FIG. 1
Part of one-sheet
hyperboloid, defined by
the two families of rulings,
perspective view
(image by the author).

FIG. 2
Photo of the Chandigarh's
Assembly, where we can see
the traces of the formwork
of the chamber
(FLC L3(10)67).

LE CORBUSIER AND GEOMETRY IN PRACTICE. A STUDY OF TWO SINGULAR EXAMPLES

Leda Dimitriadi

Abstract: Le Corbusier's conviction that geometry, and more generally mathematics, carry aesthetic, functional and even moral values is well known; the use of the famous regulating lines in some of his projects and especially his work on the Modulor are undoubtedly the most obvious indications of this position. For Le Corbusier, geometry is an ideal, and several authors have noted the Platonic or Pythagorean character of his vision of mathematics. In this study, we will question in which ways geometric or mathematical principles or methods are implemented in the process of the specification of architectural forms for their construction. This study focuses on cases which present relatively complex geometric aspects, more precisely two projects which contain particular geometric surfaces, with negative curvature: the main chamber of the Palace of the Assembly of Chandigarh and the Chapelle Notre-Dame-du-Haut de Ronchamp. In the first case, the geometric regularity is apparent, in the second a very pronounced irregularity is deliberately sought. The methods used in both cases share points in common, but also present differences that are worth highlighting.

Keywords: geometry, mathematics, Ronchamp, Chandigarh.

Résumé : La conviction de Le Corbusier que la géométrie et plus généralement les mathématiques sont porteurs de valeurs esthétiques, fonctionnelles et même morales est connue ; la mise en place des tracés régulateurs dans certains de ses projets et surtout son travail pour le Modulor en sont les preuves sans doute les plus évidentes. Pour Le Corbusier, la géométrie est un idéal, et plusieurs auteurs relèvent le caractère platonicien ou pythagoricien de sa vision sur les mathématiques. Dans la présente étude, nous allons interroger la manière dont des principes ou méthodes géométriques ou mathématiques sont implémentés dans le processus de concrétisation de son oeuvre projetée (et construite). Notre étude se focalise sur des cas qui présentent des aspects géométriques relativement complexes, plus spécifiquement deux projets qui contiennent des surfaces géométriques particulières, à double courbure inverse : la salle principale du Palais de l'Assemblée de Chandigarh et la chapelle Notre-Dame-du-Haut à Ronchamp. Dans le premier cas, la régularité géométrique est apparente, dans le deuxième est recherchée délibérément une irrégularité très prononcée. Les méthodes utilisées dans les deux cas partagent des points en commun, mais présentent aussi des différences qui méritent d'être soulignées.

Mots clés : géométrie, mathématiques, Ronchamp, Chandigarh.

Resumen: Es conocida la convicción de Le Corbusier de que la geometría y, más en general, las matemáticas son portadoras de valores estéticos, funcionales e incluso morales; el establecimiento de trazados reguladores en algunos de sus proyectos y especialmente su trabajo para el Modulor son sin duda las pruebas más evidentes de ello. Para Le Corbusier, la geometría es un ideal y varios autores señalan el carácter platónico o pitagórico de su visión de las matemáticas. En este estudio, cuestionaremos la forma en que se implementan los principios geométricos en el proceso de hacer realidad su obra proyectada (y construida). Nuestro estudio se centra en casos que presentan aspectos geométricos relativamente complejos, más concretamente dos proyectos que contienen superficies geométricas particulares, con doble curvatura inversa: la sala principal del Palacio de la Asamblea de Chandigarh y la capilla de Notre-Dame-du-Haut en Ronchamp. En el primer caso la regularidad geométrica es evidente, en el segundo se busca deliberadamente una irregularidad muy pronunciada. Los métodos utilizados en ambos casos comparten puntos en común, pero también presentan diferencias que valen la pena destacar.

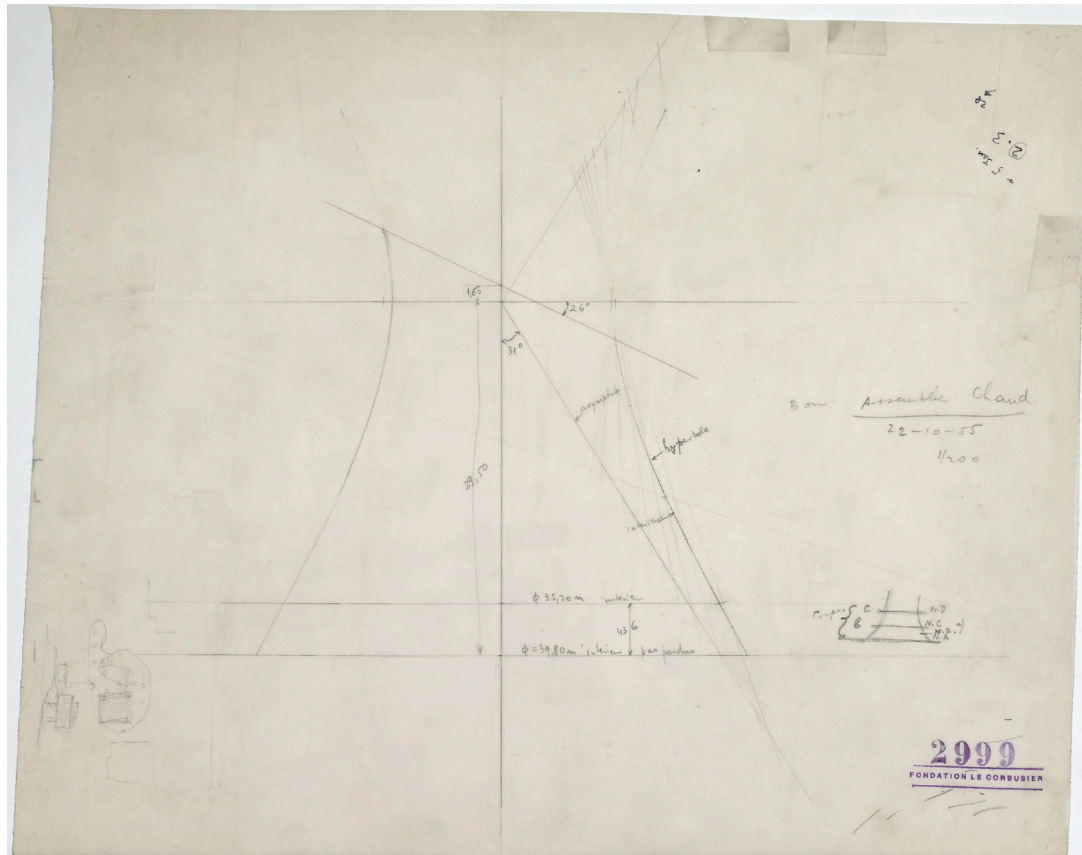**Palabras clave:** geometría, matemáticas, Ronchamp, Chandigarh.

FIG. 3
Cross-sectional study of the large chamber's hyperboloid formwork (FLC 2999).

Geometry for Le Corbusier, an ideal?

"The geometry which, in the midst of the confused spectacle of the apparent nature, has established marvellous signs of clarity, of expression, of spiritual structure, signs which are characters"[1].

Le Corbusier has placed his work, since the 1920s, in the perspective to rehabilitate mathematics in the actual act of artistic or architectural creation. In *Une maison - un palais*, published in 1928, he considers geometry as the "normal production of our brain, and *fatal*[2], because it participates in a universal rhythm"[3]. He therefore sees in geometry an order or a rule, hidden but fundamental – intrinsic qualities of the world. Le Corbusier associates aesthetic, functional and finally moral values with the geometric figures.

These beliefs about the value of geometry and more generally of mathematics are confirmed by Le Corbusier in a later text[4], written in 1946 at the invitation of the mathematician and founder of the Oulipo literary group, François Le Lionnais, for the section "Les mathématiques, la beauté, l'esthétique et les beaux-arts" (Mathematics, Beauty, Aesthetics and the Fine Arts), in a book on mathematics. Subsequently, Le Corbusier's work on the Modulor, implicitly announced in the aforementioned text, is undoubtedly the most obvious example of his attachment to an order induced by mathematics, as well as his most accomplished work in this domain.

Now, what about the development towards materialization? To what extent are the clarity of geometric principles and the rationality of science implemented in the representation techniques for the construction of Le Corbusier's buildings, when they contain relatively complex geometric objects? We will try to provide some responses to this question by studying two projects which contain particular geometrical entities, namely surfaces of negative curvature: first, the main chamber of the Palace of the Assembly of Chandigarh (1951-1964) and, second, the Chapelle Notre-Dame-du-Haut de Ronchamp (1950-1955). The choice to proceed in a somewhat antichronological order is explained by the desire to start with the geometry most familiar in the field of construction, and to move afterwards towards the most atypical example. That said, most of the documents that we will analyse are more or less produced during the same period.
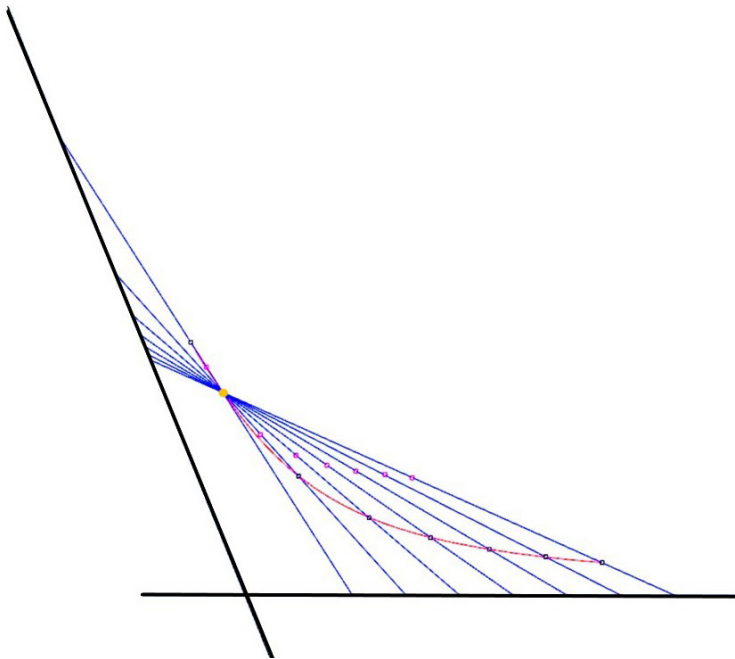

FIG. 4
Part of a hyperbola drawn from the asymptotes through a single point (in orange). Lines in black: asymptotes. Lines in blue: segments of lines passing through the given point and intersecting the asymptotes. Points in purple: the midpoints of the segments. Points in black: the symmetrical points of the given point in respect to the midpoints. Curve in red: the hyperbola, passing through the orange and the black points. Planar view (image by the author).

Analytical methods vs. graphical methods. The Palace of the Assembly, Chandigarh

The main chamber of the Palace of the Assembly is contained within a negatively curved concrete shell, which has the shape of a one-sheet hyperboloid[5], a geometry that is already familiar in architectural construction by this time[6]. According to some witnesses and related documentation, Le Corbusier was inspired by the cooling towers of a power station having this shape, which he saw once in Ahmedabad on his way to the airport[7]. The general design of the building undoubtedly belongs to Le Corbusier, but the geometric definition of the project is attributed to his collaborators in the office, in particular to Iannis Xenakis who worked on the exact graphic representation of the main chamber.

The one-sheet hyperboloid is a doubly ruled surface, that is to say it contains two families of straight lines, called rulings or generators (Fig.1). With the hyperbolic paraboloid, they are the only surfaces to have this property. But unlike the hyperbolic paraboloid, the straight lines of each family of the one-sheet hyperboloid are not parallel to a plane. Consequently, even if the rulings are sometimes used in certain constructions (for example wire-framed metal structures[8]), however the use of them in buildings is generally less simple than it is for the hyperbolic paraboloid.

In the case of the Chandigarh Assembly, no drawing has been found showing straight lines lying on the hyperboloid, and even though the shell is made of concrete, the formwork does not follow the rulings. Without doubt, it would have been difficult to put in place formwork along lines that are oblique to the axis of revolution. But apart from the practical difficulty, if the rulings are made visible in the case of a concrete structure, it can be only for one family of straight lines, as it is practically impossible to use the two of them together for the formwork. Consequently, on the one hand, the appearance of the doubly ruled surface would have only been partial, on the other hand the final appearance of the form would have been imbued with an impression of movement or even of dynamics, of an unstable equilibrium, induced by the oblique lines pivoting around the axis of symmetry of the surface[9]. On the contrary, the solution chosen by Le Corbusier, namely the formwork following the parallel circles of the surface, accentuates the impression of the building's stability, and even its monumental aspect (Fig.2).

The hyperboloid shell that encloses the chamber pinnacles to an intersection with an oblique plane, because Le Corbusier had planned an opening in the roof at a specific orientation, towards the south, to optimally allow light in when needed. The opening was meant to be sealed by what Le Corbusier referred to as a "cap"[10], which could slide on rails.

The geometric definition and the resulting construction solutions are generally based on the property of the one-sheet hyperboloid being a surface of revolution. Therefore, what needs to be defined first is the profile curve (hyperbola) and the radius of revolution. Looking at a sketch dated from October 1955 (Fig.3, FLC 2999)[11], it can be presumed that the hyperbola was probably defined geometrically by its asymptotes and a point on the plane. This sketch concerns most probably the tracing of the hyperbola, because it is catalogued in the archives under the description "Cross-sectional study of the large chamber's hyperboloid formwork"[12].

Looking closely at this sketch, we can hypothesize that the curve (hyperbola) is drawn according to a specific property of hyperbolas stating that a point on the curve is symmetrical to another point on the curve with respect to the midpoint of each line passing through the point and having its ends on the asymptotes[13] (Fig.4). Thus can be drawn, point by point, the hyperbola generating the shell of the central room of the Palace of the Assembly. We actually see in the sketch a number of lines all passing through a point – which is, moreover, a characteristic point, namely the vertex of the hyperbola – and intersecting the asymptotes.

However, two things weaken the hypothesis regarding the explanation of the sketch. First, the irregular positioning of the straight lines and the lack of a perceptible marking of all the necessary points, especially the midpoints of the segments. Second, the fact that on the drawing, the asymptotes and the point required for this geometric construction are specified by certain distances and angles, but the metric information is incomplete, therefore insufficient for the assumed geometric construction. Notably, the horizontal distance that would specify the
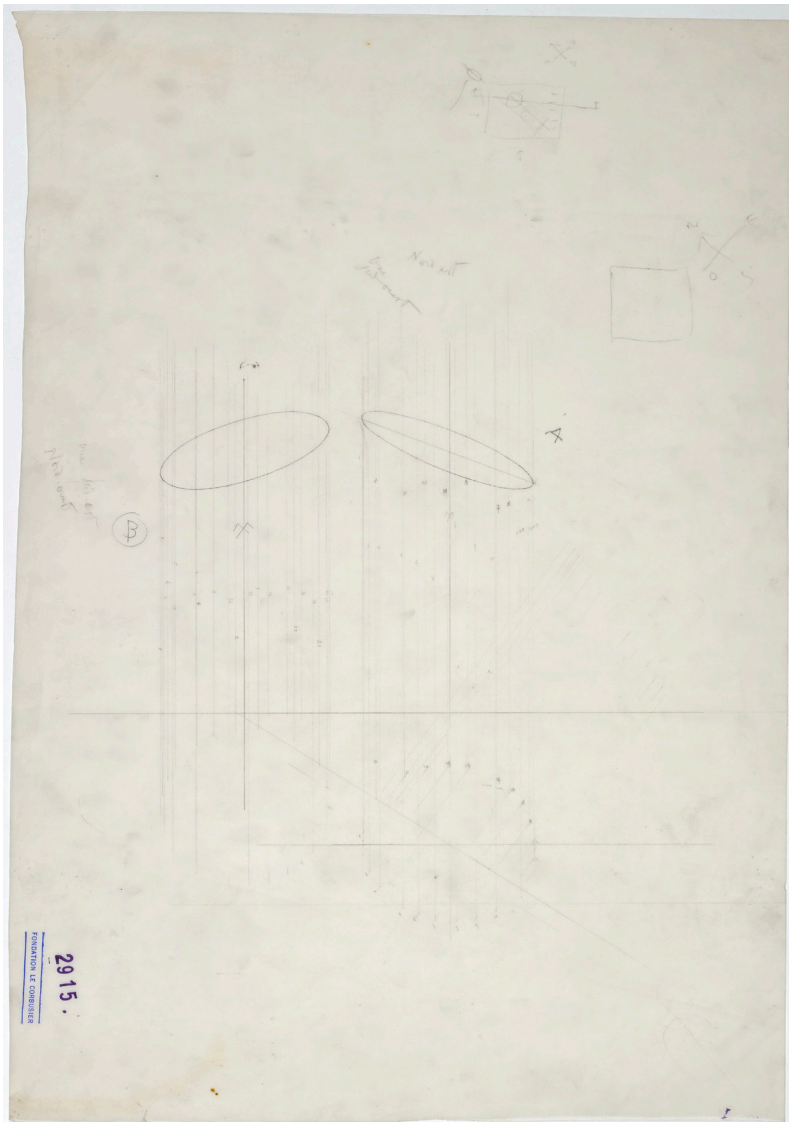
FIG. 5
Study of the upper disk
(large chamber curve), with
dimensions and legends,
orientation (FLC 2915).

aforementioned point (the vertex of the hyperbola) is missing. Had it been specified graphically without the dimension being indicated on the sketch? Was it specified on other drawings, and therefore assumed to be known? Probably.

The second geometric problem to be solved in the Assembly building is the intersection of the top of the hyperboloid with the oblique plane, inclined by 26°. Here again, graphical methods are used. In the sketch listed under the description "Graphic study drawing, drawings of upper disk (large chamber curve), with dimensions and legends, orientation"[14], we can distinguish a trace of two ellipses from a circle, which could be a horizontal section of the hyperboloid (Fig.5). The circle is punctuated by a number of radii, and the points on the circle are then plotted on the vertical projections to define ellipses point by point. The sketch looks indeed like a graphic solution in descriptive geometry using an oblique plane intersection. However, the information collected at this stage does not allow for a complete interpretation of this drawing; a more thorough analysis is needed.

More elaborate studies of the so-called chamber's "cap" show the real geometry of the object, that is to say they show it in normal projection. The desired intersection is an ellipse whose axes are defined by measuring the radii of the rotating surface at specific heights on the profile curve. But the overall design of this opening is more sophisticated than that: its shape is that of an oblique cone with an elliptical base, and its main structure is a set of parallel trusses. There is no need here for more complex methods, two projections are sufficient: the trusses are designed one by one on the front projection using measurements on an orthogonal projection of the elliptical opening (so that the real lengths can be measured) and on a vertical section of the object at the main axis. This geometric study, made by Xenakis on May 11, 1956 (Fig.6, FLC 6072), includes plans, sections and other projections, as well as constructive details in the form of axonometric representations.

Despite the uncertainties that persist at this stage concerning the complete geometric interpretation of certain documents, there is no doubt that graphic methods coming from Euclidean geometry and descriptive geometry were used for the definition of the object.

We do however find in Le Corbusier's archives drawings of the hyperboloid that present excessively precise dimensional annotations about certain angles and distances. This couldn't in any case result from graphic methods. In fact, in February or March 1957 (therefore a year and a half after the first drawing sketches of the hyperboloid) Le Corbusier contacted external consulting engineers to calculate the static behaviour of the shell in reinforced concrete and its rebars. The Greek engineer Georges Pavlopoulos (known as Pavlo), who was probably recommended by Xenakis, thus began a study of the structure with the rigorous mathematical definition of the geometric form: the graphic outline was not providing sufficient information for the static calculations, the analytical formalisation was needed. Using infinitesimal calculus, Pavlo gave exact numerical specifications of the characteristics of the surface, and he attained a precision of the slope angles to a hundredth of a degree[15], and of the linear dimensions to the third decimal place – which in a practical sense is a rather superfluous accuracy given the constructive methods for a building of that size made out of concrete.

The archives contain plans made by Pavlo and Vuong's consulting office[16]. Pavlo and Vuong therefore provided a series of execution plans in June and July 1957, reporting the dimensions resulting from the analytical method
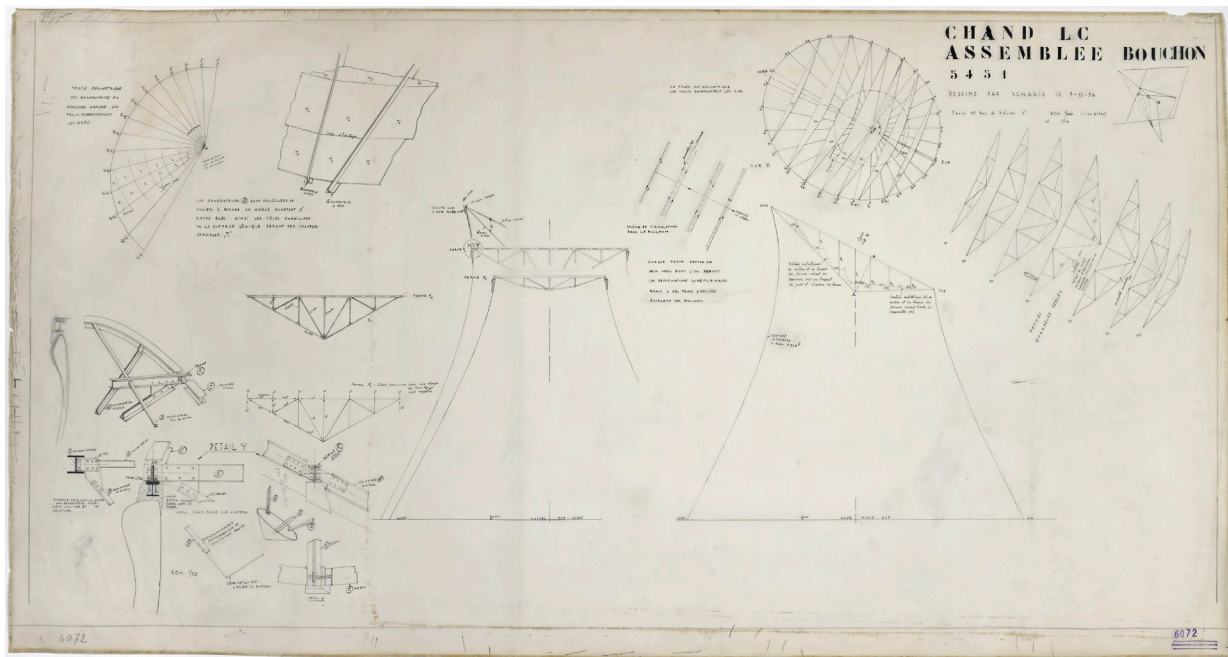
(Fig.7). They specified both the basic geometry and the technical details of the project. The archival research therefore indicates that the Assembly chamber's shell was in reality "designed" twice: once using graphic methods, which had the objective of defining the architectural forms, and a second time using analytical methods, for the static calculation and the technical details. In each of the two processes, there is a remarkable coherence in the geometric or mathematical reasoning, which takes into account the specific properties of the emblematic figure chosen for the project, that of the hyperboloid of revolution. Furthermore, some of these properties – for example the existence of parallel circles on the surface, demonstrating that it is a surface of revolution – are visible on the final form.

Graphic methods for a form with an atypical appearance: Ronchamp

The Chapelle Notre-Dame-du-Haut de Ronchamp, which contains negatively curved surfaces like those of the chamber in Chandigarh's Palace of Assembly, is however quite different from the latter in terms of the guiding ideas of the architectural project. Ronchamp was designed by Le Corbusier (and his collaborators) from 1950 and on, and it was built during 1954-1955. Its shape, which today could be described as "organic", is a singular example of atypical curved surfaces in modern architecture, since an uninformed visitor cannot clearly identify the geometric figures that compose it. According to Le Corbusier, his inspiration came from the natural world, inanimate or living[17]: fragments of various objects, wood, stones, fossils or organic remains, all of which feed a morphological imaginary – the "objects of poetic reaction" (« Objets à réaction poétique »). The chapel has a highly expressive sculptural form, which combines straight lines with well-defined curves in order to avoid as much as possible right angles and strict vertical or flat surfaces (Fig.8). The plan of the building consists solely of curves which appear to have been traced freely.

The building is constructed of load-bearing reinforced concrete, non-load-bearing masonry, coated with lime, and cement sprayed on rubble from the old ruined chapel recovered on the site and held with the help of a metal mesh. The roof is made of concrete which covers eight metal trusses, cast in a formwork made of wooden planks whose marks on the concrete remain visible. The formal principle is that of an empty shell composed of two parts, like a carapace.
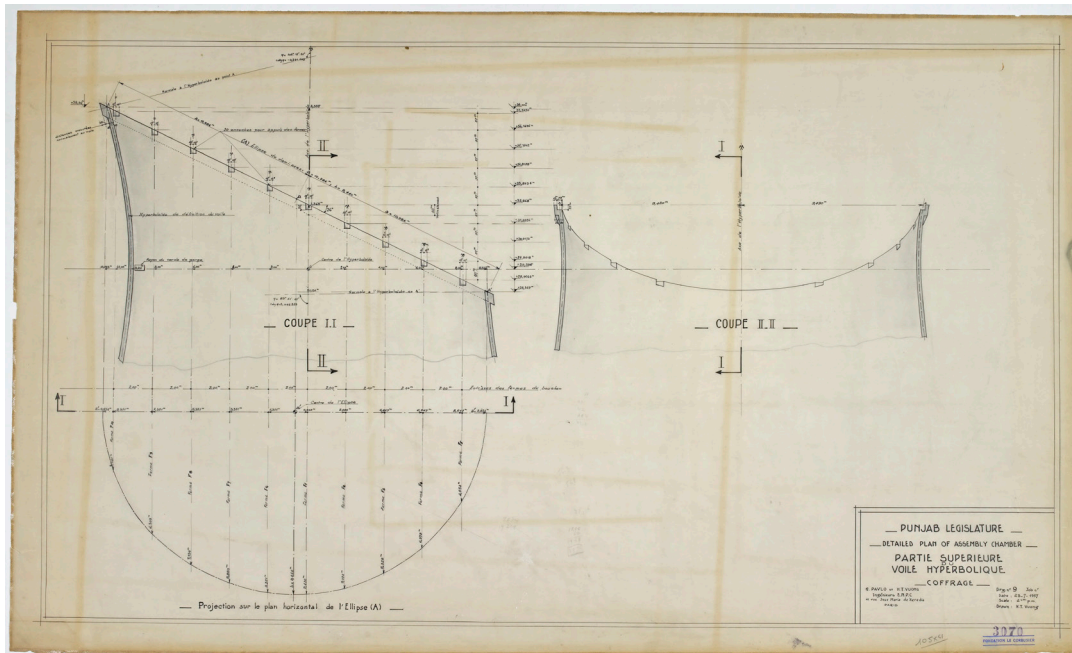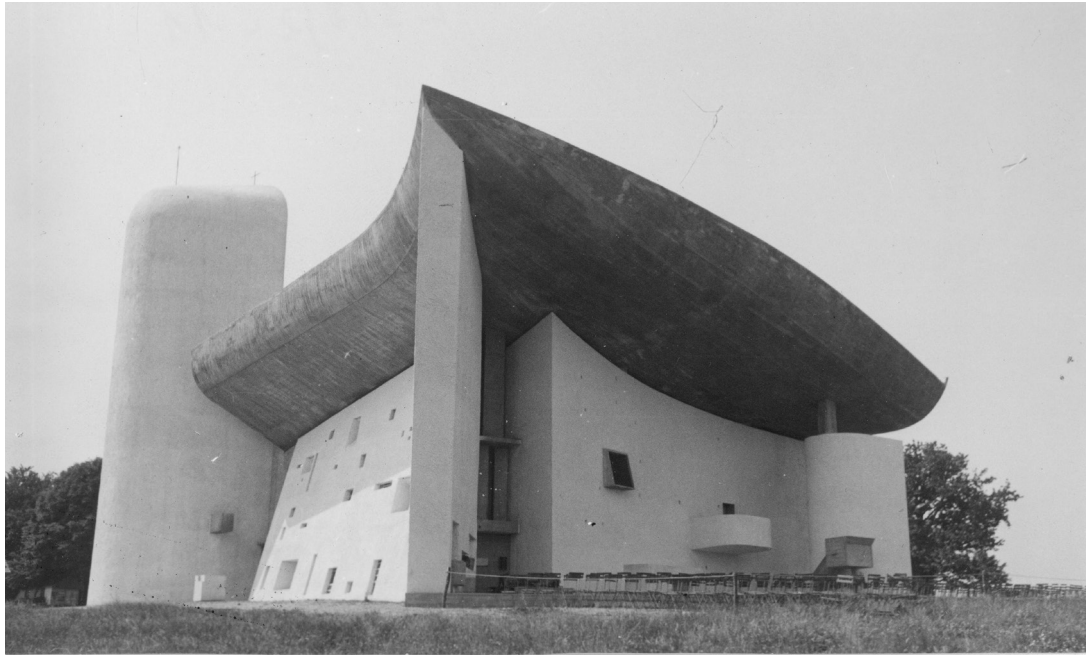
The shape of the roof and its structural principle are inspired by a crab shell[18]. With a slight curvature but clearly legible in space, it does not present any recognizable geometric regularities, its appearance approaching that of a natural object. Furthermore, the interior void is not perceptible from the outside, giving the visitor the impression of a heavy monolithic mass. According to testimonies[19], Le Corbusier had outlined the formal intentions of the project, but its precise geometric definition and design were entrusted to his collaborators, mainly to the architect André Maisonnier.

Geometrically, the roof appears to be composed of free-form surfaces, but they aren't really. According to publications and notes found in the archives, the general geometric definition is that of a conoid. A conoid is a negatively curved ruled surface, the rulings meeting a straight line (the axis) and a curve (the directrix – in reality, an infinity of curves), staying parallel to a plane (the directrix plane) (Fig.9).

According to the publication by Danièle Pauly (1980), the roof is composed of two parallel conoids[20]. In reality, the two surfaces of the roof, upper and lower, are not exactly parallel: we see on the plan entitled "Epure des fermes 6-7-8" (Sketch of trusses 6-7-8)[21] that for truss no. 8, which serves as a directrix[22] of the conoid, the height at the level of the median vertical member is 2.26 m (dimension which comes from the Modulor), but gradually decreases to 2.12 m. towards the ends. In fact, Danièle Pauly corrects her initial assessment in a later publication, admitting that they are not perfectly parallel[23].

The "Façades plan"[24], drawn by Maisonnier in 1951 and completed or corrected by Sacki in 1952, gives a lot of information on the top surface of the roof (Fig.10). In this drawing, there is a small "Diagram indicating the principle of construction of the conoid and its position in space (top surface of the cover)"[25]. It is an axonometric sketch which in fact shows the construction of the conoid of the top surface: the conoid is indeed defined by an axis – a straight line corresponding to truss no. 1– and a directrix – a curve corresponding to truss no. 8, the two being connected by nine straight lines (rulings). The diagram is positioned in relation to characteristic lines of the plan, with the help of dotted lines. Therefore the conoid is visibly delimited by an exterior outline in the shape of a trapeze which has two right angles on the north side.
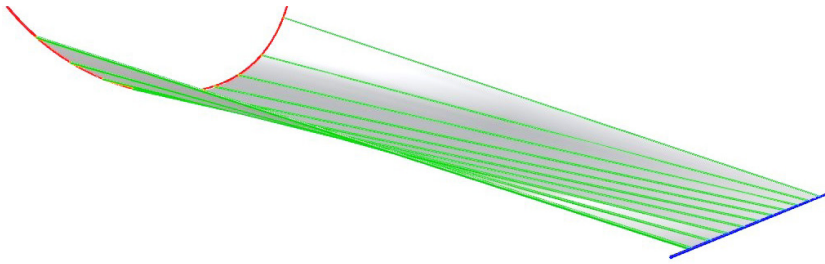
FIG. 9
Part of a conoid surface. In red, the directrix curve; in blue, the axis; in green, the rulings. Perspective view (image by the author).

The largest part of this plan is occupied by a "Drawing of the shape of the roof"[26], seen in plan, where the truss no. 1 is named 'first generator' (*première génératrice*) and the no. 8, 'second generator' *(deuxième génératrice)*[27]. In this drawing, the rulings are more numerous than those in the small diagram, and their projections are visibly parallel to each other, which means that the rulings are all parallel to a vertical plane: this is the last condition needing verification so that it can be confirmed that it is indeed a conoid. The rulings are not perpendicular to the axis (which is, as mentioned previously, the straight line of truss no. 1), because they do not follow the north outline where the right angles of the right trapezoid are located, but rather the south outline, which is not perpendicular to the trusses. Claude Maisonnier observes that the rulings are parallel to a vertical plane containing the "sacred axis" of the chapel, as he says[28]. Therefore the surface is not part of a right conoid[29].

On the same drawing is represented, on both sides of the plan view, the geometry of the two extreme trusses, that is to say the directrix and the axis of the conoid, folded down. The geometric construction of the directrix is further elaborated in a diagram. Looking at this sketch, it becomes obvious that it is not really a continuous curve, but that it results from the assembly of two straight lines and an arc of a circle, tangent to the two straight lines at the respective points of contact[30]. Therefore, the part of the surface whose directrix is the arc of a circle is a portion of a circular conoid, and the parts of the surface whose directrix are straight lines are hyperbolic paraboloids.

To resume, the surface is not typically a conoid but an assembly of three conoids, and more precisely of an oblique circular conoid and two hyperbolic paraboloids, although it is difficult to recognize the hyperbolic paraboloids in the final form. It is interesting to underline here that even if the hyperbolic paraboloid is a familiar surface in the domain of construction at the time[31], this particularity of the surface seems to have gone unnoticed. Besides, it probably has no implications for the design nor for the construction of the roof. Therefore, this particularity of the directrix is almost never mentioned in publications. For Claude Maisonnier, son of André Maisonnier mentioned above, the curve is a hyperbola[32]. This was perhaps the initial intention, the hyperbola having subsequently been approximated roughly by an arc of a circle and two straight lines.

The research at this stage has identified only one author having "seen" the hyperbolic paraboloids of the roof of Ronchamp – but without precisely characterizing the central conoid: Robin Evans, who writes, in *The Projective Cast*[33], several pages on the chapel; he himself does not cite any other author having made this observation.

Given the construction of the conoid from the upper parts of the two trusses no. 1 and no. 8, which are respectively the axis and a directrix of the conoid, the profile of the intermediate trusses can be determined algebraically or graphically. To do so graphically, it would have been necessary to trace a number of rulings seen from the front by using the sections of the two farms mentioned just before, and then measure on these rulings some dimensions significant for the intermediate trusses. Drawings which appear to correspond to this graphic process are found in the archives, without any title, comment or annotation[34] (Fig.11).

The final contour of the roof does not correspond exactly to the underlying geometric construction based on the rectangular trapezoid plan mentioned above. It extends beyond the trapezium almost completely on two sides (south and east), it partially extends beyond it but is mostly truncated on one side (north), and it is truncated on one side (west).
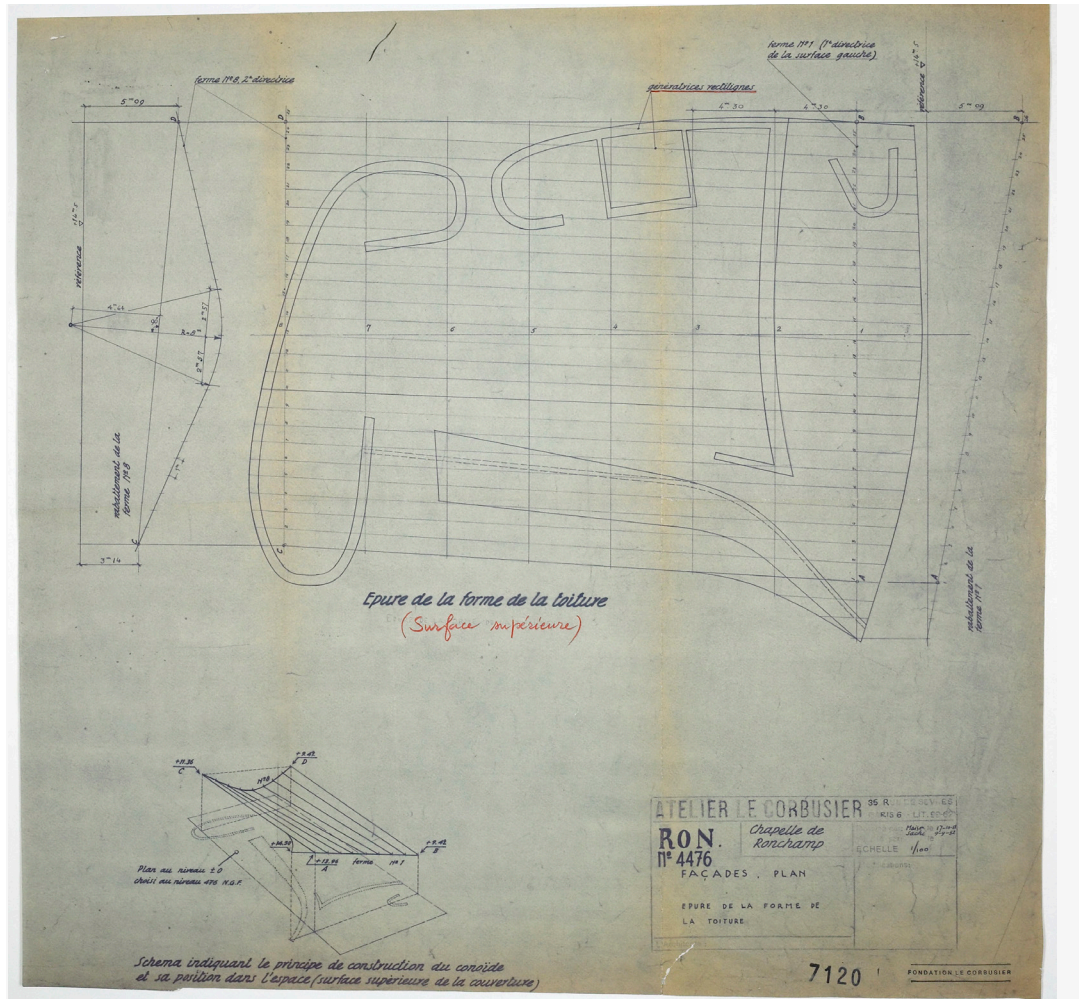
At the points where the geometric construction exceeds the limits of the roof (where it is therefore truncated), the trusses are slightly adapted accordingly. At the points where it is the roof which protrudes, the geometric construction is extended according to a logic which clearly goes in the direction of the initial formal intentions of the architect – the appearance of an organic form – rather than according to the logic of the underlying geometry. Thus, trusses whose lower and upper linear elements are parallel or almost parallel according to the basic geometric construction, do not reveal this parallelism in the final form of the building. This results in the characteristic curved shape of the south and east outlines of the chapel (for example, the truss no. 0 – See the section drawing at the bottom of the plan FLC 7117. (Fig.12).

Some trusses are defined as an association of straight lines and tangent circular arcs, the centre and radius of which are specified on the drawing graphically and also by a given dimension (this is the case for truss no. 4), but this is not the case for all trusses (Fig.13). Besides, a certain regularity is often sought: constant angles or distances for certain trusses. André Maisonnier describes the great difficulty that the team had in defining geometrically the ends of the roof, which escaped its skills in descriptive geometry. Maisonnier seems to attribute this difficulty to the limits of descriptive geometry itself – he says: "We had studied descriptive geometry a great deal, but at the extremities of the [roof] shell geometry did not enable us to find the junctions and express the double curvature"[35].

The idea that descriptive geometry was not sufficient to solve the problem is, however, difficult to admit, given the spectrum and the complexity of the geometric problems solved by Gaspard Monge, founder of descriptive geometry, and his disciples from the end of the 18th century.

According to Claude Maisonnier, the solution found was not graphic: André Maisonnier had intuitively constructed a wooden model on which he fixed a fine metal canvas coated with paraffin, which he cut using a razor to give it the desired curved shapes. Those curved surfaces have therefore not been defined or identified mathematically. The drawings of these parts of the roof were made by taking measurements from the physical model[36].

Two different geometric methods are therefore at work: on the one hand, a rational basic framework, with strong regularities; on the other hand, extensions of geometry by "accessory" elements, which attenuate the regularity and accentuate the impression of organic shapes. Nonetheless, these "accessories" are additions, which mainly concern the finishing of the form, therefore what is most visible. It is thus about presenting as totally irregular a shape whose basic geometry is quite regular, mathematically speaking. In general, there is a rational geometric description as a starting point, which is afterwards deliberately made more complex adding details, which are not really defined mathematically if Claude Maisonnier is right. However, it is ultimately these small details which give the roof the appearance of an organic shape, while the basic geometry, even if it is not as rigid as a plane or a portion of a sphere, it is far from being "free-form".

The graphical methods used rely on descriptive geometry techniques without scrupulously following the rules and conventions of presentation and coding. Furthermore, they are often rather rudimentary, scientifically speaking, and they are even used in a fragmented or variable manner.

In order to provide all the necessary information for the construction of the building, the architects segmented the surface and defined graphically several sections. Here, elementary methods of descriptive geometry were used. The division of the surface is done according to a grid applied to the entire plan of the building, which corresponds to the constructive system: the trusses supporting the roof. An effort was made to simplify and rationalize the forms.
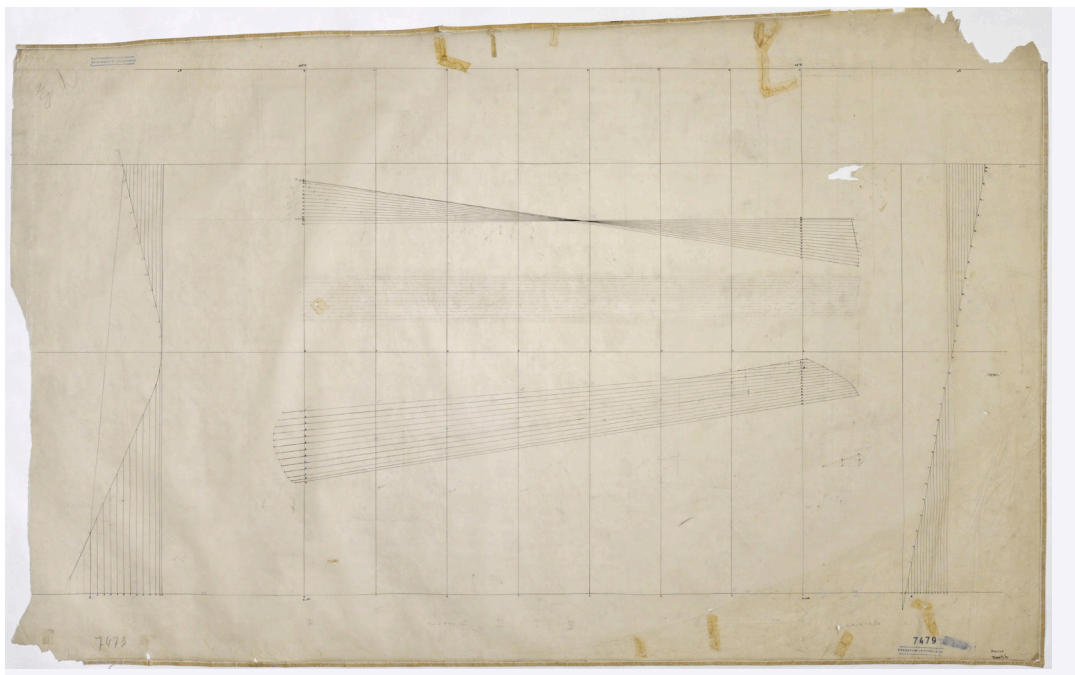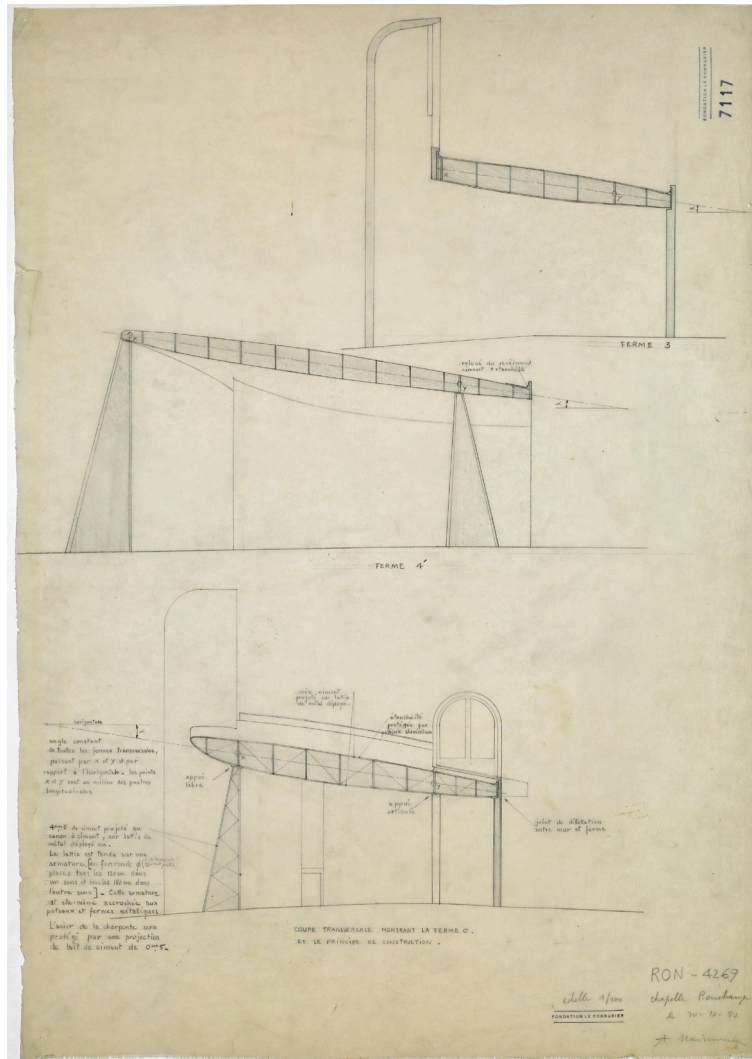
FIG. 11
Ronchamp. Sketch without title (FLC 7479).

Finally, in the quote from André Maisonnier already mentioned, the architect suggests that analytical methods were used by external engineers to solve problems in which the architects had difficulties (such as those concerning the roof connections), or to confirm the solutions proposed by the designers. He says: "At Chandigarh as at Ronchamp, we were giving dimensions that corresponded almost exactly with those established by more accurate methods"[37]. However, it is difficult to conclude at this stage that in the case of Ronchamp there was an analytical description of the entire geometry of the negatively curved surface, as in Chandigarh (it seems unlikely, but more exhaustive investigations would have been necessary to confirm this assumption).

Form versus geometry?

If the geometric properties are decisive in the definition of the formal object, they can be interpreted and shown in multiple ways depending on the architectural intentions of the architect (this is the case of the Assembly chamber in Chandigarh) or even hidden (as with Ronchamp).
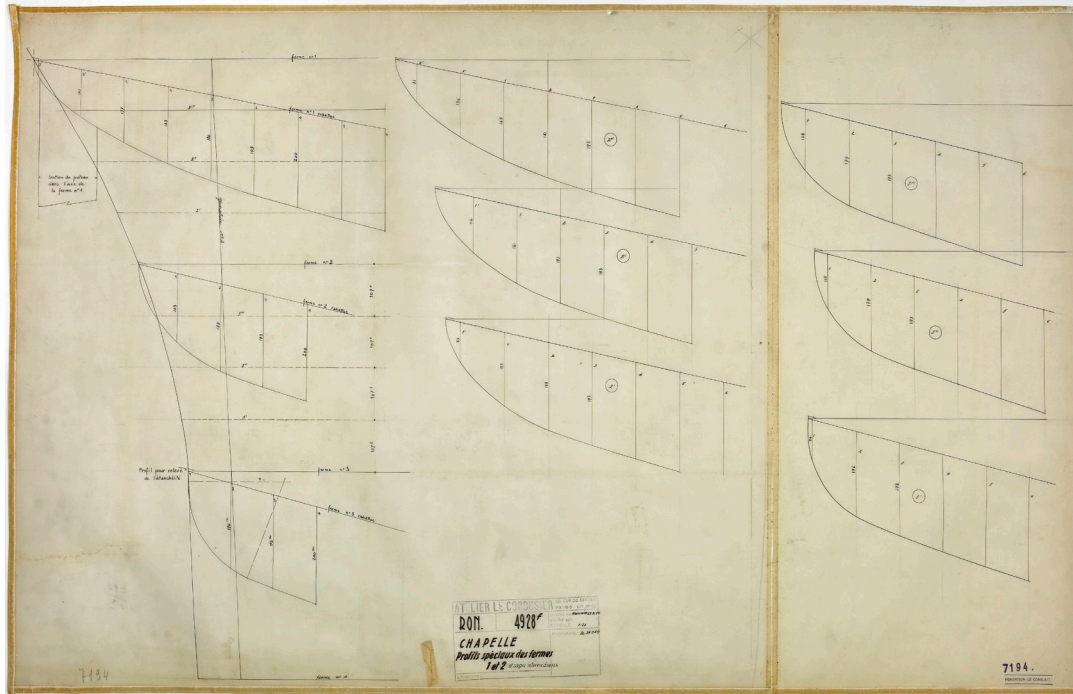
In what concerns the architectural convictions, this means that in the case of Ronchamp, Le Corbusier did not in reality have any particular position concerning the coherence of the geometric system put in place, which responds to the needs of the construction. Especially in the case of Ronchamp, the geometric system is largely hidden and is not given proper value. Robin Evans rightly observes that the wooden slats of the formwork of the visible (lower) part of the roof do not follow the rulings, as one would expect for technical reasons (in order not to have to bend the slats, for example), but they follow transverse curves, which accentuates the curvature and makes deciphering the ruled surface difficult – "impossible", he says[38] (Fig.14). The basic geometry therefore serves the final form without the architectural design being subjugated to it in principle. This position obviously contrasts with other approaches (the Modulor, the regulating lines) of Le Corbusier, who attributes to geometry an aesthetic value, in the philosophical sense of the term, a value which appears to arise from a metaphysical consideration.

With Ronchamp, it would seem that, if a certain regularity of the basic geometry is necessary to rationalise the representation and then the construction of the chapel, however this regularity and rationalisation are not part of the architectural intentions of the architect, who seeks a natural, organic, irregular appearance. Geometry is betrayed in favour of other types of architectural intentions. Thus, the most visible parts of the roof of the chapel not only do not result from the basic geometry, but also present an almost completely different aspect: they are surfaces with positive curvature, while the basic geometry is of negative curvature. As sometimes happens in nature, the underlying "rule" is hidden – but with Ronchamp, it is only partially applied.

Ronchamp is probably a singularity in the work of Le Corbusier. But one wonders whether, even with the architectural intentions indicated for this project, it might not have been possible to find a more mathematically coherent geometrical solution, even hidden, and whether Le Corbusier, though lacking the skills to conceive it himself, might not, as with the Modulor, have desired it. However, unlike his research for the Modulor, with Ronchamp he sought a particular, singular form, not a method, nor a demonstration, this is probably why he somewhat forgot his own saying that in nature "everything isn't chaos except on the outside", whereas inside there is "a relentless order"[39].

FIG. 13
Ronchamp. Special profiles of trusses (FLC 7194).

FIG. 14
The Chapelle Notre-Dame-du-Haut de Ronchamp, inside view (FLC Ronchampint1).

Auteur

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Notes

1 Le Corbusier, *Une maison - un palais. A la recherche d'une unité architecturale*, Paris: Connivences, Coll. de "l'esprit nouveau", 1989, 3 (G. Crès et Cie, 1928). Translated by the author.

2 The word "fatal" (the same in French in the original) could be understood in the sense of inescapable, or relative to some ultimate destiny.

3 In French: « production normale de notre cerveau et *fatale*, parce que participant à un rythme universel ». *Ibid*.

4 « L'architecture et l'esprit mathématique », *in* François Le Lionnais (ed.), *Les grands courants de la pensée mathématique*, Paris: Hermann, 1998 (1948), 481.

5 The use of the terms hyperboloids, hyperbolic paraboloids or conoids here, often make reference to a part of such surface, the surface itself being infinite.

6 Validmir Shukhov's one-sheet hyperboloid towers are probably the first modern constructions of this shape; they date from the beginning of the 20th century.

7 According to witnesses, seeing the towers, he stopped to visit the construction site, and later did a sketch of them. See Vikramditya Prakash, *Chandigarh's Le Corbusier. The Struggle for Modernity in Postcolonial India*, Seattle: University of Washington Press, 2002, 116, and Willy Boesiger (ed.), *Le Corbusier: Œuvre complète, 1957-65*, vol. 7, Basel: Birkhäuser, 1995, 80).

8 Shukhov's towers are an example. For these metal constructions, the two families of generators are used.

9 This is the case of the water tower in Essarts-le-Roi in Yvelines, which is made of concrete. Single-family rulings, materialized as concrete ribs, give it a twisted appearance and an impression of movement.

10 Literally, the French word « bouchon » used by Le Corbusier means « cork ».

11 This unsigned drawing is probably by Xenakis, judging by the graphic style and the annotations, which are very similar to those of another drawing of the same object, which he signed on the same date (FLC 6073).

12 « Dessin d'étude en coupe sur coffrage grande salle schéma de traçage hyperboloïde », in the original.

13 In other words, if from a known point of the hyperbola a line is drawn which intersects the asymptotes, the symmetrical point of the first point on the line with respect to the middle of the segment defined by the intersections, is another point of the hyperbola.

14 « Dessin d'étude graphique, épures de disque supérieur (galbe grande salle), avec cotes et légendes, orientation », in the original. FLC 2915.

15 Degree meaning here the trigonometric unit of measurement.

16 Pavlo and Vuong held a diploma in civil engineering from the Ecole nationale des ponts et chaussées, one of the most famous schools of engineers in France.

17 Danièle Pauly, *Ronchamp. Lecture d'une architecture*, Paris: Ophrys, 1980, 52.

18 *Ibid*.

19 Claude Maisonnier, *La chapelle de Ronchamp. Naissance d'un chef-d'œuvre*, Editions du Linteau, Saint-André de Roquepertuis, 2021.

20 Danièle Pauly, *Ronchamp lecture d'une architecture*, op.cit., 61.

21 FLC 7164.

22 As mentioned above, a directrix of a conoid is a specific curve (isoparametric), which meets the rulings of the surface.

23 Danièle Pauly, *Le Corbusier : La Chapelle de Ronchamp*, Basel: Birkhäuser, 2008.

24 FLC 7120.

25 « Schéma indiquant le principe de construction du conoïde et sa position dans l'espace (surface supérieure de la couverture) », in the original.

26 « Epure de la forme de la toiture », in the original.

27 This mathematical terminology (*génératrice*, in the original in French) is actually improper in the way it is used in this drawing. In the case of the conoid, these lines are called the axis (*axe*, in French) and the directrix (*directrice*, in French), the generators (*génératrices*, in French) being the rulings.

28 Claude Maisonnier, *La chapelle de Ronchamp. Naissance d'un chef-d'œuvre*, op.cit., 77.

29 In a right conoid, the director plane and consecutively the rulings are perpendicular to the axis.

30 They are tangent because it appears on the drawing that the radii at the extremities of the arc are perpendicular to the straight lines.

31 Bernard Laffaille, one of the most important engineers then, who had collaborated with Le Corbusier by 1953 if not earlier, was working (amongst others) on hyperbolic paraboloids since the thirties. A little later, in Le Corbusier's office, Xenakis designed the Philips Pavilion, composed only of hyperbolic paraboloid surfaces. So, even if it can be, at the limit, hypothesised that the hyperbolic paraboloid was not known by Le Corbusier's collaborators when the study for the chapel began, it should have been known by the time the descriptions of the project were published.

32 Claude Maisonnier, *La chapelle de Ronchamp. Naissance d'un chef-d'œuvre*, op.cit., 77.

33 Cambridge Mass.: MIT Press, 1995, p. 305 and note 96, p. 398.

34 Archives FLC 7479 (drawing listed in the archives as "Study drawing / Drawing of roof rebate, plan and sections with dimensions and legends", in the original: « Dessin d'étude / Epure de feuillure toiture, plan et coupes avec cotes et légendes »), et FLC 7269. See also FLC 7355.

35 « Nous avions fait le maximum de l'étude en géométrie descriptive ; mais aux extrémités de la coque la géométrie ne permettait pas de trouver les raccordements et d'exprimer les doubles courbures. ». Hélène Cauquil, Marc Bédarida (dirs), *Le Corbusier: l'atelier 35 rue de Sèvres*, Paris: Institut Français d'Architecture, 1987, 15, cited by Robin Evans, *The Projective Cast*, 303 (in English) and note 91, 398 (the original in French).

36 Evans, Robin. The Projective Cast, Claude Maisonnier, *La chapelle de Ronchamp. Naissance d'un chef-d'œuvre*, 96-98.

37 « A Chandigarh comme à Ronchamp, nous donnions les dimensionnements qui correspondaient presque exactement à ce qui s'avérait juste par des calculs plus poussés ». Hélène Cauquil, Marc Bédarida (dirs), *Le Corbusier…*, op.cit, 15, cited by Robin Evans, *The Projective Cast*, op.cit., 303 (in English) and note 91, 398 (the original in French).

38 *The Projective Cast*, op.cit., 314. As Robin Evans explains in note 123 (399), the rulings were used in the structure supporting the formwork, and therefore did not leave visible traces.

39 In the original in French: « tout n›est pas chaos qu›au dehors; tout est ordre au dedans, un ordre implacable ». Le Corbusier, *Une maison - un palais*, op.cit., 12. Translated by the author.