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Rodrigo Gil de Hontañón's new arithmetical structural rules at the parish church in Villamor de los Escuderos

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In 1638 Galileo's *Dialoghi delle nuove scienze* established the rudimentary foundations of modern structural analysis. Gothic master masons long before had used empirical geometric constructions to determine and preserve useful structural and formal ratios. Before 1538 the Castilian architect Rodrigo Gil de Hontañón devised innovative arithmetical structural rules using square roots and summations, displacing traditional constructive geometry in his practice. Although powerful, Rodrigo's formulae were still empirical, exhibiting no understanding of physical or dimensional units. Rodrigo invented his formulae at the end of an era that accumulated much experimental evidence with little theory to explain it. The formulae mystify modern technicians who expect a physics-based engineering, but Rodrigo's formulae are a century older than Galileo and the birth of modern physics.

The older Gothic spatial geometric constructions used what Lon Shelby (1972) called *constructive geometry*, the manipulation of geometric forms and procedures without understanding the logical structure that would either justify them or prove them inconsistent. Rodrigo's search for meaningful structural ratios used what Charles Sanders Peirce called *abduction* or *retroduction*. (Fann 1970, 5–10) While induction is a search for generalities from specific facts, abduction is a search for a theory from those same facts. The theory need not be «true» or even reasonable, but must try to structure and organize experience, and can be an intermediate step towards a deeper scientific understanding. Rodrigo's structural rules represent a late stage in the development of abductive reasoning in the masonic world. His formulae are more mathematically sophisticated than what 13th or 14th century masons could have produced, but seem grounded on the same body of constructive experience.

In a Baroque architectural compendium of 1681 the architect Simón García from Salamanca transcribed what we have left of Rodrigo's writings. (García 1681; Rodicio 1992) In Simón's chapter 6, 18v-19r, Rodrigo claims to have been puzzled a long time about the correct depth of a buttress supporting an arch such that the depth is neither more nor less than is exactly needed. He asked many Spanish and foreign masters if they knew any such rule, and got only rules of thumb and formulae that did not meet his criteria. Hence he undertook to create some rules that would accomplish this. Seven of his formulae survive, and they give required sizes for piers and buttresses, and the correct weight of a keystone. (Kubler 1944; Hoag 1958; 426–35, 441; Sanabria 1982)

Rodrigo imposed two conditions on satisfactory rule for buttress depths. First, the rule must be general; it must work for any arch. Second, it must give only a sufficient depth, as much as is required to support a given load and no more. Generality and sufficiency were important but uncontested concepts. Rodrigo sought positive results without studying mechanisms addressing his conditions. For example, sufficiency could lead to a precariously balanced buttress, swaying to any added load. If buttress and arch formed an integral unit, which one would fail first? Would slippage and hinging between voussoirs undermine the arch before the buttress became unstable? Rodrigo mentions a safety factor in 18r, but does not question how much redundancy is needed nor where. The requirement of generality is also problematical, because different arch shapes or voussoir depths affect thrust angles and balance. In Rodrigo's era, the only theoretical study of vault thrusts had been Leonardo's tentative application of Archimedean principles to the analysis of arches and their supports, which yielded no practical results. No satisfactory statement of this problem was published until the end of the 17^{th} century.[1] Rodrigo wanted a synthetic formulation, a proto-mechanical recipe like the gothic geometric constructions, or alchemical recipes for gold, that would give reliable values. Despite his lack of conceptual tools, at least two of his rules suggest some experimentation. (Sanabria 1982, 289)

Rodrigo began his career completing unfinished projects of his father, the great Late Gothic master mason Juan Gil de Hontañón, who died in 1526. Among these was the sanctuary of the parish church of Nuestra Señora de la Asunción in Villamor de los Escuderos, executed between 1526 and 1536. (Figure 1) On June 6, 1526, some three months after Juan Gil's death, Rodrigo contracted to continue the work following his father's specifications. In a letter of intent of September 3, 1529, he promised to complete the vaults by June 1531. (Casaseca 1989, 130–3) As in many contracts of that time, the builder absorbed all construction costs to completion. Only bidders with substantial resources or backers, experience, and a record of success could qualify. Rodrigo posted a bond with three guarantors on September 10, 1529. Obviously he was no newcomer, but a young principal of a well-established business. In 1536 Rodrigo completed work on the sanctuary, and after a contested appraisal that led to a lawsuit, the church paid for this campaign late in 1537. (Figure 2)

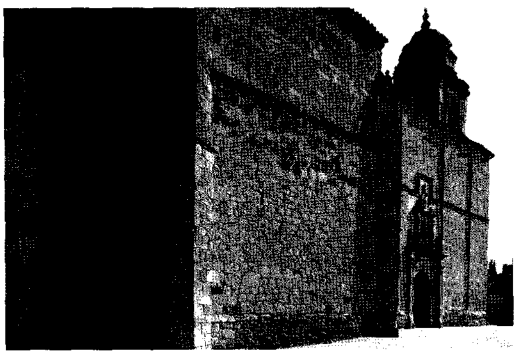

Figure 1
Villamor de los Escuderos. Parish church of Nuestra Señora de la Asunción. North flank of church, showing the rubblework sanctuary and north transept in the left foreground, and the ashlar nave to the right. Note that the massive nave buttresses project only slightly beyond the chapel walls

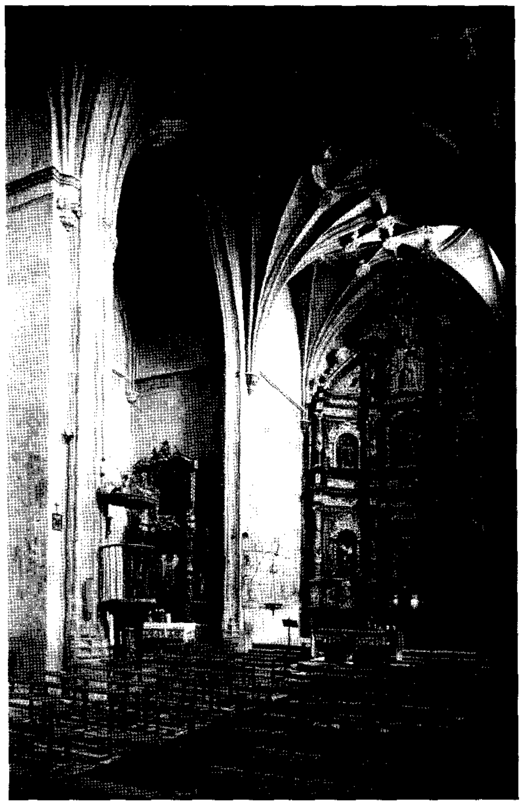

Figure 2
Villamor de los Escuderos. Parish church of Nuestra Señora de la Asunción. Sanctuary, designed by Juan Gil de Hontañón before 1526, and executed by his son Rodrigo Gil, between 1526 and 1536

Despite the conflict, Rodrigo remained master of Villamor until his death. In 1538 he started work on the nave of the church, altering his father's design in part by using one of his new structural rules for piers. He visited Villamor for fifteen days in May or June of 1540, as recorded at the archives of the cathedral of Salamanca, and appointed Gonzalo de la Atalaya as his *aparejador* (general contractor). (Chueca Goitía 1951, 147) Construction was patronized by Antonio del Aguila, bishop of Zamora 1546–60, whose coat of arms appears in the north portal and the *hornacinas* (chapels between buttresses). Rodrigo's nave is as high as its hornacinas, an unusual variation of a hall church, repeated later at his churches at Santa María de Guareña and the chapel of the Hospital de la Misericordia in Segovia. (Figure 3) The nave walls are of ashlar, contrasting with the rubble of the sanctuary. Its massive buttresses are nearly flush with the exterior wall.

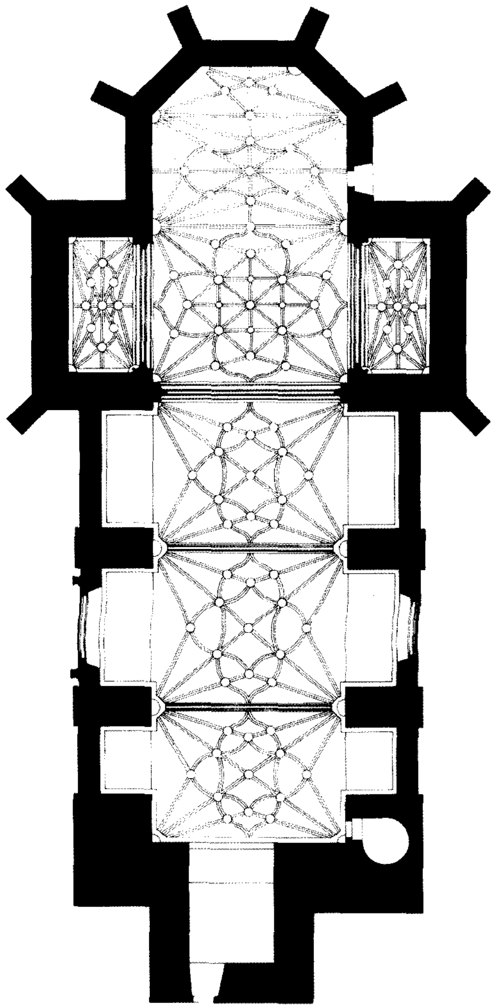

Figure 3
Villamor de los Escuderos. Parish church of Nuestra Señora de la Asunción. Nave, designed and executed by Rodrigo Gil de Hontañón after 1538. Note the massive butresses separating the chapels, whose height is the same as that of the nave

The plan of Villamor resembles generically two plans in Simón García's book, the Third Temple Design by Human Analogy in 4v and the Fifth Geometric Temple Plan in 14v-15r. (Figure 4) The plan of the nave is irregular, its three bays are approximately 5.83, 6.75, and 5.85 meters long, respectively.[2] Thus no exact relationships hold between it and the formulaic plans in Simón García. The nave is as wide as the sanctuary, approximately 8.40 meters. The *hornacinas* are about 2.20 meters deep. Their depth seems unrelated to the nave width, and was determined instead by the pier formula. Structural sizing governed spatial ratios in this classicized gothic construction. Clearly Rodrigo had invented his new formulae by this time, dating much of his literary output to the beginning of his career.

Wall buttresses between the *hornacinas* are thicker than transept walls. These buttresses differ clearly from those of the sanctuary, and are double squares in plan. They measure 3.35 × 1.70 meters, which equals 4.01 × 2.03 *varas de Castilla* of .836 meters, or 12.02 × 6.10 Castilian feet of .279 meters. Their size and double square proportion follow a structural formula discussed at length in Simón García's *Compendio*, first in chapter 2, 5r-5v, used while designing a church, and again in chapter 6, 17v, where it is explained. The formula yields the width W of the buttress at the springing of the vault. The plan of the buttress is preordained to be a double square, so its depth is $2W$. Rodrigo specifies a complex operation:

$$W = \frac{1}{3} + \sqrt{H + \frac{2}{3}\sum P}$$

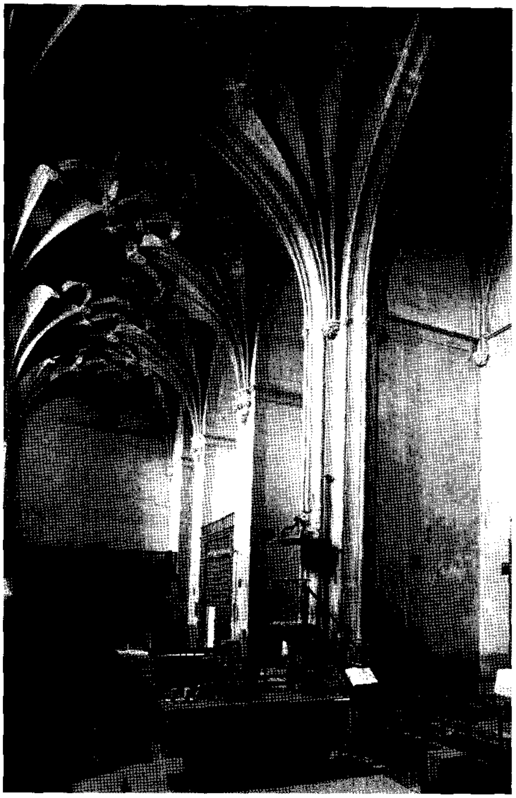

Figure 4
Villamor de los Escuderos. Parish church of Nuestra Señora de la Asunción. Plan. Redrawn after an original survey by Marco Antonio Garcés and Luis Navarro

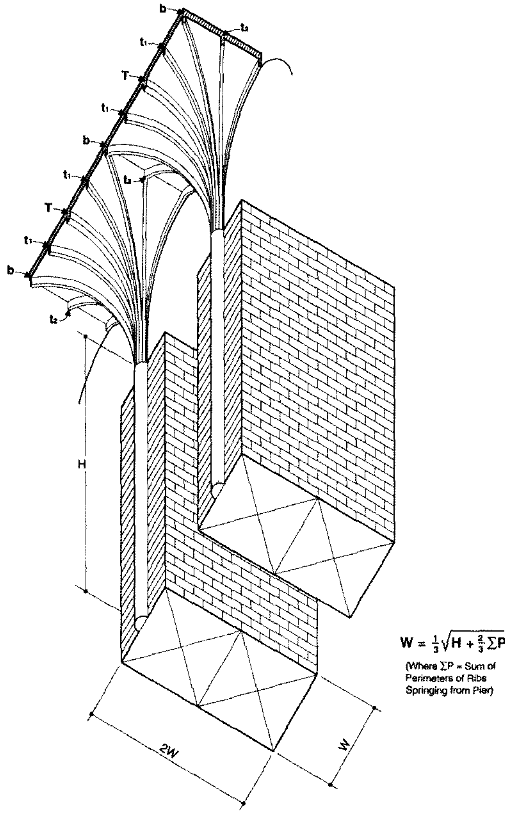

Figure 5
Rodrigo's second arithmetic formula, given in Simon García's *Compendio*, 5r-5v, and 17v. Because of the square root operation, the formula yields proportionately larger buttresses for larger units of measurement. It appears to have been calibrated for Castilian feet of .279 meters

where H is the height of the buttress to the springing and $\sum P$ is the sum of the perimeters of all ribs converging on the buttress, whether transverse, diagonal or tiercerons, measured from the springing to their respective keystones, usually a quarter circle. (Figure 5) At Villamor the height to springings is about 9.8 meters = 35.125 feet = 11.724 *varas*. The sum of perimeters of the five ribs is about 28.2 meters = 101.075 feet = 33.736 *varas*.

That this formula was a novelty in Spain is clear from the awkward, painfully bloated and thick buttresses creating wide expanses of unarticulated walls. It is possible but unlikely that Rodrigo knew and tried to emulate either ancient thick Roman walls, or Francesco di Giorgio's structural formulae, apparently reused by Bramante in the Roman High Renaissance. (Betts 1993) A more likely possibility is that he misapplied the very rule he invented.

Rodrigo's formula is dimensionally inconsistent, expressing length as the square root of length. This means that results change depending on the units used. Results using *varas* will differ by a real factor of $\sqrt{.836/.279} = \sqrt{3} = 1.73$ from results using Castilian feet in the same formula. Normally Rodrigo specified dimensions in feet. Using feet his formula yields buttresses of $1.88 \times .94$ meters, not the dimensions of nave buttresses, but closer to those in

Juan Gil's sanctuary that measure approximately 2.5 × .9 meters. Using *varas* the formula yields buttresses of 3.26 × 1.63 meters, or 3.90 × 1.95 *varas*, very close to those built. The small upward adjustment to 4 × 2 *varas* was reasonable, although we cannot be certain as to the exact values used for the sum of perimeters of ribs, which could throw the results off by a few percent.

Neither Rodrigo nor his *aparejador* could have known that the formula garbled units of measurement and so was sensitive to the units used. By specifying building dimensions in *varas* instead of feet the buttresses were inadvertently enlarged 1.73 times. Whether the architect or the *aparejador* was responsible is not clear, but in one of his infrequent inspection visits to the site, Rodrigo must have discovered that this was an unusually massive structure by the standards of Spanish gothic construction. He made no obvious corrections to the building in progress, which would have been difficult. Villamor was the most massively buttressed building in Rodrigo's work, proportionately heavier even than the cathedral of Salamanca. He learned not to trust his rules blindly, a lesson that young designers relearn to this very day.

NOTES

1. The earliest theoretical analysis of arches and their abutments was in Philippe de la Hire, Traité de Mécanique, published in Paris in 1695, using funicular force polygons. In 1730 Pierre Couplet advanced the analysis by determining the permissible limits of lines of thrust, graphic depictions of summed forces. Leonard Euler's 1740s work on elastic curves ushered a new horizon. See Timoshenko, History of Strength of Materials, chapters 2, 3; Jacques Heyman, «Couplet's Engineering Memoirs, 1726–1733», Arches, Vaults and Buttresses, 221–44.
2. The church was surveyed in 1984 by Marco Antonio Garcés and Luis Navarro. Copies of their drawings are at the Archivo del Servicio de Restauración de la Junta de Castilla y León in Valladolid.

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