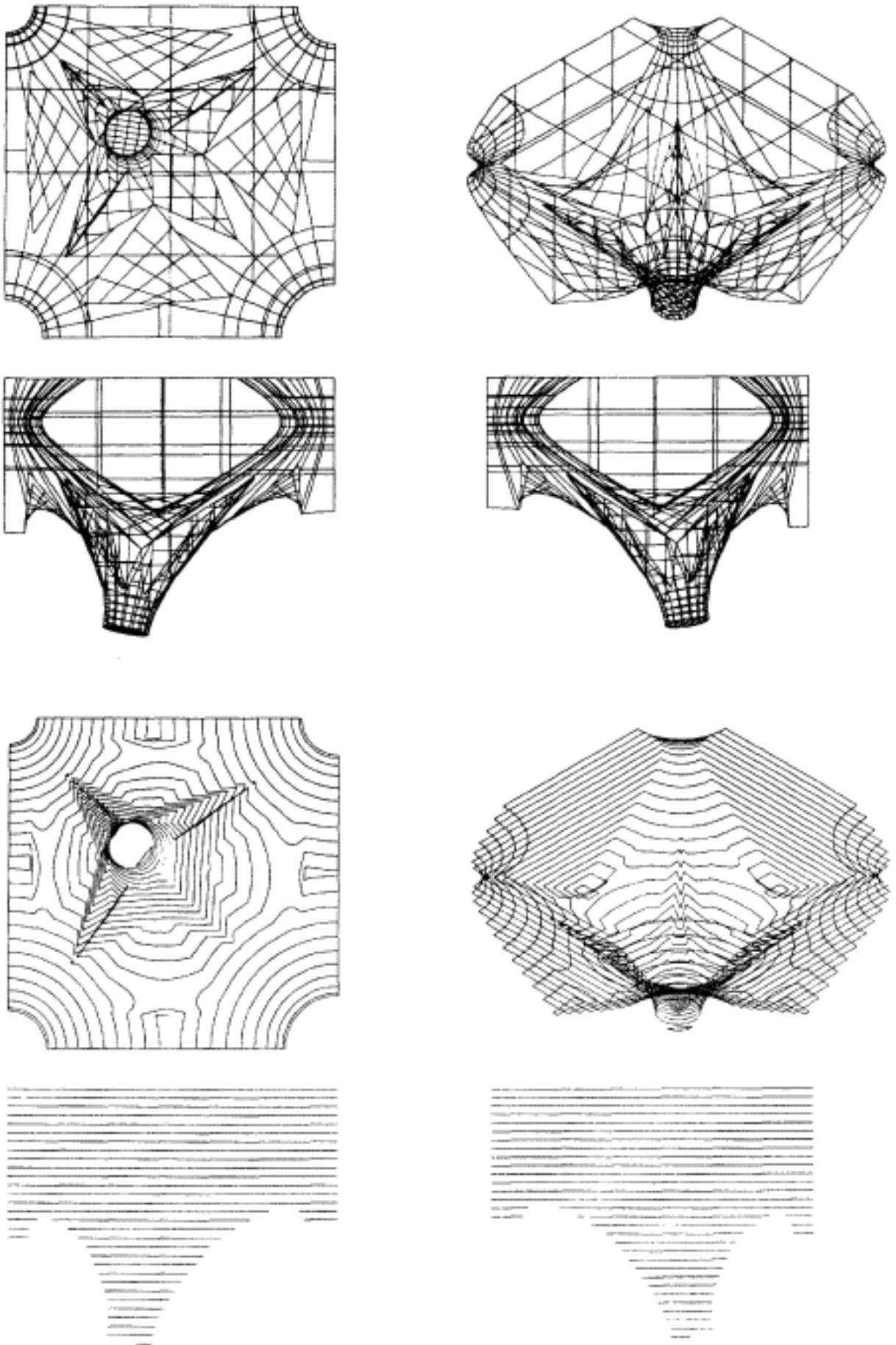
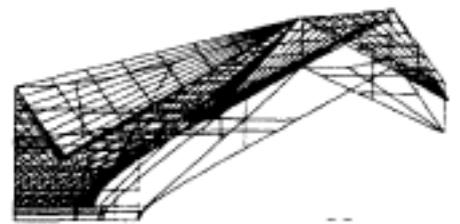
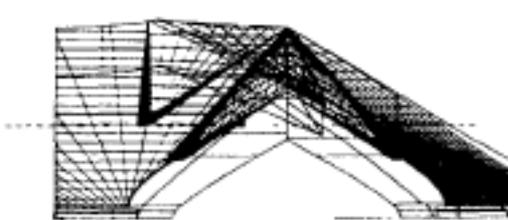
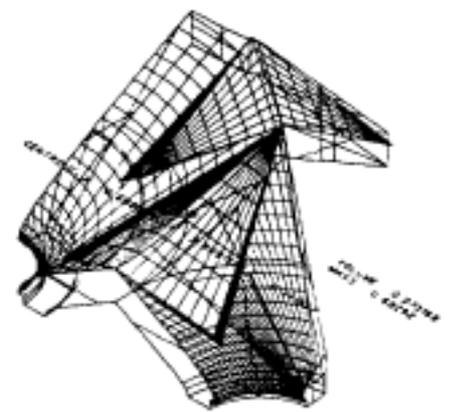
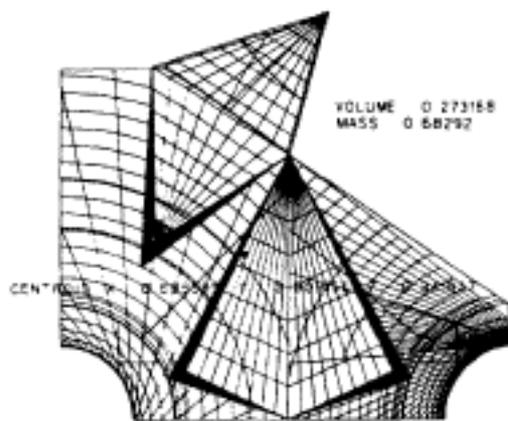
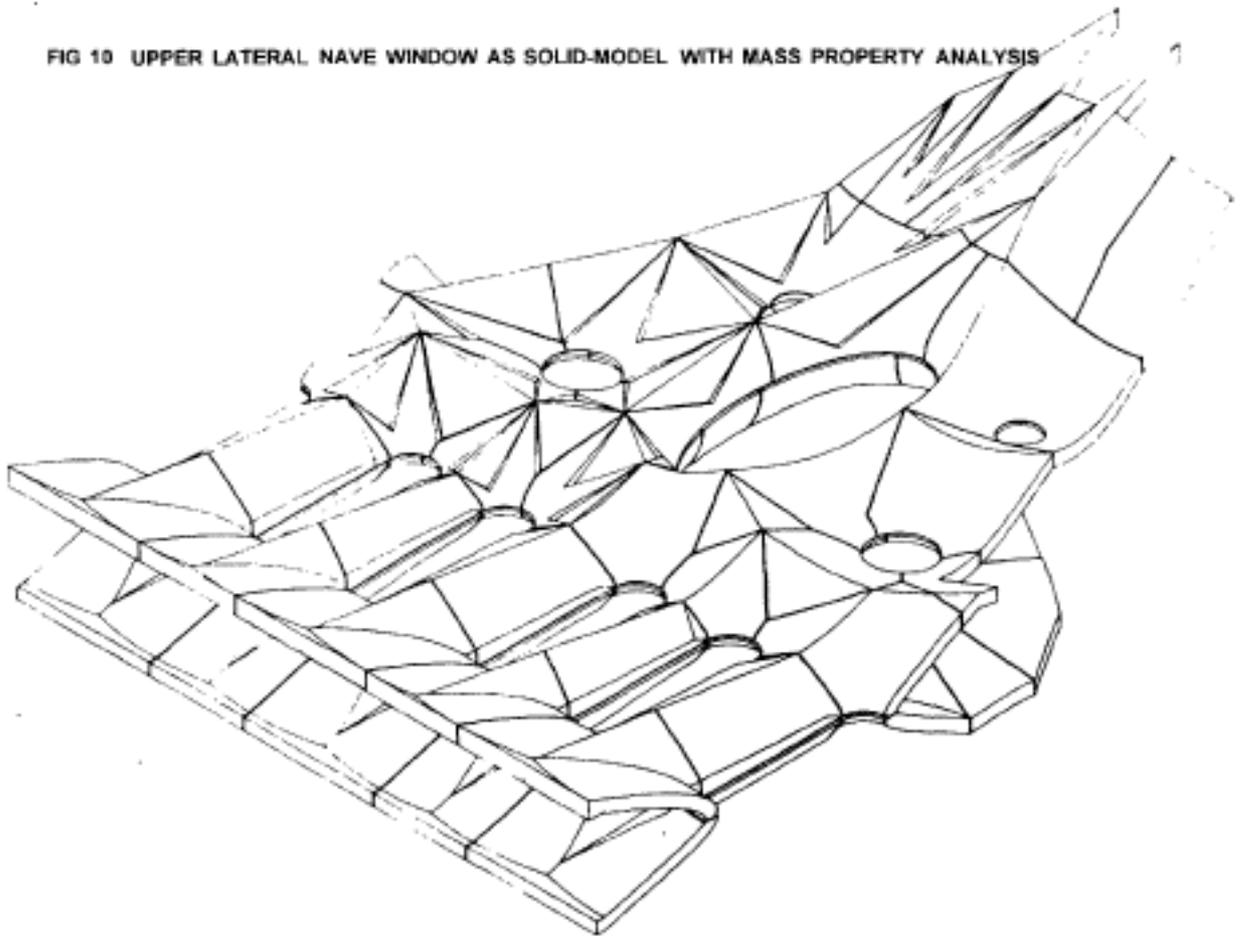


FIG 9 INTERSECTION OF COLUMN AND ROOF VAULT (TOP) WITH INCREMENTAL SECTIONS (BELOW)

FIG 10 UPPER LATERAL NAVE WINDOW AS SOLID-MODEL WITH MASS PROPERTY ANALYSIS



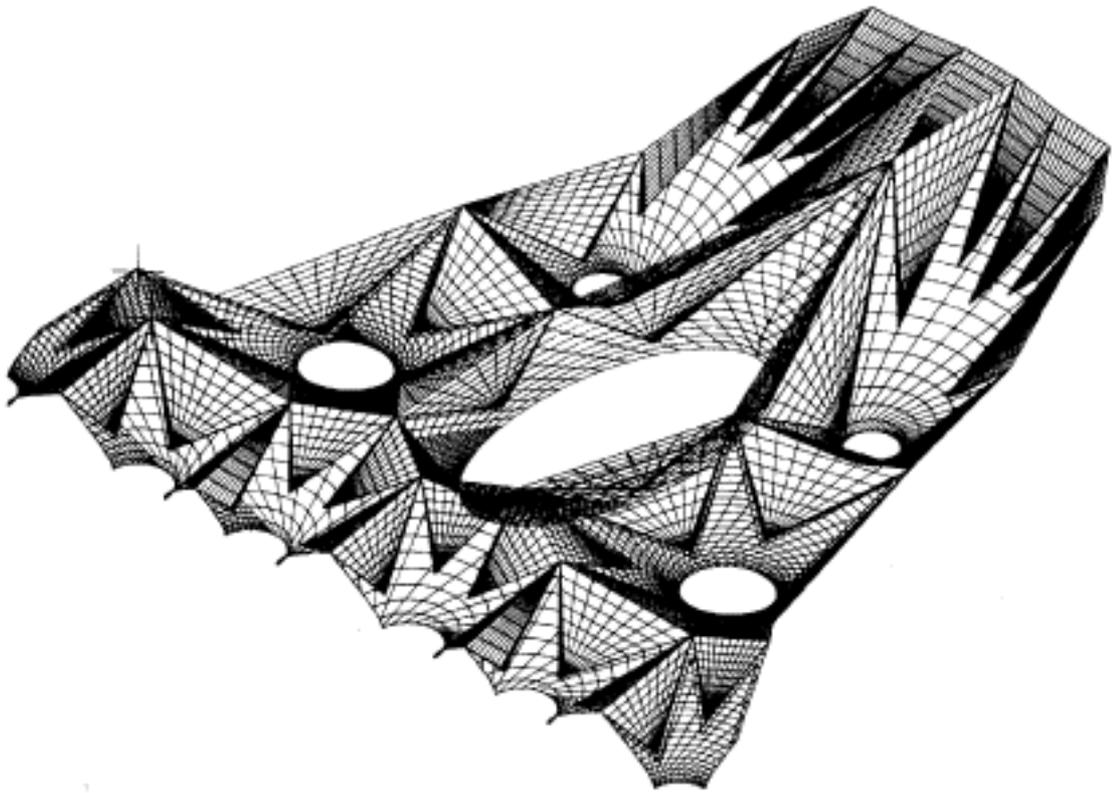


FIG 11 UPPER LATERAL NAVE WINDOW: INTERSECTED SURFACES FOR RENDERING (AND NC)

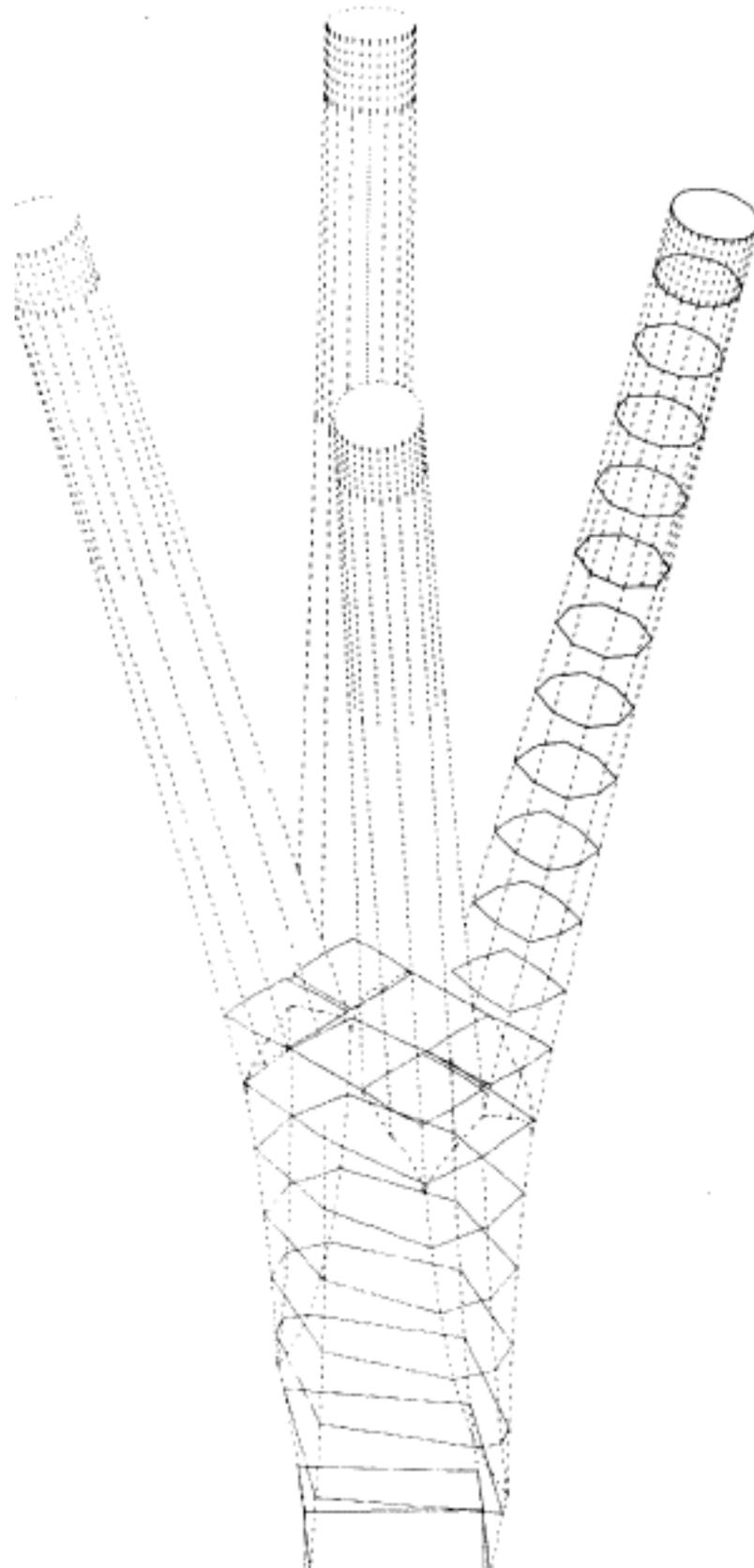


FIG 12 NAVE VAULT SUPPORT COLUMNS

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