The cathedral of Palma de Mallorca is the chef d'œuvre of Catalan or Mediterranean Gothic. However it has not received the attention it deserves and in the classical works on Gothic architecture it is only briefly mentioned. There is only one architectural monograph by Cram, published in 1932, which is, from a historical point of view, completely outdated. It includes, however, the only published detailed survey and plans of the cathedral to date—a new survey by Fuentes is included in the present book, and a detailed structural survey has been made recently by Fuentes and Guerra.¹ The history of the cathedral’s construction was first correctly described by Durliat in 1960 thanks to his study of the account books. Indeed a large quantity of original sources is kept in the Chapter Archive of the Cathedral. Several partial publications have dwelt on this treasure of information. In 1999, Domenge summarised his work of two decades in the Archive and gave a detailed history of the construction in the 14th century; the bibliography of this book gathers all the contributions up to that date. The

¹ Plan of the cathedral of Palma de Mallorca by Cram 1932.
2 Transverse section of Mallorca Cathedral showing the main dimensions by Fuentes and Guerra.

It is the great nave which has attracted most attention from art and architectural historians. It has enormous dimensions (fig. 2). The height of 44 m to the intrados of the vaults can be compared with that of the highest Gothic vaults (Beauvais 48 m, Cologne 46 m, Amiens 42 m). The span of the central aisle of 19.2 m (between columns centres) is the greatest of the three-aisle Gothic cathedrals (see Beauvais 15 m, Amiens 14.6 m, Cologne 14.8 m). But the main structural feature are the very slender columns, widely spaced, with a ratio of diameter at the base to height of around 1/15 (compared to 1/7 in Beauvais and 1/6 in Amiens and Cologne). The combination of the enormous height and the great slenderness of the columns produces a great space similar to that of the *Hallenkirchen* but filled with light due to the elevation of the central nave (fig. 3).

3 View of the interior of Mallorca Cathedral.

same author has contributed extensively to further parts of the history in unpublished reports of the Universitat Politècnica de Catalunya and several other publications. In these works Domenge also studied the history of the numerous interventions after the completion of the cathedral in the 16th century, transcribing the expertises written by different masters over three centuries.

The building consists of three main parts, from East to West (fig. 1): the small chapel of the Holy Trinity, the Royal Chapel and two apsidal chapels, and the great main nave of three aisles with lateral chapels.

The phases of construction can be summarised as follows:

- 1306–11 Building of the Holy Trinity Chapel.
- 1330 Royal Chapel.
- 1370–1460 The first four bays of the great nave.
- 1460–1525 The work stops.
- 1525–90 The next four bays until the façade are completed.
- 1590–c. 1900 Various works of restoration in the vaults of the great nave.
- 1860–96 Rebuilding of the façade.
The great size of the interior space and the effect it produces in the visitor was noted in some 19th-century handbooks. In 1816 the Spanish translator of Laborde comments that «there is no traveller who does not take this work for a temerity of art», and Piferrer in 1842 said that «whoever, for the first time, sits on the threshold of this church, is astonished by a sense of fear and awe». For Pierre Lavedan it was «the most beautiful victory of the spirit over the matter of the Middle Ages». However, Durliat, after quoting Lavedan, remarked: «let us emphasise, however, the fragility of such a victory, obtained at the expense of safety». Durliat then cites the numerous works of repair and reconstruction of the vaults in the centuries following their completion – studied in detail by Domenge.

Consonant with the enormous vaulted space, the external buttressing system is the biggest of all Gothic buildings, and the image of the cathedral from the sea is impressive (fig. 4). For Lavedan the buttresses are «like an immense set of organ pipes». Durliat described the buttressing system as a «huge expense on external buttresses», and remarked «that what was spared in the interior was spent in the external buttresses». There was an enormous determination to establish lightness, but «the nave of Palma cathedral did not succeed in overcoming the weight of matter», and, together with Beauvais, «established the limits of medieval building techniques».

It is no wonder, then, that when Joan Rubió i Bellver (1870–1952) published his extensive monograph on the cathedral of Mallorca in 1912 for the Yearbook of the Catalan Society of Architects, «Conferencia acerca de los conceptos orgánicos, mecánicos y constructivos de la Catedral de
Mallorca» (Conference about the organic, statical and construction concepts of the cathedral of Mallorca), he dwelt extensively on structural matters. In fact he published the first complete structural analysis of a Gothic cathedral, including detailed estimates of the loads, the simplifying hypothesis employed, and the process of analysis and calculation of the thrusts. The text was enriched also with comments and criticisms regarding the essence of Gothic structure. Before discussing Rubió's contribution, we will sketch the state of the art with regard to Gothic vaults analysis c. 1900.

Analysis of Vaults and Buildings c. 1900

Masonry arch theory originated in the last quarter of the 17th century. During the 18th century the theory developed, and by the first half of the 19th century it was possible to design arch bridges safely. The statics of domes was also studied in some cases (Saint Peter's in Rome; the Pantheon in Paris), by dividing the dome into a series of half-orange slices that form a series of arches. However the analysis of spatial vaults and buildings was beyond the current tools of analysis.

The diffusion of the idea of line of thrust c. 1850 enormously improved the understanding of arch analysis, providing a framework for the development of static analysis. In the 1860s Culmann defined the field of graphical statics, and the rapid development of the discipline in the 1870s marked a turning point in the understanding of masonry architecture. The first applications were to simple arches, but by the end of the 1870s the first equilibrium analysis of a typical Gothic bay was attempted. It seems that the first paper published on the subject was written

5 Early equilibrium analysis of cross vaults and Gothic buildings by Planat, 1887.
by Paul Planat (1839–1911) in 1877, imagining the vault’s webs divided in a series of elementary arches; he then computed the total thrust of the vaults by combining the thrust of the different webs. However Planat did not enter into the detail of the internal forces in the cross vaults until a later work published in the following decade (fig. 5).

It was in Germany where the first complete equilibrium analysis of a groined or cross vault was made by Wittmann in 1879 (fig. 6). Both Planat and Wittmann were following the idea of dividing the webs of the cross or groined vault into elementary arches, which were supported on the cross arch (or groin), and which in turn transmitted the whole weight of the vault to its springings. The following year Gottgetreu published the first complete analysis of a Gothic vault and its buttresses.

The main figure in the development of equilibrium analysis of vaults and buildings is Karl Mohrmann (1857–1927), professor in the architecture school of Hannover (and later of Riga), who, in the third enlarged and revised edition of Ungewitter’s Gothic handbook published in 1890, included statical analysis of all the relevant elements of a Gothic church (cross vaults, flying buttresses, buttresses, towers and spires, windows,
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7. Analysis of masonry elements and buildings, made by Mohrmann in the 1890s. Left: Flying buttresses and nave columns; right: Summary of the equilibrium analysis of Strasbourg Cathedral and discussion of the role of walls over the transverse arches.

8. Buttress profiles deduced from statical considerations. Left: Mohrmann, 1890; right: Guadet, 1902.
etc.), showing a deep insight into all the problems involved (fig. 7). It is today still the most complete statical analysis of Gothic architecture.\textsuperscript{15}

It was, however, Planat who was the great publicist for statical analysis through his numerous publications, included in the journal \textit{La construction moderne} (founded in 1885), several handbooks, and an encyclopaedia of architecture, all with many reprints and editions.\textsuperscript{16} His approach was more direct and simple than that of Mohrmann, but this made the problem more easily understandable (fig. 5). He usually avoided using the polygon of forces, making the composition of forces directly on the drawing of the element or building under study. This simplicity contributed greatly to the diffusion of the simple equilibrium approach within France and all European countries under Francophone influence (Spain, Belgium, etc.).\textsuperscript{17}

In all, the works of Mohrmann and Planat had a great influence, in their respective areas, on the subsequent handbooks on masonry architecture. At the beginning of the 20th century, a section on the graphical statics of arches and vaults was common in any architectural or construction manual. The graphical equilibrium method was used very soon to check the stability of existing buildings; for example, in 1891 Benouville checked the equilibrium of the cathedral of Beauvais. Ideas of equilibrium analysis also influenced architectural treatises. Guadet's chapter on «Les églises voutées» (vaulted churches) in his \textit{Éléments et théorie de l'architecture} (1902) discusses the problem of equilibrium and even proposes the mathematical form of equilibrium for a flying buttress. In fact this idea that the traditional forms of buttresses could be improved following equilibrium analyses had already been suggested by Mohrmann\textsuperscript{18} (fig. 8) and, as we shall

\textsuperscript{9} Graphical analysis of buildings in Spain. Left: Church of San Vicente, Ávila, analysis by Repullés y Vargas in 1889; right: Church of Santa María de Castro Urdiales, analysis by Laredo y Carranza in 1908.
see, was fully exploited by Gaudí who worked out the idea independently in the 1890s.

**Statistical Analysis of Gothic Churches in Spain**

In the last quarter of the 19th century there is evidence of the interest of Spanish architects in the statical equilibrium of buildings. In the schools of architecture students received a background in graphical statics (although most of the handbooks in the library of the School of Architecture of Madrid are French, there are also a number of German ones). A surprisingly early attempt at graphical analysis was made by the architect Vicente Paredes Guillén (1840–1916). Preparing the design for the neo-medieval church of San Juan Bautista (built in 1888) he had already made a statical analysis in 1878, following the approach proposed by the architect and civil engineer Eduardo Saavedra. The theory of Saavedra, pre-graphical statics, was cumbersome and it seems it had no practical application, except for Paredes' attempt cited above.

In the 1880s several Spanish architects were already making statical analyses of churches and cathedrals in the context of structural expertises. In 1884 Fernández Casanova made a detailed statistical analysis of the crossing of Seville's Cathedral; a few years later, Repullés y Vargas made an equilibrium analysis of the church of San Vicente in Ávila in 1889 (fig. 9, left). These studies were not published. The mastery of graphical statics is evident and the systematic use of the force polygon suggests another influence besides that of Planat. This matter needs further research, but it appears that such equilibrium analyses were already frequent at the beginning of the 20th century. The same Repullés y Vargas published in 1900 a complete equilibrium study of the stability of his design for the basílica of Santa Teresa in Alba de Tormes (fig. 10) and Laredo y Carranza made also a complete analysis of a Gothic church in Castro Urdiales in 1908 (fig. 9, right).

It was the Catalan architect Antoni Gaudí (1852–1926), however, who understood better
than anyone, in Spain or the rest of the world, the potential of equilibrium analysis. Gaudí did not limit himself to checking the stability of traditional forms, but invented and constructed new equilibrated works. According to one of his main disciples, Joan Rubió i Bellver (1870–1952), Gaudí was already using graphical statics in 1880. His design for one of the retaining porticos in Park Güell deserves to be mentioned (fig. 11, left). The drawing is undated, but must have been made before the building of the park (1900–14), and as the retaining porticos were built first, it was probably before 1900. By then, Rubió was working in Gaudí’s workshop, where it appears that he took charge of the structural aspects of the design. Without doubt he worked on the design of the viaduct of Bellesguard (also with inclined columns) and on the retaining porticos in Park Güell. Other members of Gaudí’s office were also working on structural designs. In the late 1890s Berenguer, Canaleta, and Goetz were constructing a great hanging model (scale 1:10) for the church of the Colonia Güell. It appears that statical tests with hanging models were combined sometimes with simple graphical calculations.

Around 1900 therefore a team of young architects and engineers under the supervision of Gaudí were breaking new ground in the structural analysis and design of masonry vaults and buildings. Gaudí continued to use graphical equilibrium tools for architectural design throughout his career, either hanging models or graphical statics, depending on the problem under study. Another example is a drawing, which may date

11 Gaudí’s equilibrium design. Left: Retaining portico in the Park Güell, probably c.1900; right: Portico of the west façade of the Sagrada Familia. Statical analysis of the vaults, Barcelona c.1910.
from c. 1910, that describes his equilibrium analysis for one of the porticos of the Sagrada Familia in Barcelona (fig. 11, right). Like Planat, Gaudí liked to show the graphical composition of the forces on the drawings.

**The Equilibrium Analysis of Rubió i Bellver, 1912**

Joan Rubió i Bellver published in 1912 a long study of the stability and construction of the cathedral of Mallorca as part of his collaboration with Gaudí on restoration work in the cathedral. Although after 1900 Rubió began working as an independent architect, and with remarkable success, eventually becoming one of the leaders of so-called Catalan Modernism, he maintained a close relationship with Gaudí and collaborated with him in many important projects, either in the design or the construction phase. Rubió's collaboration with Gaudí on the restoration work in the cathedral of Mallorca spanned more than a decade. Gaudí received the commission in 1903, and worked intensely, with frequent visits to Palma, until 1912, when he quitted abruptly after a harsh argument with a member of the chapter. Afterwards, Rubió took charge of the work and continued for several years. During the period 1900–12, Rubió accompanied Gaudí on most of his visits and assisted him on every occasion.

Over the years Rubió inspected the construction of the cathedral carefully and eventually made a thorough study of the construction and stability of the whole cathedral. In 1911 Rubió delivered a long lecture on the «organic, mechanical [statical] and construction concepts» of the cathedral on the occasion of a visit to Palma by the Catalan Architectural Association. The following year he published a long paper based on the lecture in the *Anuario de la Asociación de Arquitectos de Cataluña*, the Yearbook of the Catalan Architects Association. More than half of this paper (55 pages) is dedicated to explaining in detail Rubió's structural analysis of the cathedral. Although as we have seen statical analyses of Gothic churches and cathedrals had already been made, Rubió's analysis of the cathedral of Mallorca went further: never before had such a detailed study of a great Gothic cathedral (or any masonry structure of comparable size and complexity) been published. Furthermore he inter­spersed many general comments and judg­ments about Gothic structure in general, which are of great interest when seeking to understand the ideas of Gaudí's circle.

**Main Dimensions of the Nave**

The large nave of the cathedral consists of eight bays with a total length of around 75 m. Seven bays have a length of 9 m (column centre to column centre) and the bay of the Mirador (the fifth from the choir) a length of 12 m. The overall width of the great nave (between the inner para­ments) is roughly 52 m: the central nave 19 m, the lateral aisles 10.5 m, and the chapels 5 m deep. In figure 2 the typical section has been drawn, indicating the heights to the bosses: central nave 44 m, lateral aisles 29 m and chapels 18 m. The buttresses have a width at their base of 8.5 m and a height, ignoring the pinnacles, of 38 m (fig. 2).

The main structure of the cathedral is a system of «porticos» formed by the transverse arches of the central and lateral naves, the columns, flying buttresses, and external buttresses (fig. 14). These porticos have a typical thickness of 1.65–1.70 m, that is, the thickness of the columns, transverse arches with superincumbent walls, flying buttresses, and buttresses, with differences amounting to only a few centimetres. The vaults and walls that close the clerestory, the lateral nave vaults, and the chapels are disposed between these porticos.

**The Nave Columns**

Rubió concentrates his analysis on the great nave and identifies as critical the equilibrium of the slender columns (fig. 3). Some preconceptions about the structural behaviour of Gothic structures from the previous century seem to have preoccupied him as they contradicted what he
actually observed in the building. Rubió begins by remarking that the typical medieval disposition of a great nave flanked by two smaller and lower side aisles is not as easy to study as it might seem at first glance. The usual assumption, that the thrusts of the great nave are perfectly equilibrated by the flying buttresses and the thrust of the lateral aisles so that the nave piers receive a perfectly vertical axial force, is very often not true, Rubió remarked. However the idea that slender columns could only support an axial force appealed strongly to Rubió who as we have seen inclined the columns of the retaining porticos at Park Güell (fig. 11, left), and worked on the hanging model of the church of the Colonia Güell, which also has inclined columns.

In several parts of his Dictionnaire, Viollet-le-Duc supported the assumption that nave columns receive a vertical load due to the balancing of the horizontal thrusts of the nave and the addition of vertical loads. However Viollet's knowledge of statics was insufficient, and his struggles to understand the problem may have caused some confusion among his followers who eventually decided to adopt a simplified version of Viollet's ideas. (See, for example, the article «Construction» where the matter is discussed in several parts, with different arguments). In any case it seems that Viollet was well aware that it would be impossible for the usual case of three naves – one central and two lateral – of different heights to obtain a purely vertical axial load on the nave column. He then came to the idea that the column could «lean» to accommodate the slightly inclined force thanks to an «articulation» at its base. Choisy in his Histoire de l'architecture of 1899 tried to explain the problem that the slender Gothic piers could lean slightly to accommodate an «imperfect equilibrium». The ideas of Viollet-le-Duc and Choisy became dogma for many decades among architects and medieval archaeologists.

In 1912 Rubió undertook a true tour de force to reconcile these contemporary ideas (Viollet-le-Duc, Choisy) and his own preconceptions against Gothic (which were in fact Gaudí's ideas about Gothic, as we shall see) in completing his statical analysis of the problem. The following passages by Rubió would be indecipherable without knowing some historical context: «In many cathedrals, including Mallorca, to make an analysis, it is necessary to suppose that the columns have become unbalanced, losing their verticality; consequently, the loads that run through the system of nave arches no longer act on the columns directly, but rather they impinge on the line of thrust, either of the central nave or of a lateral aisle». In this way, continues Rubió, «(...) all the dead weight becomes live weight modifying the line of thrust» (Rubió's italics). However he accepted this reluctantly and in the next paragraph he insisted that with the assumption of a vertical force in the columns it is impossible to obtain an equilibrated state for the
cathedral and exclaims: «The cathedral of Mallorca should not stand! But, since it has stood for several centuries in solemn majesty, there is no other choice but to surrender to the obvious and load the dead weight on to the line of thrust».  

Rubió then looked for visible evidence of this leaning of the columns and found that they do indeed lean inwards slightly towards the centre of the nave. Here he found the final justification to free the internal forces in the column from Viollet's straitjacket of «verticality» (accepting implicitly some articulation at the base): «Seeing the cathedral and the movements of its columns, it seemed to me that I should do the calculations based on the assumption that the columns have leaned towards the main nave, and I did so». Rubió attaches a photograph showing this leaning (fig. 12).

In fact the out of plumb of the columns in Mallorca is the usual deformation which can be observed in many Gothic churches and cathedrals.

It is produced by the thrust of the lateral naves at the head of the columns. The clerestory walls, receiving the thrust of the upper vaults, incline in the opposite direction, and the two inclinations are both present to the eye of the observer. However, Rubió's concern is explained mainly because this deformation contradicts both Viollet/Choisy’s (vertical thrust) and Gaudi's (leaning column) «dogmas»: in Mallorca an inclined thrust passes through a vertical column. As we shall see, to Rubió this discrepancy was a great defect. (However, Planat and Mohrmann showed no distress in allowing the forces to run freely inside the slender columns and depart from the axis. See figures 5 and 7)

**Equilibrium of a Typical Bay**

To check the equilibrium of the columns effectively, Rubió proceeds to make an equilibrium analysis of a «typical bay». We will describe it here in some detail for its historical interest, but also because it is a good example of how to apply the equilibrium approach to the analysis of a complex real building. As Professor Heyman says, «it is impossible to obtain an exact solution in any problem in engineering (...) we could never be certain that we obtain a correct answer, and the only way to make any progress at all with a problem is to make some assumptions».

There are some crucial implicit assumptions in the analysis by Rubió; namely, he was well aware that masonry has a very good compressive strength and an insignificant tensile strength. This leads to a fundamental geometrical statement: the forces can only be transmitted in compression inside the masonry. On the other hand Rubió does not even mention the possibility of sliding or the effect of friction, being well aware that it plays no role in the problem. Rubió, then, is making use of the three key assumptions for the Limit Analysis of masonry structures. In fact this was the case for most analysis in the 19th century and early 20th century. It is thus important for both the construction historian, and the architect
or engineer involved in the analysis of historical masonry architecture, to note that Rubió’s analysis is completely correct within the frame of «modern» analysis of such structures.

Another simplification that can be made is to assume the bays are all equal: in fact they are not, apart from small differences, because the bay of the Mirador is significantly greater (fig. 1). In this way the analysis is much simplified, without losing the relevant precision, by working with an «analogue» bay. Rubió, then, «invented» a typical bay with a length of 10 m, roughly the mean of the lengths of the Mirador (12 m) and one adjacent bay (9 m). The plan and section drawn by Rubió are schematic, but approximately represent the global form (except for the bay of the Mirador where the length presents an error of 15%) (fig. 13). Note that in the plan, one of the bays is missing: the eighth bay, adjacent to the facade, is substituted by two chapels, apparently designed to provide good buttressing to the nave arcades. It appears that Rubió used the plans of an unexecuted proposal for the strengthening of the facade.

The Structural Portico
Rubió also simplified the geometry of the transverse portico. Here he took some care in measuring the heights and overall dimensions. He probably threw plumb lines through the holes which perforate the ridges of the vaults to measure the heights. In figure 14 the idealised section of Rubió (fig. 15) is compared with the actual section of one of the porticos, measured by Fuentes and Guerra with a precision of millimetres. The global geometry of Rubió is essentially correct.

The analysis proceeds to identify the elements which constitute the spatial bay under study. Rubió is explicit about this: «To study the equilibrium of the cathedral of Mallorca we must consider six hypothetically variable quantities, six forces which, compounded and counterbalanced, have to give a vertical or almost vertical force passing through the column». These are the loads arising from the six elements which act on the column: the central transverse arch and vault; the lateral transverse arch and vault; and the two flying buttresses.

Rubió enumerated the following six forces or loads:
1. The resultant of all the forces developed within the main transverse arch.
2. The resultant of the thrusts of the two diagonal arches of the main vault, which compose to give a single force.
3. The resultant force from the high flying buttress.
4. The resultant force from the low flying buttress.
5. The resultant force from the transverse arch of the lateral vault.
6. The resultant force from the thrust of the two diagonal arches of the lateral vault.

These forces correspond to the six elements which act on the column; they are «active» in the terminology of Viollet-le-Duc as they transmit loads and exert a thrust. There are other
«passive» loads: the weight of the walls of the clerestory and over the nave arcades; the weight of the pinnacles; and the weight of the column and external buttresses.

Rubió proceeds to analyse all these «active» elements: «The first thing that must be done, after calculating the volumes and weights, is to draw each and every one of the lines of thrust of each and every one of the elements: transverse arches, diagonal arches, and flying buttresses». Following the advice of many textbooks on arch analysis, Rubió states that:

These lines of thrust have to be made double for each element (...) the one that with less reaction [horizontal component of the thrust] is possible to make it pass inside the section of the arch, and the other that with more reaction it is possible to also pass through the same sections, to know the limits within which the final solution can be enclosed.10

In what follows we will describe Rubió’s analysis, which he summarised in the following drawing (fig. 15). All the relevant dimensions and thrusts are represented and both a scale of forces and lengths are indicated. He assumes a uniform density for the masonry of 2 100 kg/m³ (21 kN/m³), except for the column where he considered the hard stone had a density of 2 400 kg/m³ (24 kN/m³). Rubió did not indicate the actual size of the drawing but it was probably of great size to reduce the errors to a minimum. Although the drawing is the final result of the analysis we introduce it now as we are going to make frequent references to it later.

**Flying Buttresses and Transverse Arches**

To analyse the transverse arches and flying buttresses, Rubió imagined a series of vertical sections which are identified by letters. Here he is following the method recommended in many textbooks, based on the fact that the form of the line of thrust in arches is, for practical purposes, not affected by the family of sections considered, which may not coincide with the actual stereotomy of the arch. The detailed tables, printed at the end of the paper, are good examples of how to proceed in a real
case. We reproduce in figure 16 the table corresponding to the inferior flying buttress.

Rubió did not include in his paper the calculations of the minimum and maximum thrusts of the flying buttresses, transverse arches, and vaults. It appears that he was not aware that, in the case of the flying buttresses and transverse arches, although the minimum thrust can be calculated, the maximum value is «infinite» as it is possible to trace a straight line inside the masonry (the real maximum thrust is about 1000 tonnes). As a matter of interest, we have calculated the minimum thrusts for the flying buttresses and the lateral transverse arch and have compared them with the final values used by Rubió (fig. 17, see fig. 15).

It is evident that there are infinite possible equilibrium solutions – the flying buttress is a hyperstatic arch with three redundancies. Rubió eliminates two redundancies by locating the point of application of the thrust at the head of the buttress in the centre of the section and assuming the thrust is horizontal. This leaves only one unknown to be chosen. It could be either the magnitude of the thrust at the head, or the point of application of the resultant at the left section. Rubió adjusted the value of the horizontal thrust, increasing it considerably from the minimum, to obtain the satisfactory global equilibrium solution of figure 15, which also permits a check to be made that the thrust line passes inside the masonry of the flying buttress.

Cross Vaults
The construction of the vaults is complex. The apparent simplicity of a quadripartite vault hides a sophisticated structure, which can only be guessed at within the general context of Mediterranean construction. The cross and transverse ribs, made of hard stone, spring from an enormous tas-de-charge, presumably of ashlar stones of the same type. Some kind of fill may also exist on top of the tas-de-charge. Above that, there will be a «fill» made of vessels – hollow ceramic pots.

To calculate the vault thrust Rubió used the so-called «slicing technique», which as we have

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La resultante de este trazado se une con la sección 7 (c) de ambos con el peso T (8).

16 Detail of the table of the loads of the inferior flying buttresses. Top right: Value of the calculated horizontal component of the thrust, 26 000 kg. The buttress is divided by vertical sections at, J, K, L, M, ... from right to left (see figs. 15 and 17). From left to right in the table: Designation, dimensions (length, breadth, height), volume, specific weight, partial load, total load, and observations.

17 Minimum thrust lines (thin lines) and final thrust lines chosen by Rubió (thick lines) in the flying buttresses, with indication of the values of the horizontal component of the thrust. Right: Corresponding force polygons (see fig. 15). Forces in tonnes.
seen was routinely employed in cross vault analysis. The analysis is summarised, again, in a single composite drawing (fig. 18). The webs of the vault are divided into elementary arches. These arches are supported on the diagonal arches which transfer the loads to the vault springings. Rubio’s analysis followed that of Planat in which he usually considered that the elementary arches transmit only vertical loads to the diagonal arches. This simplifies the calculation and the line of thrust obtained is not very different from the more «exact» method of considering the horizontal components of the thrust of the elementary arches (as Wittmann, see fig. 6). The pattern of the division of the vault webs is similar to that applied by Repullés a decade before (fig. 10).

Some unique elements exist in this vault in Mallorca. The transverse arches also support a large ashlar wall (fig. 19, left); on top of the large central boss there is a great stone pyramid (fig. 19, middle); heavy stones are placed on the upper ridges (fig. 19, right) (we shall discuss the functions of these imposed loads later as well as Rubio’s critique of them); and finally the extrados of the vault webs support a system of slender walls, which in turn support slabs that formed the original terrace (the wooden roof was added at a later date) (fig. 18).

Rubío had to estimate the dimensions and weights of the boss and the diagonal arches in both vaults. For the central vault, he estimated...
the weight of the boss as 0.5 tonnes, and that of the pyramid on top (fig. 19, middle) as 4.4 tonnes; he assumed the section of the diagonal arches was 0.5 by 0.7 m, which he considered a «prudent» estimate (the actual dimensions are 0.46 by 0.54 m, from the intrados). For the webs he assumed a thickness of 0.15 m (the actual thickness is 0.20–0.25 m). There are some differences compared to the actual dimensions measured in a recent survey, but this does not affect Rubió’s analysis. These differences are irrelevant for the global equilibrium, as we will discuss later.

The assumptions regarding the lateral vault are more difficult to make. Rubió recognised the impossibility of knowing the dimensions of the boss and the section of the diagonal arches. In some bays of the vault there are also stone pyramids on top of the bosses, which protrude through the terrace. He assumed the weight of these bosses, again, as 0.5 tonnes; and the section of the arch as 0.4 by 0.6 m (actual dimensions 0.34 by 0.45 m). He assumed the terrace was supported by a series of vertical slender walls of the soft marés, a local stone.

With these data, based on direct inspection and reasonable estimates, Rubió proceeds to calculate the thrusts of the vaults. He assumed a division in elementary «arches», represented in figure 18, and then elaborated detailed tables of all the weights acting on the diagonal arches of both vaults. The «slicing» consists in dividing each part and then drawing the thrust lines inside the cross arches and calculating their thrust. Eventually he combined all the thrusts on both arches meeting in the portico to determine a single resultant force – the thrust of the vault. Rubió assumed this method would be known by the reader and included the drawing of figure 18 with no explanation.

In figure 20 a part of figure 18 has been extracted and some letters and figures have been added to explain Rubió’s equilibrium analysis. He assumes that the ribs are carrying the weight of the webs, that is, the load of the vault shell is transmitted somehow to the transverse and longitudinal arches, DC and DA, and the cross ribs DB. The web DAB is divided by the line DE (AE = EB) and, in a similar way, the web DBC is divided by the line DF (BF = FC).

The sector DAE is supported by the arch AD embedded in the wall of the clerestory. An imagined rib parallel to the wall could transmit the vertical loads, but the possible thrust will be exactly equilibrated by the opposing arch. Rubió simply ignores this part. This seems to have been a common assumption, since Repullés did the same in his vault analysis. See the plan in fig. 10.

The cross ribs support the sectors DEB and DBF belonging to different shells. Rubió imagines these shells divided by vertical planes and

20 Top: Division of the webs in elementary stripes (see fig. 18); bottom: Structural action of the vault components. The trapezoidal load, DEBFD, acts on the diagonal ribs and produces a thrust of 20 tonnes; the triangular load, FDF, acts on the transverse rib and is considered as being part of it (see fig. 15).
computes the weight of each slice, which transmits this whole load to the extrados of the rib. In the sector DEBF two segments meeting in the cross ribs have been emphasised. Their weights add to the weight of the corresponding part of the cross rib to give a single, combined vertical load. These loads are transmitted by the cross rib (fig. 18) to the springings of the rib, producing an inclined thrust with a horizontal component of 20 tonnes. The thrusts of the cross ribs combine in a single thrust in the plane of the structural portico with a horizontal component of 36 tonnes. The thrust line runs comfortably within the rib and there is no need to look for maxima or minima of the thrust since the range of variation would be small.

Rubió's division of the ribs differs from those of Planat and Wittmann (figs. 5–6) in that he is not trying to explain the mechanism of conveying the load from the segments to the rib; he has simply chosen a convenient way to compute the loads on the cross rib and thus obtain an equilibrium solution.

The action of the sector DFCF, whose load is transmitted to the main transverse arch, is included within the global analysis of the structural portico. These transverse arches are loaded with heavy ashlar walls (fig. 19, left) in the same way that the bosses of the diagonal arches are loaded with heavy pyramids of stone (fig. 19, middle). Rubió comments on the necessity of the large loads on the transverse arch. They ensure that:

The transverse pointed arches of the main nave would not become unbalanced, and their apexes, the high points, would not rise, due to the enormous vault loads acting on the lower third of the arches; it was necessary to load the arch with walls of a considerable weight to ensure that the lines of thrust in this arch did not pass outside the masonry. In addition, it was necessary to erect heavy pyramids of stone on the bosses of the diagonal arches, in order to avoid the same movements, and to achieve the same outcome regarding the load path.40 Later, we will comment on criticism of Rubió's treatment of equilibration loads.

Strategy of the Analysis

Now that the thrusts exerted by the vaults are known, and that the thrusts of the flying buttresses are assumed to be horizontal and acting at the middle of the section, there are still several unknown resultant forces. Each flying buttress has an unknown quantity (the value of the horizontal thrust) and both transverse arches have two unknowns (an arch has three redundancies; symmetry eliminates one). We have, then, a total of six unknowns for the assumed division of the structure into the elements discussed above. Now it is possible to attempt a graphical analysis by making successive trials.

Of course Rubió did not think in these terms, but he knew very well that it would be difficult to find solutions and that it was essential to make simplifying assumptions. After many trials he arrived at one equilibrium solution (fig. 15) which he considered satisfactory: «it has been necessary to spend long days in heavy and thankless work, to do and undo, to test a solution and to try another, and in the end we have achieved a result that, although satisfactory, like the one presented here, does not leave the mind at ease».41 He is explicit about his strategy. He was well aware that for the column of the nave to be stable the force acting on its capital must be either vertical or very nearly so: «During the many different attempts to find a satisfactory solution, we were convinced that it was necessary to give as much as possible to the reactions [thrusts] of the larger nave so that the curves [thrust lines] will pass high, so that, after being partly counteracted by the flying buttresses, would result in as vertical lines of thrust as possible».42 The drawing of figure 15 reveals in great detail the state of equilibrium. Following Planat and Gaudí (figs. 5 and 11) Rubió draws the composition of forces and the thrust lines in the same diagram — there are two scales, one of lengths and other for the forces (in the buttress the force scale is halved to maintain the length of the forces within reasonable limits).
The highly synthetic diagram in figure 15 is difficult to understand as it gives no indication of the process followed to arrive at this particular solution. In what follows we will try to explain Rubió’s analysis. Figure 21 is a simplification (part of fig. 23, left). Only the lines of thrust have been drawn and the different thrusts have been identified.

The horizontal thrust $H_0$ (48 tonnes) eventually chosen, acting in point 0, combines with successive strips of masonry until reaching point 1. There, the inclined thrust of the arch combines with the horizontal thrust of the upper flying buttress $H_{fs}$ (21 tonnes), which transmits its load horizontally through the masonry. The thrust line changes its direction and continues downwards until point 3.

Independently, the horizontal thrust of the lower flying buttress $H_{fi}$ (26 tonnes) is transmitted horizontally to point 2 where it crosses the line of action of the vault thrust $T_v$ (horizontal component 36 tonnes, as calculated before, fig. 20; vertical component of 76 tonnes, from the table of loads). These forces combine into a resultant which meets the thrust line of the transverse arch at point 3. The thrust line changes direction again and continues to point 4 where it meets the vertical force, $V_w$, the weight of the wall, column, roof, and pinnacle included in the bay. The combined load is a total of 229.87 tonnes.

The resultant force is conveyed through the masonry until it meets the thrust of the transverse arch of the lateral nave, $T_{vi}$, in point 5. This thrust has a horizontal component of 28 tonnes, which makes the resultant almost vertical. It continues until point 6, where it meets the thrust of the lateral vault, $T_{vi}$, with a horizontal component of 18 tonnes. It should here be noted that Rubió ignores the weight of the masonry between points 4 and 6, which corresponds to the longitudinal arches of the nave and the superincumbent wall until the level of point 4. This is of course a safe assumption, and greatly simplifies the graphical analysis. But it is remarkable that Rubió is considering a «weightless» masonry structure which nevertheless could transmit loads; this is a clear sign of his deep understanding of masonry analysis.

After point 6 the resultant thrust is almost vertical, but is inclined now towards the lateral nave, pointing towards the centre of the base of the column (fig. 15). The inclination is so small that, in the drawing, the weight of the column (153 tonnes) can be ignored and the force represented by a straight line. However, as we shall see later, he does consider the weight of this element when computing the stresses at the base of the column.

**Stability of the Buttresses**
After obtaining a satisfactory equilibrium state for the columns, Rubió checks the stability of the buttresses. In figure 23 (left) the whole equilibrium solution has been redrawn after figure 15,
including the detail of figure 21. After obtaining a satisfactory equilibrated state for the column Rubió wants to study the transmission of forces through the immense external buttress, without doubt the largest mass of buttressing masonry in the whole of Gothic architecture (roughly 9 m deep, 1.7 m wide and 38 m high, without pinnacles), with a total weight around 1200 tonnes. To put Rubió’s analysis in context a brief discussion of the state of buttress analysis c.1900 is needed.

Buttress theory was not of interest to 19th-century engineers: at that time the aim was to find the «actual» or «true» thrust of the arch. This involved the solution of a hyperstatic problem and all analytical efforts concentrated on this task. Once the arch thrust was found, it was considered a case of simple statics to check the stability of the buttress, viz. the overturning equilibrium of a monolithic solid. Very few authors were interested in checking the internal forces inside these large elements. In bridges, the weight of the abutments is of the same order as that of the arch; in buildings, however, the weight of the buttress is typically an order of magnitude larger than the weight of the whole vault.

Culmann, in his *Graphische Statik* (1866), was probably the first to discuss the different ways of «slicing» a buttress in order to draw the possible thrust lines inside its masonry by considering both vertical and inclined or horizontal planes of section (fig. 22, left). Mohrmann in 1890 also discussed the problem with reference to Gothic buttresses; he stated that it is better to consider horizontal planes, but suggested modifying the inclination near the springing of the vaults (fig. 22, middle). Koechlin in 1889 was the first to suggest a way of studying the transmission of thrust in the upper part of bridge abutments; in a small zone, vertical planes are considered and then the analysis will follow with horizontal joints (fig. 22, right). These three handbooks were widely known throughout Europe and Rubió probably consulted them, or at least knew about them from his lectures in the Architecture School of Barcelona (he graduated there in 1893).

As for considering the safety of buttresses, there were several approaches available, but around 1900 the usual-method assumes that the line of thrust at the base of the buttress should be contained within the middle third of the section; this guarantees a geometric safety coefficient of 3.
It is evident in figure 23 (left) that Rubió is extrapolating Koechlin's suggestion to apply it to the whole buttress. The buttress is divided into vertical slices, but he combines the thrusts of the flying buttresses into only the upper part of the vertical slice of the main buttress. This produces a zigzag line, a, b, c (...), h. Only the part of the buttress above this line contributes to stability; the part below just «rests» on the ground. The line divides the buttress approximately into two equal parts.
and, if this assumption were correct, the Gothic masters wasted an enormous amount of material (as we shall see below, this corresponds to Rubió's negative appreciation of Gothic).

The line of thrust passes dangerously close to the perimeter of the section of the buttress, giving a geometrical safety coefficient of 1.4, which is less than half the usually accepted value. However Rubió does not seem alarmed by this, and simply remarked on the large difference between the actual form and that required for the mechanical transmission of forces. This part of Rubió's analysis is defective and, as we shall see, he accepted it because it confirmed his ideas about the weaknesses of Gothic design. Koechlin's idea of studying only the upper part of the abutments in detail, to check for possible sliding failures, is sensible, but it is not rational to ignore the actual construction of the buttress in horizontal layers of masonry and the contribution made by one half of the volume of the buttress.

We have repeated the analysis of the buttress using Rubió's values of the thrusts of flying buttresses, lateral vault, and transverse arch, considering horizontal joints (fig. 23, right). The picture is now completely different: the line of thrust is nearly vertical and the whole buttress is in compression, as the resultant is passing within the middle third of the section (geometrical safety coefficient of 3.1).

**Stresses**

After arriving at a satisfactory equilibrium solution, Rubió calculated the stresses in some critical cross sections (figs. 15 and 23, left). The first cross section is in the central transverse arch near the level of point 3 (he does not make the location explicit), where the thrust is acting at 0.40 m of the intrados of the arch. He does not give the details of the calculation, which gives a stress of 19 kg/cm² (1.9 N/mm²).

The second cross section is at the head of columns, level 6. Here, with a resultant force of 456 tonnes, Rubió obtains a stress of 34 kg/cm² (3.4 N/mm²), assuming a linear distribution. However, although not mentioned in the text, in his figure 15 there is evidence that he calculated the stress for a uniform distribution, obtaining a value of 27 kg/cm² (2.7 N/mm²) (fig. 24).

Eventually, he calculates the stress at the foot of the column. He adds to the force at the column head, 456 tonnes, the self-weight of the column calculated as 153 tonnes (he supposed a hard marés of 2400 kg/m³), obtaining 22 kg/cm² (2.2 N/mm²).

These values of 19 kg/cm² and 34 kg/cm² (1.9–3.4 N/mm²) are considered by Rubió upper limits admissible for the stones in question. This is disputable. The hard marés can have a crushing strength from 200 to 500 kg/cm² (20–50 N/mm²). Thus even a very high stress of 30 kg/cm² would imply factors of safety around 10. This factor was considered adequate in many building and engineering manuals of the 19th century.

**Summary of the Statical Study**

After his equilibrium analysis Rubió summarised his main conclusions. First, he remarks that there is «a great disproportion between the intensity of the thrusts of the main nave and those of the smaller nave». He attributed this to the great size of the higher flying buttresses, which «demand very large reactions against them», and suggests that they could have been omitted. He attributed to them the need for the large walls on top of

24 Detail of fig. 15. Stresses at the head of the column in kg/cm² assuming: left: Uniform stress distribution; right: Linear variation of stresses.
the transverse arches, but eventually he recognises that «thanks to the influence of the high flying buttress, the line of thrust is maintained close to the intrados of the transverse arch».

Secondly, he insists on the need for the column «to lean» to carry the inclined load on its head. As we have seen, he formulated this in a strange way: «the actions and reactions between the different arches are not enough to keep each other in equilibrium on the column, and it is necessary to arrive at the supposition of its being out-of-plumb, in order that the dead loads that load acting on it become live loads, and influence the shape of the line of thrusts».

As a result the column bends and inclines (see above).

Further, he claims that «the column is incorrectly positioned». According to Rubió, by moving the column 45 cm towards the lateral nave, the «load would have passed through the axis of the column». This bad placement has motivated the bending and out-of-plumb of the column. However the lower tier of flying buttresses is «very exactly placed and has the weight and curvature that are necessary and sufficient». This is disputable. Such a change of geometry would require a new analysis and probably the load at the head would be slightly inclined again.

The wall on top of the transverse arches of the lateral naves, which reaches the level of the terrace, has an important role according to Rubió. Its «weight, which may seem superfluous here, has the advantage of making the line of thrust from this arch, with very slight [vertical] reaction, provide a relatively important final thrust (…) in a location that is well suited to achieving the required combination with the forces transferred from the main nave», that is, to produce an almost vertical resultant on the head of the column. He concludes the statical summary emphasising that the critical stresses found in the transverse arch and in the column (see above) «can be considered a maximum practical limit of load given the two classes of limestone which are employed in their construction».

Discrepancy between Geometrical and Statical Forms. Rubió 1913

The main objection made by Rubió concerning the equilibrium state of the cathedral of Mallorca, one which permeates the whole paper, is the discrepancy between the geometrical forms of Gothic and the statical forms deduced from the equilibrated flow of the forces. Just a year after the publication of his study of Mallorca Cathedral, in 1913, he published an article with the title «Dificultats per arribar a la síntesi arquitectònica» (Difficulties in achieving an architectural syntheses), where he discussed at length the problem of eliminating «the dualism of the supporting and supported elements, and arrive at the implantation of the unique element that in itself carries a single law of equilibrium and a continuous development of the form». New developments in the mechanical sciences should free the building of churches and cathedrals from all the «adherence and complements» which until then had been used to guarantee the equilibrium of the buildings, by adopting «forms adapted to the scientific simplicity and statical reality». The «statical solution» should be applied to individual elements, but «it is primarily concerned with (…) the general disposition of the constructed organism». According to Rubió, Gothic constructions lack this overall statical conception.

This paper by Rubió constitutes a manifesto for the new structural design method invented and promoted by Gaudí. It embodied «the integral knowledge of the approach to the problem of equilibrium and the way to resolve it. The knowledge of the way the forces are developed within the constructed whole will lead to a way of building adapted to the dictates of that science». As a consequence of this knowledge, fear and ignorance «have ceased to be the first cause of the general layout of the temple and its constructed forms».

All hidden forms are illicit and «in all cases preference should be given to those few which contain the statical solution». However Rubió
remarks that the statical solution is not enough: «statics is too sterile to produce harmonic forms between the various elements that make up the building». To produce these harmonic forms the science of construction should be combined with geometry, which is «the language of architecture». The building reaches perfection with the use of the most simple geometrical forms: simplicity is the prerequisite of harmony.

Then follows an appreciation of traditional design: «Until today the equilibrium of the temple [church or cathedral] was the child of experience. The equilibrium of the mutual actions and reactions that unfold within this organism was impossible to establish using safe data». To proceed in the same way would be «irrational». Equilibrium was established a posteriori: «The temple having been established, its general measures being proposed, it was later necessary to think of the parasitic and supplementary constructions that balanced or propped it up». Now, says Rubió, it is possible to determine the adequate form so that these «supplementary means» are no longer necessary. In the Gothic, these auxiliary means are «the external buttresses, the flying buttresses and the pinnacles». Eliminate these supplementary means from the Gothic and «the harmony between ribs and pointed arches disappear, the tall columns could not subsist and the cathedral would be absolutely impossible».

Rubió then insists that «geometry and statics must be intimately twinned and they must not develop independently from each other but, fused, they must form the constituent elements of the architectural organism». This is the critical aspect where the fight between the different schools is concentrated, a formidable and transcendent issue, so important that «it can be absolutely assured that without finding a solution, no new architecture is possible». The problem is so complex and difficult that «it could absorb a whole life of research and trials», Rubió concedes that there may be several ways, «but it is really an indignity to refuse to research and struggle, and live miserably on archaeological remains».

The study of the conditions of equilibrium, even in a temple of medium complexity, is «the study of the adaptation of forms of construction to the laws of statics that regulate their equilibrium, is a formidable work that frightens the most
courageous, due to the amount of meticulous work that it demands». Any method which will tend to simplify this painful work would have transcendental importance. Rubió claims that Antonio Gaudí has been the only one who has confronted the solution to these problems of understanding, advancing the architectural solution. After Rubió Gaudí developed a method of successive trials, using graphical statics, and applied it to different problems from the 1880s onwards. However graphical statics is only adequate «when all the forces are placed on the same vertical plan» (fig. 11). Since lines of thrust are not located in the same plane, the more convenient approach is to use hanging models «to convert all the compressive forces acting within the construction masses into tensile forces acting on suspended weights» (fig. 25). The work still implies successive trials «but the number of trials necessary to reach the coincidence of the construction lines and the statical funicular lines is very limited». 

Rubió and Gaudí on Gothic Structure

As we have seen, Rubió considered Gothic architecture to be flawed because of the stark discrepancy between its geometry and the flow of forces inside the masonry. Throughout the whole monograph about Mallorca Cathedral Rubió shows an ambivalence towards Gothic architecture, repeating same criticism again and again. He dedicates two sections to discussing first the «negative» and then the «positive» aspects of Gothic. In considering the negative aspects, he was deeply influenced by his master Gaudí. Gaudí never published his architectural ideas; we only have reports of conversations with his disciples in which he regularly put forward his views and which were later published by them.

Gaudí despised Gothic architecture. Two quotations serve to illustrate his acid criticisms. He said to his disciple Martínel: «The Gothic is an industrial art, inasmuch as it repeats the elements without paying attention to the proportion; and in order to hide false structural forms, place ornaments where it is convenient to distract attention. It’s like a hunchback who preens, who puts little flags to hide the hump». Another quotation confirms his view: «Gothic art is imperfect, it is half resolved, it is the style of the compass, of the formula, of the industrial repetition. Its stability is based on the permanent propping of the flying buttresses, it is a defective body that is supported by crutches».

Negative Qualities of Gothic

The main negative criticism refers to the discordance between the Gothic forms and the curves of equilibrium. As buildings increase in size, says Rubió, the divergence between geometric paths and those derived using statics becomes more apparent and, upon arriving at the extraordinary dimensions of the naves of Mallorca, the divergence is so great that it becomes absolutely indispensable to go to the rescue of the geometric forms using hidden artefacts (and is therefore not acceptable) so that the conditions of equilibrium can be achieved within the preconceived geometric forms [my italics].

He is referring to the great weights on top of the transverse arches and the keystone of the cross arches (fig. 19). Although he recognises the actual need for these «hidden artefacts» he could not avoid expressing disgust instead of a sense of wonder at the contemplation of such sophisticated equilibrium.

The convenience of placing loads on the vertex of pointed arches was well-known by Gothic architects (e. g. Gil de Hontañón); it was also mentioned by some Renaissance authors (Alberti) and commented on in some Baroque stonecutting manuals (De Challes, Tosca). In the 19th century several authors used statics to justify these dispositions of additional weight. For example Hatzel in 1849 showed that adding a load on top will bring the thrust line inside the section of the pointed arch, until it eventually reaches the filling (fig. 26, left). Mohrman, in his additions to
Ungewitter's handbook of Gothic construction in 1890, expressed very clearly the equilibrating effect of the additional loads, this time referring to the collapse mechanisms (fig. 26, right).

Rubió was well aware of the mechanics of pointed arches and refers explicitly to the transverse arches:

[to prevent] the transverse pointed arches of the main nave from becoming unbalanced, and its vertex, its high point from rising because of the weights that, coming from the enormous vaults, load its lower thirds, it was necessary to load some walls of a considerable volume so that, from its origin, the line of thrust of this arch did not come out of the massif.

Rubió also criticises the form of Gothic arches; they should not have been pointed and then, these great loads would not have been necessary. The same occurs with the vault webs; the vault ridge is pointed and «they have to be loaded also with a row of thick stones to be able to maintain them in equilibrium». Considering all these weights, invisible from the floor of the cathedral, but present in Rubió's mind, he exclaims: «[it] is frightening to consider that they are suspended over our heads, at a height of more than 40 metres, with the only support being the miserable stones, small in size, from which the ribs are formed».

Eventually, he remarks that the divergence between the geometric forms and the statical forms increases greatly with the size of the building: «(...) as the monument grows, all these differences increase and when certain measures are passed, it is very difficult to resolve so many irregularities, and the monument is practically impossible.» Rubió does not explain why this happens. As we shall see, masonry design is essentially proportional and independent of size. However if the thickness of the vaults remains constant, then the problem is non-proportional, and purely geometrical rules are no longer valid. The same occurs with the weight of the stabilising keystones - the size of the load needed to restore equilibrium varies non-linearly.

Positive Aspects of Gothic

On the positive side, Rubió praised the «unity» of Gothic architecture:

Unity of material: everything is stone. Unity in the forces: everything works in compression, the most adequate force for stone (...) Unity of forms: the pointed arch is
everywhere, both in construction and ornamentation. Unity of construction: if any single piece is removed from this ideal Cathedral (...) everything falls apart and collapses.\textsuperscript{77} This last assertion deserves separate treatment in the following paragraph.

\textbf{«Critical» Equilibrium of Gothic Structures}

It appears that this last idea, that the equilibrium of a Gothic cathedral is so delicate that the removal of a single element will cause collapse, was common c. 1900. As we shall see, Rubió did not mean this literally, but many authors adhered to it. According to Formigé in 1928, in the Gothic structure each part is connected with the whole building, and, therefore, the whole building is dependent on each part. If you press the argument to the limit, then, the apse of Notre-Dame, where the equilibrium has been pushed to the limit, it will suffice to remove only one stone to provoke the collapse of the whole building.\textsuperscript{74}

It is a frightening remark! Of course, it is absurd to think that a building could have stayed for several centuries in a critical or limit equilibrium – and Rubió was completely aware of this. But it may be that this idea appealed to that romantic view of Gothic proper of the second half of the 19th century. Indeed the structure of Gothic cathedrals has always been a source of awe and wonder. Guarino Guarini (1624–83), a Baroque architect, but nonetheless an admirer of Gothic structures, understood the problem. He commented that, in contrast to the Romans who «made a great display of solid disposition of its buildings», the Gothic builders «also intended to build sturdily, but in such a way that it would appear very fragile, almost as though a miracle was needed for the building to stand up at all» and even if the Gothic buildings «are not pleasant to behold, they astonish the intellect and leave the spectator dumb-founded».\textsuperscript{79} James Essex (1722–83), an English carpenter and architect who initiated the critical study of Gothic, also speaks of the pleasure that these buildings afford to «a curious spectator» and the «instruction to the studious architect» to try to understand by «what contrivance they are made strong while they appear so light and airey».\textsuperscript{80} Modern architects and engineers are not immune to this appearance of critical equilibrium and the fear it causes. In assessing the safety of Gothic cathedrals they have to face this fear, with the help of the theory, in order to be able to appreciate the essential safety demonstrated by the survival for many centuries of what appears to be in danger of imminent collapse.

\textbf{Safe Equilibrium?}

Rubió expressed an ambivalence about the equilibrium of the cathedral of Mallorca. It comes, it appears, from the long and painful work of successive geometric trials (every trial led to a new drawing) until he arrived at his solution for equilibrium (fig. 15): «It has been necessary to do this work of trial (...) many times!», and Rubió exclaims: «The cathedral of Mallorca is so delicately held!».\textsuperscript{81} In another part of his study he expresses again his lack of complete satisfaction with the solution: «(...) in the end we have achieved a result that, while satisfactory, as the one presented here, does not leave the spirit completely satisfied, nor is the solution so indisputable as to leave no room for doubt». However, he remarks, these doubts must be «in matters of detail, since, of course, the fundamental aspects cannot fail to be verified, unless it is taken for granted the absurdity that a monument that has survived for several centuries is in a poor state of equilibrium» [my italics].\textsuperscript{82}

Rubió wondered how the medieval master builders could have arrived at this solution. He thinks they would not have dared to undertake the work if they had been aware of the dangers of erecting the stonework almost at the limit, risking «to the ruin of an immense building, made at the cost of so many sacrifices and centuries and more centuries of works».\textsuperscript{83} The builders must have viewed things globally and «either by a compensation of weights to the right and left of the column in relation to the width of the respective
Comparison of Mallorca Cathedral with other churches and cathedrals.
naves, or by some other synthetic means, to solve *grosso modo* these very delicate questions*. He expresses his admiration: «The art of the stonemason at the service of ingenious equilibrists, men full of scientific spirit and lovers of all the minutiae of drawing». The equilibrium solution was achieved only after much work:

See how much artifice must be used to cover a space 40 metres wide. Columns, arches, cross ribs, vaults, double flying buttresses, immense external buttresses, supplementary loads on the vaults, all composed and combined with unspeakable searches, after endless trials, after a titanic struggle of several centuries against the difficulties which is presented by so complicated a balance.⁸⁵

All the effort spent in understanding the equilibrated flow of forces within the masonry, in considering the distribution of the masses, has been worthwhile: «the whole process of Gothic art is stamped in these curves of equilibrium, that I believe that for the first time in the history of architectural monographs, are here exposed».⁸⁶

**Comparison with other Cathedrals**

Rubió ends his study comparing the cathedral of Mallorca with some other important churches and cathedrals. The aim is clear – to show its superiority. Here Rubió abandons his criticisms of Gothic and concentrates on the singularities of Palma, in particular the very slender columns, the enormous height of the lateral naves (the highest of Gothic), and the vast space of the central nave (not the highest, but the largest considering both height and span). To make his arguments more apparent, Rubió includes visual comparisons with thirteen churches and cathedrals, made after the drawings of Dehio and Bezold⁸⁷ (fig. 27).

Now Rubió forgets all his criticism and embarks on a series of positive comparisons. For example he claims that Mallorca Cathedral is «Of all the buildings built in the Gothic style, the one with the highest aisle, the most spacious central aisle and the tallest and thinnest columns; it is undoubtedly the one that has made the most of the building's organisation, using the construction methods of Gothic art». He praises also the economy of material: «The cathedral of Mallorca is undoubtedly the one with the least quantity of materials seen from the inside, it encloses within itself a greater volume of useful space».⁹⁹ In speaking of the extraordinary supplementary and hidden artefacts, now Rubió turns the argument to the positive:

The supplementary means of balancing the construction are extremely extraordinary and, despite this, the divorce between its geometric forms and its curves of equilibrium is so great that it can be affirmed that, following Gothic procedures, it would be extremely difficult to cover a church of three naves of greater dimensions than this.⁹⁰

Rubió also considers that the elevation of the clerestory over the lateral naves is optimal, having the keystone of the lateral naves at the level of the springing of the central vault. In Santa María del Mar and Barcelona Cathedral (fig. 27) «the second nave is higher than the starting point of the arches of the main nave». As a consequence «the central nave is drowned by the lateral naves».⁹¹

Rubió concludes his discussion saying:

The cathedral of Mallorca is, then, of all the cathedrals, the one that employs the organisms proper to the Gothic with the greatest possible simplicity, and with a size which it would not be prudent to pass, and which no other cathedral has surpassed. Consequently, it can be affirmed that it is the greatest and most perfect organic, construction and statical success of the Gothic style.⁹²

**Conclusions**

Rubió was perplexed about the equilibrium of the cathedral. It took him a great deal of work and ingenuity to find a satisfactory equilibrium state. He considered this state as delicate and precarious can be traced through history. However is it reasonable to think that a structure which has stood for more than five centuries
is in a precarious state of equilibrium? Rubió himself wondered about this paradox.

It is within the framework of modern Limit Analysis of Masonry Structures, developed mainly by Professor Heyman during the last 50 years, that this apparent contradiction is resolved. There are infinite possible equilibrium states for the cathedral of Mallorca (indeed, for any hyperstatic structure). The structure moves and adapts to the always changing conditions of the environment. But, thanks to the Safe Theorem of Limit Analysis, if it is possible to find «one» situation of comfortable equilibrium for it (for example, Rubió's, but any other would serve equally), then this is an absolute proof of the safety of the structure. The structure is as «intelligent» as the analyst and will find its own solution before falling down.

A recent analysis has confirmed the validity of Rubió's study, and shown how, in spite of its apparent fragility, the structure of the cathedral of Mallorca is robust and sturdy, and admits of, not one, but infinitely many equilibrium solutions. Viollet-le-Duc, thanks to his experience and deep understanding of Gothic, expressed inadvertently the Safe Theorem in almost poetic form: «The skeleton yields or resists, following the needs and the place; it seems to be alive because it obeys opposed forces and the stability is only acquired through the equilibrium of those forces».

Another source of dissatisfaction for Rubió was the discrepancy between the «statical forms», which he had studied in detail working with Gaudí, with the actual geometrical forms of the cathedral. Also, he considered all the Gothic apparatus of pointed arches, ribs, and transverse arches as supplementary, like «crutches» to the building. The heavy loads located on top of the transverse arches, central bosses, and vault ridges were to him, «parasitic», «hidden artefacts», a proof of fear and ignorance. As we have seen, this is disputable. Is it best to build a catenary arch (complex geometry, all the stones had to be cut using different templates), or to build a pointed arch (simple geometry, all the stones equal) and load it so that it functions as a funicular structure? There is no doubt that the second solution is much more economical. The same occurs with the inclined pillars or buttresses: they would have needed a complete centering or scaffold from ground level to the top to build them. A regular column or buttress, built vertical, needs only a light scaffold to raise the stones. However Rubió's enthusiasm for what was a new way of design for the architecture, free from its «archaeological» roots, is wholly understandable.

Perhaps unfortunately, by 1912, when Rubió wrote his study of Mallorca Cathedral and published his «manifesto» for an equilibrated architecture a year later, the world of construction was experiencing a Copernican swerve. Never in history had such a change occurred: the different architectural «styles» had always used masonry and the problem remained the same: how to design an arch or vault that stands and to provide a buttress system to resist the thrusts. New materials and industrialisation were pointing to another type of structure working in a completely different manner, either in bending (framed structures) or using axial forces (trusses).

Some architects ignored this change and followed the «wrong» way: Martinell and Jujol, and Rubió himself, continued to experiment with arches and vaults with catenary forms. In America, Rafael Guastavino Sr. also postulated a new future for architecture based on the use of tile vaults and using steel elements to conveniently redirect their thrusts. Between 1880 and 1909, he experienced great success, working with the best architects, and seeing his works published in the best architectural journals. The work of his son, Rafael Guastavino Jr., was just as good and original, but received no attention. Arches and vaults were not a part of the language of Modern Movement of architecture. He continued to build them for conservative institutions: the church, banks, and the army.

It may be surprising to a modern engineer or architect specialising in historic masonry structures that Rubió's graphical equilibrium analysis is completely correct. Is a «by-hand calculation»
exact enough? Could it be compared with sophisticated computer packages offering FEM, linear or non-linear, or Discrete Elements? All these computer programs aim at something impossible: to know the «actual» or «true» state of the structure. A unique solution. There is overwhelming evidence that this is impossible. As Professor Heyman has pointed out many times, the set of equations of equilibrium, material and compatibility is extremely sensible to very small changes of the boundary conditions. These boundary conditions are essentially changing, ephemeral, and there is not an «actual» state, but a state «here and now». A change of the phreatic level, a small earthquake or vibrations from traffic, a big storm, the construction of a road nearby, the normal change of masonry, interventions of restoration, etc., any of these normal events will produce tiny changes in the boundary conditions which may produce enormous changes in the internal forces. However they will not affect the safety of the structure.

In this changing environment it is the theory which is permanent. The Safe Theorem of Limit Analysis leads to Heyman’s approach of equilibrium. As Professor Heyman says, the Safe Theorem is: «The rock on which the whole theory of structural design theory is now seen to be based».

If it is possible to find an equilibrium solution with the internal forces comfortably inside the masonry, then the structure is safe, and any small change will not affect its safety. How to handle the equilibrium equations is perhaps a matter of taste. But it is not automatic process. It requires experience and ingenuity, and a complete control of all the assumptions made.

1 Fuentes / Guerra Pestonit 2016a.
2 Universidad Politécnica de Catalunya 2003; Universidad Politécnica de Catalunya 2006–08; Domenge i Mesquida 2010; Domenge i Mesquida 2017; Domenge i Mesquida / Conejo 2008.
3 Laborde 1816, 464; Piferrer 1842, 151.
4 «C’est la plus belle victoire de l’esprit sur la matière à laquelle ait assisté au moyen âge», Lavedan 1935, 166.
6 Domenge i Mesquida 2006.
7 «On a comme un immense jeu d’orgues», Lavedan 1935, 168.
8 «(...) formidable dépense d’appuis extérieurs (...) ce qui avait été gagné à l’intérieur fut dépensé au dehors, la nef de la cathédrale de Palma n’a pas réussi à vaincre la pesanteur de la matière. (...) permet d’évaluer les limites des techniques médiévales», Durliat 1962, 167.
10 Huerta 2008.
11 Culmann 1866.
12 Planat 1887. Planat was vice-director of the journal La semaine des constructeurs where he attended to the correspondence of subscribers. Some of this correspondence referred to vault analysis and eventually Planat included these analyses in his 1887 book.
13 This «slicing technique», as professor Heyman (1995) calls it, had already been used in the 18th century; when Poleni (1748) used it to check the stability of Saint Peter’s dome. Several authors considered this approach for groined vaults from c. 1800. The approach was not continued because of the difficulties involved in even simple arch analysis before the use of graphical statics.
15 Ungewitter 1890. Another handbook with numerous graphical analyses of vaults of any form was published by Karl Körner (1838–1907) Professor in the Technical School of Braunschweig, Körner 1895.
16 Planat 1887, 1888, 1905. La Construction moderne had a section called «Consultations techniques» in which Planat offered solutions to specific problems posed by subscribers to the journal. Some of the cases studied were incorporated later into his handbooks and Encyclopédie.
17 The diffusion of the equilibrium or statical approach to masonry architecture at the end of the 19th century is still in need of detailed study. It was positively «explosive» and within two decades of the publication of Culmann’s book there was widespread evidence of its use and development throughout Europe and the United States.
18 Ungewitter 1890.
19 Eduardo Saavedra was the most important Spanish contributor to arch and vault theory; see Huerta 2008, 762. In his translation of Michon’s Instruction sur la stabilité des constructions (1848), published in 1860, he added a series of long notes, and one of them addressed
the «Stability of groined vaults», Michon 1860, 143–147. There, he applied Michon’s graphical methods to calculate the vault thrust, imagining the vault divided into slices.


21 Rubió began to work in Gaudi’s workshop just after finishing his education in architecture in 1893. He probably worked there full time until 1900. According to his nephew Rubió Tuduri (1952, 7), he collaborated actively in the early designs for the Sagrada Familia.

22 Puig Boada 1976, 7.

23 Huerta 2006.


25 Rubió Bellver 1912.

26 All these measures are rounded up. The detailed survey by Fuentes / Guerra Pestonit 2016a shows variations from the «ideal» geometry of only a few centimetres. This is always the case when a historic monument is surveyed. During construction, particularly when construction spans a long period of time, imperfections accumulate and the structure moves and deforms, adapting to soil settlement. As a result the geometry of the building deparths slightly from what was intended. The builders made corrections when the imperfections became apparent. There are very few studies of the mechanical deformations of masonry structures, comparing the original dimensions with the actual state. For the distortions due to cracking see Guerra Pestonit 2009; for those due to soil settlement see Heyman 2018, a detailed study of the problem with reference to the construction of King’s College Chapel in Cambridge.

27 The above measurements have been taken from the survey by Fuentes / Guerra Pestonit 2016a. The dimensions employed by Rubió in his analysis show slight differences which do not affect the result of the structural analysis.


29 «[le pilier gothique] Prise entre les contre-poussées de la voûte et de l’arc-boutant, elle risque, si les efforts sont imparfaitement balancés, de s’incliner légèrement dans un sens ou dans l’autre: afin de tenir compte de cette situation d’équilibre limite, on lui laisse pour ainsi dire une certaine mobilité sur sa base», Choisy 1899, II, 311. The matter is discussed in several parts of the Dictionnaire. The most detailed exposition is in the article «Échelle», Viollet-le-Duc 1861, vol. 5, 150. Paul Abraham criticised harshly and at length this idea of «l’articulation à la base», Abraham 1934, 72.

30 They began to be questioned in France around 1900, principally by Brutails: «Les théories de Viollet-le-Duc sont flottantes et trop souvent erronées; il lui arrive de dénaturer les faits, et l’illustration même de ses volumes est subjette à caution», Brutails 1908, x. Such criticisms grew slowly in France. In Spain it appears that the first serious criticism was published by Torres Balbás 1920. The big blow came eventually from an engineer, Victor Sabouret, who in 1928 published an article with the provocative title: «Les voûtes d’arêtes nervurées. Rôle simplement décoratif des nervures», Taking Sabouret’s criticisms as a point of departure, and including all previous criticisms, Pol Abraham, mounted what has been considered the definitive assault to Viollet’s theories. The book by Abraham is a violent attack, on all fronts, on whatever Viollet-le-Duc affirmed about the Gothic; indeed, such «violence» is unusual in scholarly books. However Abraham studied with great care the work of Viollet and the book is a treasure of information for the technical debate about Viollet-le-Duc’s rational interpretation of Gothic, full of provocative and fertile ideas about Gothic constructions, Abraham 1934.

31 Rubió Bellver 1912, 112–113.

32 «En muchas de las Catedrales y en la de Mallorca así se verifica, para hacer su cálculo, es preciso suponer que las columnas se han desequilibrado, perdiendo la verticalidad y entonces las cargas que por intermedio del sistema de arcos formeros gravan las columnas ya no lo hacen directamente, sino que cargan sobre la curva de presiones, ya de la nave mayor, ya de la nave menor. (...). Entonces todo el peso muerto se convierte en peso vivo carga sobre el vacío y modifica la curva de presiones», Rubió Bellver 1912, 112–113.

33 «La Catedral de Mallorca no debería sostenerse! Más como hace varios siglos que se aguanta con solemne magedost, no queda otro remedio que rendirse a la evidencia y cargar el peso muerto sobre la curva de presiones», Rubió Bellver 1912, 113.

34 «Por otra parte, vista la Catedral y los movimientos de sus columnas, parecéome debía hacer los cálculos partiendo del supuesto de que las columnas se habían desplomado hacia dentro de la nave mayor, y así lo hice», Rubió Bellver 1912, 113.

35 Heyman 2011.


37 Fuentes / Guerra Pestonit 2016a.

38 «En la Catedral de Mallorca hay que tener en cuenta, para estudiar su equilibrio, seis cantidades hipotéticamente variables que constituyen seis esfuerzos, los cuales compuestos y contrabalaceados han de venir a dar un esfuerzo vertical ó casi vertical, pasando por la columna», Rubió Bellver 1912, 114.

39 «Lo primero que debe hacerse, después de efectuados los estados de cubicaciones y pesos, que también se acompañan, es trazar todas y cada una de las curvas de presiones de todos y cada uno de los elementos: arco toral, ariston y arcos botaréles. Estas curvas de presión han de hacerse dobles para cada elemento. Una de ellas ha de ser la curva de presión que con menos reacción sea posible hacerla pasar por dentro de los macizos del arco y la otra la que con más reacción sea posible hacerle también pasar por los mismos macizos. Esto con el fin de conocer los límites dentro de los cuales pueda encerrarse la solución definitiva», Rubió Bellver 1912, 115.
«En la Catedral de Mallorca, al objeto de que los arcos apuntados torales de la nave mayor no se desequilibran, y su vértice, su punta alta no se levantase, a causa de los pesos que, provenientes de las enormes bóvedas, cargan sus tercios inferiores, fué preciso cargarle unas paredes de un volumen considerable a fin de que, ya desde su origen, la curva de presiones de este arco no saliera de dentro el macizo, y además, sobre las claves de los arísterones, al objeto de evitar también los mismos movimientos y para lograr iguales efectos mecánicos, fue necesario, hacer gravitar asimismo unas verdaderas pirámides de gruesas piedras», Rubió Bellver 1912, 100.

«(...), los espacios y los sus a modo de construir, adaptar los elementos constructivos del templo presos separadamente, sino que interesaba en primer término (...) a la disposición general del organismo constructivo», Rubió Bellver 1913, 67-68.

«...) una gran desproporción entre la intensidad de las expansiones de la nave mayor y las de la nave menor (...). Esto procede de que los estribos de la batería alta son demasiado importantes y exigen contra ellos unas reacciones muy grandes (...). Gracias sin embargo a la influencia del botarel alto, la curva de presiones se mantiene cercana al intrados del toral», Rubió Bellver 1912, 120.

«(...), las acciones y reacciones entre los diferentes arcos no son suficientes a mantenerse mutuamente en equilibrio sobre la columna, y es necesario llegar a la suposición de su desplome a fin de que los pesos muertos que cargan sobre ella (por intermedio de los formores) pasen a ser pesos de actuación vivo, influyan sobre la curva de presiones», Rubió Bellver 1912, 120.

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«...), la solución mecánica no es solamente una cuestión que interesa únicamente a las formas de detall, a los elementos constructivos del templo presos separadamente, sino que interesa en primer término (...) a la disposición general del organismo constructivo», Rubió Bellver 1913, 67-68.

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rubio bellver 1912, 101.

"A la par que crece el monumento aumentan todas estas diferencias y al traspasar determinadas medidas son muy difíciles de solucionar tantas irregularidades y el monumento es prácticamente imposible", Rubió Bellver 1912, 101.

76 Huerta 2004, 518.

77 "Unidad de material: todo piedra. Unidad de esfuerzo; todo a la compresión, que es el esfuerzo más adecuado a la piedra (...). Unidad de formas, el arco apuntado por doquier en las líneas de construcción y en las líneas de ornamentación. Unidad constructiva: si quitáis una sola pieza de esa Catedral ideal (...), toda ella se desmorona y hunde", Rubió Bellver 1912, 110.

78 "(...) chacune des parties agit sur l'ensemble et où l'ensemble dépend de toutes ses parties. Poussant le raisonnement à l'extrême, on est arrivé à dire à peu près ceci: le choeur de Notre-Dame de Paris est un chef-d'œuvre d'équilibre poussé à la limite; il suffirait d'enlever une pierre pour que tout s'écroule", Formigé 1928, 103.


80 Jerold 1977, 62.

81 "Ha sido preciso hacer este trabajo de tanteo... ¡muchísimas veces! tan delicadamente se sostiene la catedral de Mallorca", Rubió Bellver 1912, 116.

82 "(...) à la postre se ha conseguido un resultado que, satisfactorio, como el que aquí se presenta, no por eso deja el espíritu satisfecho del todo, ni la solución es tan indiscriminable que no dé lugar a la duda, aun cuando ésta pueda tener efecto en cuestiones de detalle, ya que, claro está, que las fundamentales no pueden dejar de verificarse, a menos que se dé por sentado el absurdo de que un monumento que cuenta varios siglos de existencia esté en malas condiciones de equilibrio", Rubió Bellver 1912, 114.

83 "(...) esponiéndose a arruinar un edificio inmenso, hecho a costa de tantísimos sacrificios y de siglos y más siglos de trabajo (...)", Rubió Bellver 1912, 119.

84 "(...) ya sea por una compensación de pesos á derecha é izquierda de la columna con relación al ancho de las naves respectivas, ó por algún otro medio sintético, resolver groso modo estas cuestiones tan delicadasísima", Rubió Bellver 1912, 119.

85 "Arte de picapedreros puesto al servicio de equilibristas ingeniosos, hombres llenos de espíritu científico y aficionados á todas las minucias del dibujo (...). Véase á cuanto tiempo artístico se ha de recurrir para cubrir un espacio de 40 metros de ancho. Columnas, arcos, aristonos, bóvedas; dobles botarels contrafuertes inmensos, cargas supletorías sobre las bóvedas, todo compuesto y combinado con rebosamientos indedibles, después de tanteos sin fin, después de una lucha titánica de varios siglos contra las dificultades que presenta tan complicado equilibrio", Rubió Bellver, 119–120.

86 "(...) todo el proceso del arte gótico queda estampado en estas curvas de equilibrio que creo que por primera, vez
en la historia de las monografías arquitectónicas, aquí se exponen», Rubió Bellver 1912, 119.

87 Dehio / Bezdol 1887–1901. «De todos los edificios construidos en el estilo gótico, por ser el que tiene la nave lateral más alta, la nave central más espaciosa y las columnas más altas y más delgadas, es sin duda alguna el que con más aprovechamiento para la organización del edificio, ha utilizado los medios constructivos del arte gótico», Rubió Bellver 1912, 133.

88 «La Catedral de Mallorca es sin duda la que con menor cantidad de materiales vistos desde el interior, encierra dentro de sí un volumen mayor de espacio útil», Rubió Bellver, 133.

90 «(...) los medios supletorios para equilibrar la construcción son extraordinarios en extremo y, a pesar de esto, el divorcio entre sus formas géométricas y sus curvas de equilibrio es tan grande que puede afirmarse que siguiendo los procedimientos góticos, sería sumamente difícil cubrir una iglesia de tres naves de mayores dimensiones que ella», Rubió Bellver, 133–134.

91 «Si (...) tuviese la nave segunda más alta que el punto de arranque de los arcos de la nave mayor, entonces (...) tendría la nave central ahogada por las laterales», Rubió Bellver, 134.

92 «La Catedral de Mallorca es, pues, de entre todas las Catedrales, la que tiene empleados los organismos propios del estilo gótico con la mayor simplicidad posible y en un límite superior del cual no sería prudente pasar, y del cual en ninguna otra se ha pasado y en consecuencia se puede afirmar de ella, que es el éxito orgánico, constructivo, y mecánico mayor y más perfecto del estilo gótico», Rubió Bellver 1912, 134.

93 Huerta 2017.

94 «Ce squelette est rigide ou flexible, suivant le besoin et la place; il cède ou résiste; il semble posseder une vie, car il obèit à des forces contraires, et son inimmobilité n’est obtenu qu’au moyen de l’équilibre de ces forces (...)», Viollet-le-Duc 1868, vol. 4, 127.

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Viollet-le-Duc 1854–68

Warth 1903

Image Sources
2. Fuentes / Guerra Pestonit 2016b.
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11 left Rubió Bellver 1913.
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12–13, 14 left, 15–16, 18–19, 24, 27 Rubió Bellver 1912.
14 right Fuentes / Guerra Pestonit 2016a.
17, 20 bottom, 21, 23 Drawing by Huerta 2018.
20 top Rubió Bellver 1912; dashed strips drawn by Santiago Huerta 2018.
22 left Culmann 1866; right Koechlin 1889.
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26 left Hatzel 1849.
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