The relation between theory and practice in the construction of Sainte-Genevièves church in Paris: Patte's contribution

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The scientific theory of vaulted structures developed along the XVIIIth century, when the laws of Static and the properties of materials were applied. The theory of domes was born at the same time that the theory of arches and vaults, but the main discoveries are found in the expertises about the construction, stability and restoration of remarkable domes. This paper analyzes the relation between theory and practice and one of the hits of the development of dome theory. As in the case of Saint Peter's dome, the construction of the new church of Sainte-Geneviève, known later as French Pantheon,[1] at Paris, is a remarkable case of this relation in the second middle of the XVIIIth century. It is the first time that the scientific knowledge about the vaults and dome was applied to a real case before its construction.[2] Architects, engineers and mathematicians studied Soufflot's project, and mainly the dimensions of the piers, that the architect Patte found not enough resistant to support the future dome. Patte based his argumentation on La Hire's method and on traditional rules of proportion. Bossut, who was mathematician, and Gauthey, engineer, demonstrated that Patte was wrong and based his argumentation also on La Hire's method. In 1776 began the construction of the dome and was finished by Rondelet in 1790. But after its completion, the piers appeared damaged. Once again, several expertises were published about this problem and ways to repair them. Restoration works concluded in 1811. Although the stability of the dome was a secondary matter in this time compared with the resistance of the piers the theory of vaults is mentioned in these expertises.[3]

Criticism about Soufflot's project: Patte's expertise

The old church of Sainte-Geneviève was very small for the increasingly great city of Paris in XVIIIth century. In 1754 Luis XV, who had made a personal promise, decided to build a new church. In 1755 Jacques-Germain Soufflot was in charge of the project and in 1757 the site and buildings needed to build the new church were acquired. Soufflot made an estimate and started the work on foundations. In 1763 the foundations and the crypt were finished.[4]

In 1768, the pillars and main triangular piers were being built according to Soufflot's project who was considering different profiles for a dome with an inner diameter of 63 feet (20,5 m) over a Greek cross plan, Figure 2.[5] Pierre J. Patte, an architect and engraver, who was former assistant of J.F. Blondel, raises the alarm about the dangers that threaten the stability of the future dome of Sainte-Geneviève in several writings.[6]

In 1770 Soufflot defended himself from Patte's criticism,[7] who gets the authorization to publish his *Mémoire sur la construction de la coupole projettée pour couronner la nouvelle église de Sainte-Geneviève a Paris* in the same year.

This year, Rondelet, also architect, wrote an

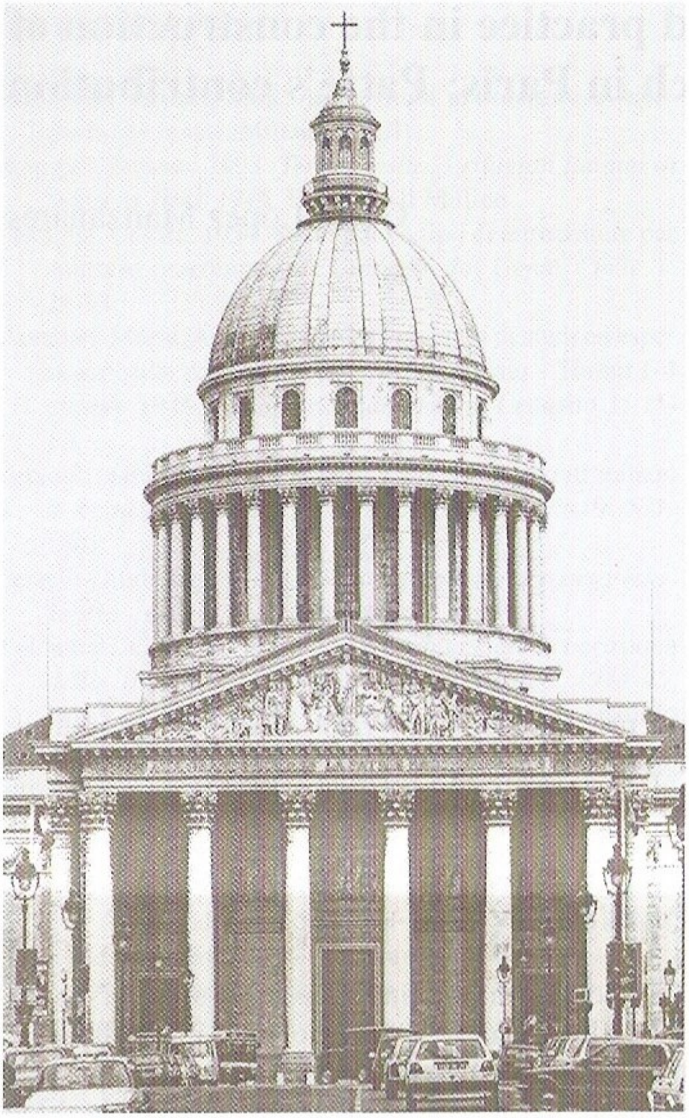

Figure 1
Front view of Sainte-Geneviève's church or Pantheon of Paris (Bergdoll 1989)

expertise where he refuted Patte's opinion. Rondelet rejected the use of Mechanic formulae because they did not take into account the material properties and constructive methods and proposed to put iron rings although in his words the domes do not cause any thrust. He won for himself the favour of Soufflot with this argumentation, and started to work with him from this moment.[8]

The mathematician Bossut ([1774] 1778) defended Soufflot's project in his first memory about vaults equilibrium.[9] Also Gauthey, an engineer, published in 1771 his *Mémoire sur l'application des principes de la Mèchanique à la construction des vôtes et des domes*, where he criticizes Patte's opinion. Patte and Bossut-Gauthey based their argumentation on the principles of Mechanics but they concluded in an opposite way. Controversy got round by the moment.

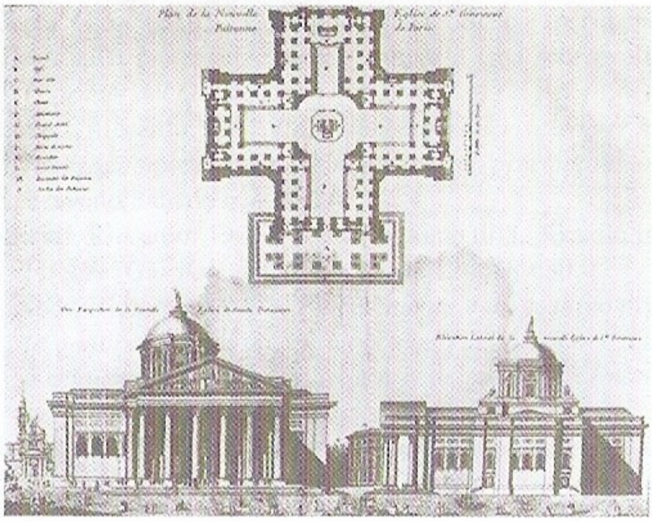

Figure 2
Soufflot's project for Sainte-Geneviève in 1757 (Petzet 1961)

Introduction

In his expertise Patte tried to demonstrate that the pillars already built did not have the right measurements to support a dome of sixty three feet diameter. That was the same that ´building over an isolated wall of three feet, nine inches of width and twenty four feet height, another wall of more than eight feet of width in the base and forty feet height, that had to resist in its edge the thrust from two great vaults.»10 In the first part, he deals with the calculation of the width of the drum wall of the dome over pendentives according to the Principles of Mechanics and the rules of proportion recommended by Fontana, that he used to check the rightness of both methods and add his own rules for other elements of the domes (Huerta 1990, 209–210; 2004, 266–78).
The width of the drum compared with the pillars is useful to know the resistance of them to support the projected dome. In the second part he analyses Soufflot's project and compares it to the most important domes built until then, the dome of Saint Peter in Rome, e.g.

In the first pages of his Mémoire Patte explains his point of view about the problem. He shows that the scientific principles allow knowing the results of a decision before doing something. In the field of construction, where the laws of equilibrium and weights rule, one must use Mathematics, ´and mainly Mechanics.»[11]

Later on, he shows the most important contributions in the field of the theory of arches and vaults. La Hire's model for the analysis of buttresses, with the later refinements, was the most accepted and the one who Patte uses in Belidor's algebraic version (Huerta & Hernando, 1998). He mentions other scientists as Parent, Frézier, and several memories of the Royal Academy of Sciences in Paris (1704, 1712, 1726, 1727, 1728, 1729 y 1730). Although he does not mention Couplet in this introduction, he mentions him in a note about the thickness of the dome. According to him these principles ´are true Mathematics»,[12] and its validity comes from the regularity of results obtained with different methods.

´Over the universal principles relative to the thrust of vaults and comparing them with the proportions of the most relevant buildings of the same type».13 Patte starts his inquiry that he had promised to do about the dome of Sainte-Geneviève in his Mémoires sur les objets les plus importants de l'Architecture: the theory and the practice.

«About the Construction of Domes raised over Pendentives.»

In the first part the aim of Patte is to obtain the width of the drum of the future dome. To do this he uses the rules of proportion that Fontana recommended and the principles of Mechanics, which served also as an occasion for him to check the concordance between the results obtained trough one way and another. At the end he adds other rules of proportion obtained by him relative to the different structural elements that the stability of the domes depends on.

Calculation of the width of the drum of the dome according to empirical rules

According to Patte, the domes over pendentives that are built over the intersection of the naves of a church can have their supports placed in a square or an octagonal plan. From the structural point of view, the true supports of these domes are the keystones of the arches that end the naves and the pendentives.

Before doing a theoretical calculation of the width of the drum is needed to define the dome that was not built yet. He explains that there are different types of dome: simple, double and triple, with wood roofs; with cylindrical drum of uniform width or with ´buttresses towards all the weight and thrust go».[14] He chooses a simple dome because he only wants to demonstrate the insufficiency of the pillars to «support a dome in the case more favourable».[15] After this, he has to decide a profile for the dome, not very reduced, nor excessive, pleasant from outside and from inside.

He based his decision upon Carlo Fontana's principles for the geometrical drawing and proportions of domes».[16]

Patte considers «it would be difficult to add anything to Fontana's comments about this matter».[17]

Patte describes in a detailed way the phases of the geometrical drawing of simple domes according to Fontana, illustrated with a drawing made by Patte for Sainte-Geneviève, fig.1 in the Figure 3. It is remarkable that he tells in a footnote that he has not found a defined proportion by Fontana: the width of the shell of the dome.

The width of the drum, one tenth of the inner diameter of the dome, and the width of the wall where the dome rests, three quarters of the width of the drum are clearly indicated by Fontana.[18]

Patte deduces from the Fontana's drawings that the width of the dome at its base is one half of the width of the drum, and this fixes for the keystone a width of one quarter, and by other side, this width is reasonably for him as a protection against atmospheric agents.[19]

Patte also mentions one by one several domes at Rome that serve to Fontana to deduce true rules of proportion.

These proportions were variable depending on materials quality and the constructive solutions. For a simple dome over pendentives, built with materials of good quality and «very hard»,[20] the width of the drum had to be one tenth of the diameter. If the materials were lighter,[21] the proportion had to increase to a ninth of the diameter.

Double domes needed an increase over these proportions. Patte added to these examples mentioned by Fontana in *Il Tempio Vaticano*, a footnote with the proportions of two great domes: S. Maria del Fiore, in Florence, with a width drum of one seventh of the diameter and the Pantheon, with one sixth. In general, the most part of the domes studied by him in Italy, England, Netherlands and Germany had a drum with one tenth of the width, as Fontana recommended.

Calculation of the width of the drum of the dome according to the Principles of Mechanics

After explaining the empirical rules for the sizing of the drum of the domes Patte got into Mechanic field, which principles he used to calculate the width of the drum. According to Patte, only Frézier ([1737-9] 1769) had studied something about the proportions of the drum of domes from a theoretical point of view, who proposed to reduced one half the width of the buttress calculated for a barrel vault in the case of cloister vaults with the same span. It is interesting to show here a Patte's comment about the width of the dome itself, where he mentions Couplet.[22] Couplet obtained the minimum width of a vault for equilibrium without friction. Patte compares the width of the shell deduced from Fontana's rules and the one recommended by Couplet for a vault, taking into account weather agents to support. Patte's contribution consists in the application of Frézier's rule to the calculation of the width of the shell of the dome, that is, to divide by two the width calculated for a barrel vault with the same span. Patte considered the same theory for arches, vaults and domes, with slight differences.

With this theory, the problem consists of obtaining the width for a pointed barrel vault with the proportions recommended by Fontana for the equivalent dome: 63 feet diameter and 24 inches of average width in the shell, over a drum with 36 feet height. He uses BÈlidor's formula,[23] based on La Hire's model.[24] He draws reference lines over the hypothetical section of the dome according to Fontana's rules. He places the hinge in the middle of the intrados section, which is not exactly situated 45∫ (the dome is pointed). At this point Patte mentions Boscovich and the Italian theoreticians because they stated that the rule of placing the hinge at 45∫ is valid when the buttresses are very weak.[25] Nevertheless, the hinge can appear sometimes in the bottom third. Patte explains this point in a footnote to justify the excessive width of the drum obtained with Fontana's rules compared with the width calculated with Bèlidor's formula.[26] According to Bèlidor, the width of the drum would be 4 feet 6 inches, compared to 6 feet 3 σ 4 inches according to Fontana's rule. Patte states «as it is known in the practice, the width obtained with Mechanics lays is not enough, it will be reasonable to increase it for the resistance force will be greater than the one thrust».[27]

Patte decides a safe coefficient of 1,4 for the theoretical calculations by comparison with Fontana's empirical rules. Patte considers that it is necessary to add 1 foot to the 4 feet 6 inches calculated because the diameter of the dome is greater than 7 or 8 *toises*, and be situated at a great height over the ground and four piers. But this is not enough; he thinks that there is to add other 6 inches because of the pendentives and to take into account the weight of the lantern that has not been introduced in the calculations and the increase of weight of the humidity in the outer shell, weight that supports the drum. In short, Patte got a value similar to the one obtained with Fontana's rule. The practice is ratified by the theoretical principles, and these are corrected by the practice.

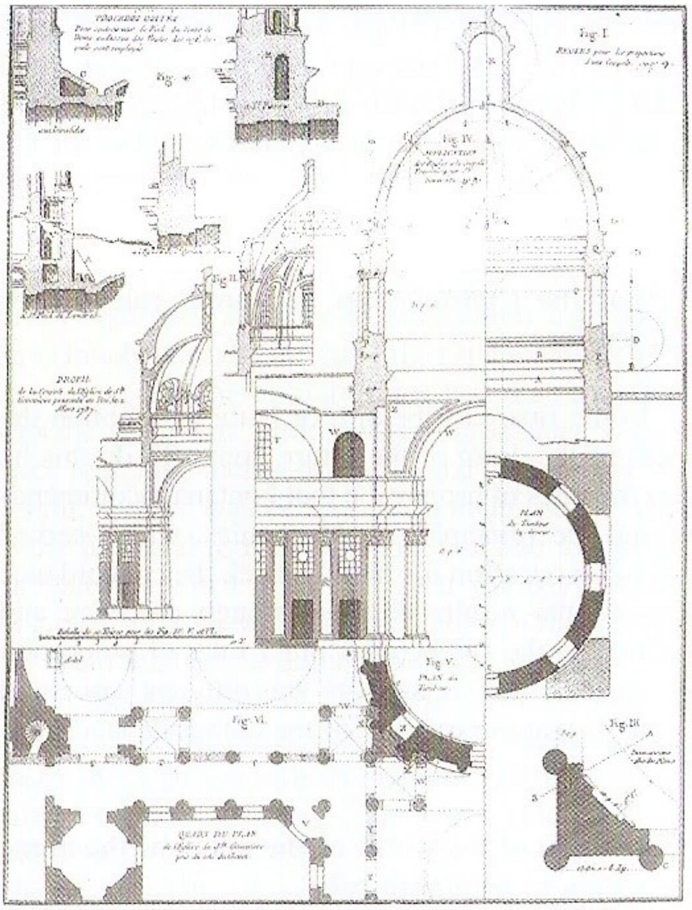

Figure 3
The stability of the piers in Soufflot's projects. Analysis of a simple dome projected according to Fontana's rules with the span of the dome of Sainte-Geneviève (Patte 1770)

Patte's rules of proportion

Once obtained the width of the drum in the case of a simple dome, Patte continues to consider the domes with drum and buttresses, where the thrusts of the dome are concentrated through stalls or discharge arches. This type of drum is the best one when the dome is double or has a very great size. The dome can be considered «as a series of slices that pass through the keystone, & and that correspond himself with the slices placed opposite».[28] The advantage of these buttresses is to take the thrust of the dome to the most resistant points, that is, the main arches and the piers instead of the perimeter cantilever.

To calculate the dimensions of these buttresses it is necessary to calculate «the action that each part of the vault exerts against the respective buttress».[29] Patte recognizes that it is more difficult to give rules of proportion in this case, since to obtain the width of the buttress in radial sense, one has to take into account the thickness and the number of buttresses, that is, the distance between axes that it has not to be very great. When this distance is double width, then the width of the buttress from the inner side of the dome coincide with the width calculated for a barrel vault with the same characteristics.[30] In any case, in real buildings the width is not less than 1/8 span; later, Patte states that its value oscillates between 1/6 and 1/8 span.

The width of the wall between buttresses is determined by the projecting part of the pendentives, and the dimensions of the different decorative elements that they have to support.

a) *Base of the drum*
According to Patte the base has the function of collect all the thrusts that come from the dome and the drum with its ornamentation to transmit them to the main arches and the piers. Besides this base, that project with regard to the drum has the function of avoid a stress concentration at the edge of the drum, which is called *Hyppomochlion*,[31] in the same way as a foundation. This function is called to *contreventer*. After this, Patte describes different ways to solve this base in the most important domes: S. Paul in London, S. Ignacio y S. Peter at Rome, and the dome of the Invalids, in Paris, drawed on the upper left corner of Figure 3.

b) *Main arches and pendentives*
Patte also gives general rules deduced from practice for sizing the main arches, pendentives and piers. A dome over pendentives rests on four points of support. The forces that they have to support come from the pendentives and the main arches. The material to use has to be a «hard stone» in the main arches and in the piers, «in a proportional way to the charge».[32] The thickness of the main arches is determined by the drum base and the width «by the weight that they have to support».[33]

c) *Piers*
The piers have to resist the forces that come from the pendentives and the main arches. In any case its lateral dimension will be smaller than the thickness of the main arch, between 1/4 and 1/7 of the diameter in practice. In relation to the overturning that would be happened in pendentives direction, the usual diagonal size is 2 or 3 times pendentives projection, although «by calculation it can be seen that it is necessary slightly more than one and a half time».[34] And, in any case, if the lateral dimension is suitable, the diagonal one is more than enough. It is interesting to explain that Patte in a footnote speaks about the different function that have the supports in the domes without drum, where horizontal thrusts are supported by the vaults and taken to the perimeter walls, and in this way the piers have to support only vertical efforts. When the dome rests over a drum the supports have to be calculated in a different way, because the horizontal thrust must be resisted also by them.

To finish this first part of his expertise Patte analyses several important domes and its structural scheme: S. Peter at Rome, S. Paul at London, La Sorbonne, Val–de–Grace and the Invalids in Paris, and makes a table with the main dimensions of their elements, Figure 4. At the end he includes a lamina where he compares the plans of these domes, Figure 5.[37]

«Proofs of the disproportion of the piers of the church of the Sainte-Geneviève»

In the second part of his memory, Patte analyses the problems of the future dome of Sainte-Geneviève projected by Soufflot, without calculations. He states «that it is known combined with their relations serve to determine the value of the unknown».[35]

First he analyses the dimensions of the piers plan, whose triangular shape showed an irregularity in the width for the directions of the different efforts. On the side next to the main arches the width of the piers is 3 feet, 9 inches, whereas in the hypotenuse this value is 14 feet, 8 lines between the axes of the leant

TABLE de comparaiſon entre les dimenſions des ouvrages précédents.

	Diamétres. des Dômes.	Hauteurs ſous les Coupoles.	Largeurs des Piliers.	Epaiſſeurs des Piliers.	Epaiſſeurs des Contre-forts.
S. Pierre de Rome.	127 pi.	310 pi.	29 pi.	56	21 pi.
S. Paul de Londres.	102	253	26	26	14
La Sorbonne	38	104	7	12	6
Le Val-de-Grace	51	124	10	14	8
Les Invalides	73	182	11	15	10

Figure 4
Table with the dimensions of diameter and height, piers and buttresses of great domes (Patte 1770)

columns and 10 feet and one half in the inner part. In perpendicular direction to the inner bevel, the width varies from 10 feet in the axe of symmetry until 4 feet, 3 or 4 inches in the extreme.

The other dimensions are the future diameter of the dome, 63 feet, which implies a protrude for the pendentives of 6 Ω feet. The span of the main arches will be of 37 feet 8 inches, and their height will be in a proportion 2:1 and, therefore, the key will be placed at 77 feet height. Besides, in a footnote, Patte explains that the nave vaults will not have a great width because of the plan and width of the perimeter walls, that is, they will not contribute to the stability of the dome.

Soufflot's projects

To describe the dome Patte uses all the information available in drawings, models, engravings and medals. In the first plate there are two versions of Soufflot's project, Figure 3.

The dome was projected over a drum with Corinthian columns. The best proportion from an aesthetical point of view would be at least 2 diameters and 2/3 to the outer vault from the ground level, and would be built completely in masonry.

In as much as the curvature of the domes, in the first project of 1757 Soufflot designed a double dome with hemispherical section that supported a lantern. In 1764, Soufflot substituted the section of the outer dome for a more pointed one that would support also a lantern and a flight of steps.[36] Apart from the aesthetical problems of a conic top, Patte thought that a perfect conical section would be better and in this way it would be possible to remove the light curvature of the walls that support the great weight of the lantern.[37]

Soufflot wanted to concentrate the weight of the outer dome by means of stalls *b* corresponding to the arches of the inner dome, *a*, fig. 2 in Figure 3. Nevertheless, Patte analyses the plan in fig. V and he realises that the counteract of this ribs correspond to the weaker part of the drum, in *c*.

Patte's analysis

«Trying to consider the thrust from the most advantageous point of view».[38] Patte analyses the stability of the piers and the other elements that support the domes for a brick simple one, like the calculated dome in the first part according to Fontana's rules and theoretical principles.

But in the case of Sainte-Geneviève he asks himself if the best drum is one of uniform width or it would be better to place buttresses. In the first case, the width obtained for the drum needs a minimum dimension for the piers of 6 feet, 3 σ 4 inches. Even this width had to be greater to create a transition socle between the cylindrical drum and the octagonal plan created by the piers. Moreover, Patte thinks that it is not enough to increase the calculated width of the socle in a quantity similar to the leant columns of the drum. It will be necessary more than 9 feet in the base.[39]

Soufflot's project consisted in solid masses to be placed in the area of the pendentives that would have a cantilevered part of relative great span, with a double mission: to counterpart the supported weight by the pendentives and to improve the union with the piers. Patte considers all these elements adequate.

The second hypothesis consisted in placing buttresses. Patte prefers this way to the latter one by the explained reasons in the first part about the size of the domes, but he only considers a drum with uniform width to study Soufflot's project.

Piers

The weight of the dome is transmitted to the piers through the main arches and the pendentives. Patte recommends building the main arches again with a more resistant material. The thickness of these arches would be 9 feet, according to the calculations of the width of the drum of the dome and increased slightly to get an adequate base. This is also the minimum dimension of the piers «according to the rules of the construction art that require that the supported part will be built with diminishing size over the supporting part».[40] But this is not enough for Patte. It is necessary to have a margin of safety because the weight to support is very high. It can be deduced that Patte calculated the width of the piers as buttresses of the main arches, with a diameter of 38 feet, 3 feet width in the keystone and their springings at 57 feet height. He obtains a result of 8 feet 9 inches for the piers that he increases to 12 or 13 feet.[41] Nevertheless, the piers that were being constructed had 3 feet 9 inches, since the leant column was only on the bottom part.

The pendentives also transmit part of the weight of the dome to the piers. In Soufflot's project the pendentives would have a great development, and so they receive an important part of the weight of the dome, with a section of 14 feet length in plan, over a cantilever of 6 Ω feet.

Patte mentions again the rules of proportion for pendentives he stated in the first part of the Memory. The piers have not the right proportions that are variable in the different axes and smaller than ideal. The counterpart masses designed by Soufflot over the piers rest on their edges, where the width is more reduced.

Patte calculates again the piers in this hypothesis, but he does not give details of calculation. It is interesting how Patte explains the function of pendentives.

The piers and the springings of the main arches have to resist the overturning towards the inner part of the dome caused by the weight of the pendentives but also the overturning towards the outer part caused by the horizontal thrusts transmitted by the pendentives that prevent sliding. These are divided by arches that create the vertical joints that converge on the axe of the dome.[42] So the arm of lever would be slightly greater to the height of the piers and comparing the 4 feet 3 inches that measure the piers in perpendicular direction to the pendentive, with 8 feet 9 inches calculated for the piers resisting the main arches, it seems that the piers are not sufficient. Definitively, Patte considers all the possible overturning hypotheses of the piers and although he does not introduce the calculations, the obtained results are always unfavourable.

Global understanding of stability

Once again Patte uses the comparison between the most important domes as a way to demonstrate the insufficiency of the piers of Sainte-Geneviève. In the Figure 5 he shows several plans where he superimposes a section of the drum over a section of the piers.
From right to left Patte presents the project for the dome of Sainte-Geneviève compared to the Invalids one; the dome of the Sorbonne next to Val-de Grace one, and Saint Paul in London next to Saint Peter at Rome. It can be seen the disproportion of the piers of Sainte-Geneviève, and the non-correspondence with the drum. The usual width of the piers is between 1/4 and 1/7 diameter, but here is 1/16. Patte adds other domes in a footnote: Saint George in Venice, by Palladium, Saint Nicolas of Tolentino and the Chiesa Nuova at Rome.

The analysis of the domes in plan enables him to consider the function of the rest elements of the building in the stability. This takes him to propose certain rules to secure the future stability of the dome, once demonstrated the insufficiency of the piers, twice or three times smaller than needed, that besides «play at the same time the role of supports and buttresses»,[43] because they are far from other resistant elements.

First, he considers the possibility of building flying buttresses from the pier to the angle V in the fig. 6, Figure 3, but the construction in this area is not strong enough. There are a lot of openings and so, the flying buttress would not be effective.

A second option would consist of prolonging the walls Y, built over columns, until the pier, fig. 6, Figure 3.

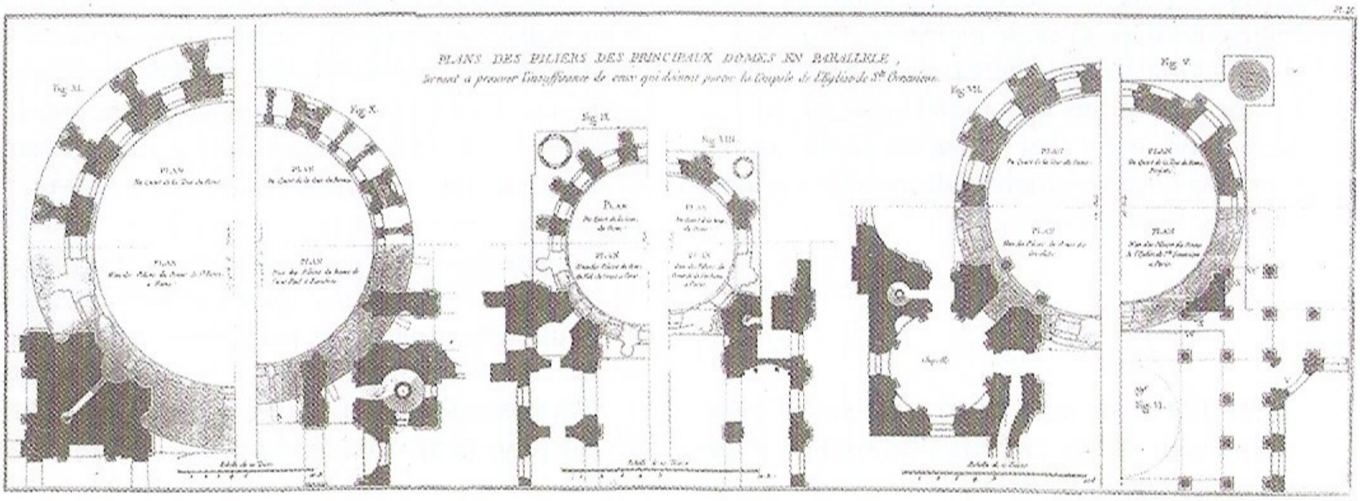

Figure 5
Comparison in plan of different domes: From left to right, Saint Peter at Rome, Saint Paul of London and in Paris, Val-de-Grace, the Sorbonne, the Invalids and Sainte-Geneviève (Patte 1770)

But they are perforated in many places, and not so much as they finish with a buttress that could counterpart the thrust of the dome. The main arch projects in relation to the width of the wall.

The problem is to equal the width of the main arch which is determined by the width of the drum with a counterpart element of similar dimension.

So Patte states that other possibility is to join in some way the columns of the piers with the nearest ones, and to create a resistant element of square plan, with a dimension similar to the width of the greatest main arch. But the needed weight in the lateral parts of the main arch, too much great for the four columns, would require lightening them by means of a stall W, and a groin or an unloading vault between the columns.

This is opposite to the stabilizer effect of the weight in the lateral parts of the main arches. Here he mentions the case of the dome of Saint Peter, in relation to the problems in the lightened piers by Bernini and the polemics in1743, when the excavated gallery in the base of the dome was considered as one of the causes of its cracks.[44]

The option of supporting the dome only over two of these columns, increasing the width of the main arch, is not possible because of resistance and overturning problems, and because they were not joined by «any iron bar».[45]

Iron rings

In a footnote Patte considers the utility of placing iron rings to correct the insufficient size of the piers, since they would help to reduce the thrust.[46] Nevertheless, his opinion is not too favourable:

a) The iron corrodes and suffers an increase of volume that ruins the masonry elements.

b) The connections between the iron bars are always weak points.

c) They suffer expansions and compressions by temperature changes.

d) The resistance decreases with the section area because of faulty forging, and mentions Musschenbroek and Buffon's experiments.[47]

Nevertheless, Patte explains that iron rings are usually placed in the domes, «in the oculus of the lantern, in the springing and sometimes also in the middle area».[48] They serve to resist the thrust when centring is removed away and permit the correct forging of mortars. He mentions the case of the dome of Saint Peter at Rome, where four iron rings were placed, that have not prevented anyway the appearance of new cracks.[49] Saint Paul of London also have several iron rings and he mentions Fontana who recommended to place three iron rings in *Il Tempio Vaticano e sua origine*.[50] But in all the cases the stability depends on the right sizing of the masonry structure and the presence of buttresses, and also on the quality of mortars and the arrangement of material, and not on the iron rings.

After analysing the validity of iron rings and all the false supports in Soufflot's project, Patte proposes the option to build a dome without drum, where thrusts would be resisted by the naves barrel vaults that would need a greater thickness. But the weight and thrust of a heavier barrel vault would be difficult to be supported by all the piers in the designed plan.

Conclusion

Patte does not find any reason to justify the size of the piers; that would be «to condemn the Construction of all famous buildings of this type»,[51] and taking into account that he considers the more favourable hypothesis of a simple dome and the projected one would be double. It is very interesting a footnote where he continues his argumentation, asking for answers to his Memory based on examples and demonstrations.

He mentions an article in the *Mercure* written by a Soufflot's friend where it is confirmed the influence of gothic principles in the project for the dome. Patte refutes this opinion and explains that the dome over pendentives has a Byzantine origin and was unknown in Gothic period. That is, they did not know the principles to build it in a right way. The slenderness of piers is not justified from this point of view, they are not sized properly.[52]

Notes

1. After French Revolution, 4th April 1791, it was decided to substitute the function of Sainte-Geneviève's church for Pantheon (Petzet 1961, 33).
2. Stocker (1987, intr.). The dome of Saint Paul in London was probably built in the second middle of XVIIth century according to the principle of inverse catenary stated by Hooke.
3. These expertises are very interesting to understand the appearance of the engineer, as Gauthey, who deals with statical problems, and the new role of mathematicians as Bossut and the architects, Patte and Rondelet, in the study of structural problems. The first polemics was about the project and the second one, twenty five years later about the restoration of the building (Straub 1953, 127–129; Bergdoll 1989; Huerta 1990, 209–210; 2004, 266–78; Gonz·lez-Moreno Navarro 1993, 157–188; L^upez 1998).
4. For chronology tables see Stocker (1987, 1–3); Heyman (1995).
5. According to Parsons ([1939] 1976, 627), the French foot is equal to 0,3248 m.
6. Heyman (1995, 279–81) draws attention to the fact that the faulty way of placing the stones of the piers of Sainte-Geneviève was proposed by Patte (1769) as a usual method of construction in Paris. The wedges that were introduced in the joints reduced in a considerable amount the effective support area if mortars would suffer a retract and also the edge of the voussoirs receive a lot of charge. Guillerme (1989, 152) considers Patte an ambitious and intriguer man.
7. In a conference held on 2nd April 1770 (Guillerme 1989, 152).
8. Guillerme (1989, 152) mentions that Rondelet even describes the places where the iron rings should be placed, note 13 (Rondelet, 1770). In 1797, Rondelet states that the domes do not thrust against the drum, but the meaning of this is equal to a drum with a width equal to the thickness of the dome.
9. Bossut ([1774] 1778) read his first memory in the French Royal Academy of Sciences on 12th July 1770 but he published his article several years later. He studied an ideal dome of Sainte-Geneviève in this memory but in a theoretical sense (López 1998).
10. Patte (1770, 3)
11. Patte (1770, 5)
12. Patte (1770, 6)
13. Patte (1770, 7)
14. Patte (1770, 8)
15. Patte (1770, 8)
16. Fontana (1694, L.V, ch. XXIV)
17. Patte (1770, 9)
18. Fontana determines the thickness of the dome at the springing, 3/40 span of the dome, which can be deduced from the corresponding plate (Fontana 1694; Huerta 1990, 2004). Perhaps Patte thinks that it is excessive and considers that Fontana has forgotten to recommend a rule about it.
19. Patte (1770, 9, nn. 3)
20. Patte (1770, 10)

21. A lower density in the drum compared to the upper parts corresponds to a smaller balanced weight.
22. Patte (1770, 12, nn. 6)
23. Belidor (1729)
24. La Hire (1712)
25. Patte (1770, 13, nn. 8)
26. Patte is wrong about hinge position. There is an intermediate position that requires the greatest width for the buttress.
27. Patte (1770, 12). Gauthey's expertise tries to demonstrate that La Hire's method is actually a practical one and includes a safe coefficient. See Huerta & Hernando (1998) about the character of La Hire's model.
28. Patte (1770, 13)
29. Patte (1770, 13)
30. If the distance between axes is double the thickness of buttresses, the part of dome that weighs over is also double than the corresponding one to a half distance. So the width of the buttress would be double than the calculated one for a uniform drum, that is, equal to the width of a barrel vault with the same span.
31. Patte (1770, 14, nn.9)
32. Patte (1770, 15)
33. Patte (1770, 15)
34. Patte (1770, 16)
35. Patte criticizes Bramante because he projected insufficient piers for Saint Peter's dome. Nevertheless, Miguel Angel made quickly a cheap model where he established definitive proportions for the piers. He recommends a previous reflection about the structural project.
36. Patte (1770, 20)
37. Patte comments that there was a wooden model of this second version of Soufflot's dome and an elevation in *Curiosities of Paris*, by Pigagnol. Patte (1770, 22, nn. 15).
38. Patte (1770, 23)
39. Patte (1770, 25)
40. Patte (1770, 26)
41. He does not give any geometrical scheme or numerical calculations about the piers. The geometrical coefficient of safety is arbitrary.
42. Patte (1770, 27)
43. Patte (1770, 29)
44. Patte (1770, 31)
45. Patte (1770, 33)
46. Patte (1770, 32, nn.19)
47. Musschenbroek (1741); Poleni (1748)
48. Patte (1770, 32, nn. 19)
49. Six iron rings were placed around Saint Peter's dome, two of them for substituting the broken rings. (Poleni 1748, 454). By other side, there are documents of 1763 in the Archivio della Fabbrica that confirm the appearance of cracks alter placing iron rings. (Di Stefano 1980, 21). Rondelet put iron rings and chains around the dome and Patte criticizes them in 1799.
50. Fontana (1694, 325)
51. Patte (1770, 35)
52. He criticizes the construction of Sainte-Geneviève in several writings after 1770. Patte (1778, 1799).

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