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SANTA MARIA NOVELLA AND THE DEVELOPMENT OF A FLORENTINE GOTHIC STRUCTURAL SYSTEM

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ABSTRACT

The Dominican Church of St Maria Novella is one of the most outstanding examples of Gothic architecture in Italy. Within the frame of a grant from the Kress Foundation European Preservation Program a research was carried out focused on the nave with the aim of understanding its distinctive design. The investigation carried out on site using non destructive techniques (NDTs) is described together with a first interpretation of the results

1. INTRODUCTION

The first of the great Florentine basilicas to be completely covered with cross vaults, the Dominican church of Santa Maria Novella (1279-1355) has long been recognized as one of the most outstanding examples of Gothic architecture in Italy. It served as a structural model for the nave of the Cathedral of Florence, among others, and continued to be much admired throughout the Renaissance. One of the major factors that accounts for its success as a design is the unified interior space of the nave with its soaring domical cross vaults.

Like their counterparts in other regions of Europe, Italian builders of the Gothic era experimented with new types and methods of construction, such as the domical vaults of Santa Maria Novella raised high on slender shafts, so much more daring than the domical vaulted churches of Romanesque and Gothic Lombardy, and achieved without the aid of the iron tie rods so often seen in Italian Gothic buildings. In so doing, the builders of Santa Maria Novella created that airy interpenetration of space that would come to characterize Tuscan Gothic architecture.

2. RESEARCH OBJECTIVES

The research carried out at Santa Maria Novella focuses primarily on the nave (Figure: 1), with the aim of understanding why and how it came to have this distinctive design. Ultimately, the authors would like to reconstruct the process of design and construction, identifying specific situations where builders made critical decisions regarding design and structure. In so doing, it is possible to gain a better appreciation of the achievements of the builders of Santa Maria Novella as they created what is essentially a Florentine Gothic Structural System. Mathematical models will also be used to better support the results of the investigation.

The particular distinctive features that draw our attention are the use of domical rib vaults, that is, vaults whose crowns change level along the longitudinal and transverse axis, resulting in a sense of a high canopy over each bay, the use of high side aisles with crypto buttressing, concealed above the aisle vaults. A further curiosity is the bay system, in which the first two bays south of the crossing (the nave runs north-south) are rectangular in a proportion of approximately 0.7 length: width, while the remaining four bays are roughly square (see Figure 1). The vault survey was never carried out in a refined way before.

Figure 1- View of the interior of St. Maria Novella

Although the construction of the church is known from documentary evidence to have initiated in 1279, and to have been complete in 1355, very little additional information on the sequence of construction is available. A study of some of the available documents has shown that

- by 1287 the foundations of the entire building were complete and some exterior walls were rising from the ground;

- by 1295 the Feast of Corpus Domini was held in the old church and in that part of the new church that was contiguous, i.e. the crossing;
- by 1301 the eastern half of the old church was destroyed to make way for the first two nave bays; masses are now being said there; this part of the church could be closed off at night with three doors on the front of the screen corresponding to the three naves;
- by 1302 a portal was opened in the third bay of the eastern aisle;
- by 1305 the whole of the church was "roughly sketched out" but much remained to be done inside;
- by 1320 construction of the church was still going on and the *cappella maggiore* was completed;
- by 1325 construction began on the façade wall
- but the entire building was not complete until 1355.

A hypothesis previously elaborated by Smith [1] suggests that the nave was originally proposed to be unvaulted, following Dominican building regulations in force at that time, and was originally intended to consist of seven rectangular bays in the proportion of the first two (0.7:1). At some point during construction, it was decided to vault the nave, and to adopt domical vaulting. At this time, the first two bays were vaulted, and the remaining bays were modified to four approximately square bays, which have been shown [2] to be structurally superior to domical vaults over rectangular bays.

One of the last historical products on the system of vaults in the church is the book written by [3]. The Smith hypothesis was never tested before.

The following methods have been used in the course of the present study.

- Production of Measured Drawings
- Documentation of Cracks and Defects
- Non-destructive evaluation
- Structural Modeling
- Historical Analysis and Interpretation

A particular objective has been to locate evidence to confirm or rule out the working hypothesis outlined in the previous paragraph. This multi-disciplinary investigation has been carried out by means of collaboration between engineers and architectural historians, and collaborations between the Pennsylvania State University and DIS- Politecnico di Milano. DIS is frequently involved in the diagnosis of Italian monuments [4, 5, 6]. The necessity of collaborations between architectural historians and engineers has resulted from the structural character of many of the questions surrounding the construction of the nave and the ability of certain engineering techniques to provide information on construction non-destructively.

3. GEOMETRICAL SURVEY

The geometrical properties which were surveyed in S. Maria Novella (in Figure 2 the plan of the church is reported with the spans interested by the deepest investigation) concerned the following parts and elements: (i) extrados profiles of the two vaults of the central nave named EPV-S2, EPV-S5, (ii) profiles of the pillars and of the intrados of the vaults (IPV-S2 and IPV-S5) of the three naves, (iii) the masonry tympani sustaining the timber roof from the extrados of the load-bearing arches of the central nave, (iv) the horizontal section of the three types of pillars in the church.

The topographic survey of the profile of the pillars and of the intrados of the two vaults called IPV-S2 and IPV-S5 was carried out using a laser integrated theodolite (GEOTOP), in order to check also the pillar verticality. Initially a topographic network (local system) was created, formed by a closed polygonal made of 7 vertexes and constituting the framework of the survey. On it the detailed survey of each element was based, so to minimize the increase of the accidental error inherent to the measurement (Figure: 3).

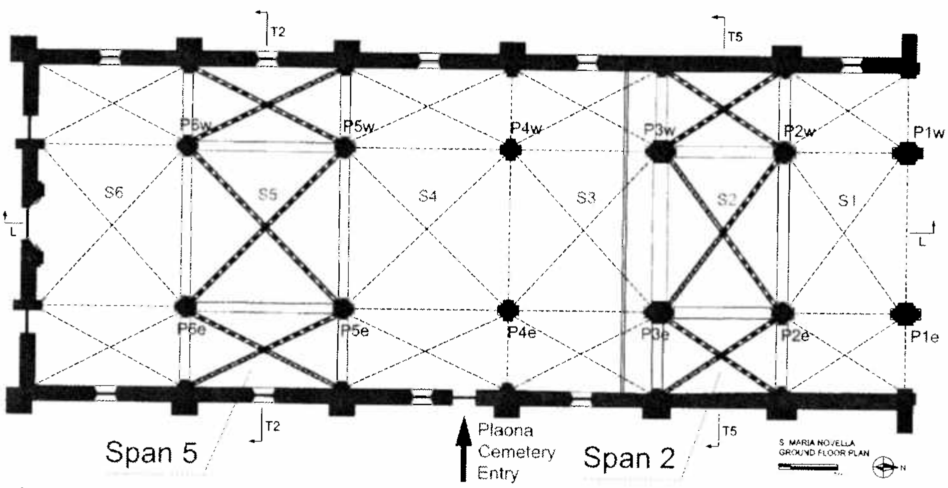

Figure 2. Plan of the church reported with the spans interested by the deepest investigation

The topographic survey of the extrados of the vaults S2 and S5 was also carried out by using the laser integrated theodolite.

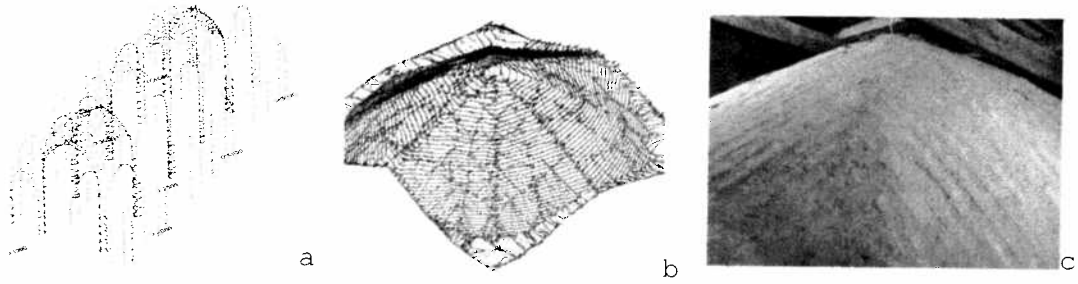

Figure 3. Topographic survey of the profile of the pillars and of the intrados of the vaults (a); 3D reconstruction of the vault extrados (b); view of the details of the extrados of a vault (c)

Also the vault thickness could be measured and was found to be around 30cm. It can be seen from Figure 3 that the geometry of the vaults is extremely complicated. The decisions made during the simplification of the geometry from the super precise total station data to a symmetric geometric model are critical.

4. NON-DESTRUCTIVE EVALUATION

A number of non-destructive methods have been used in an effort to understand the nature of concealed parts of the building fabric. These methods have been applied in complementary fashion, with the findings from each investigation used to substantiate the findings of the other investigation methods.

4.1. Impulse-Echo

The impulse-echo method was used to determine the elastic properties of the material in the vaults and, on an experimental basis, to investigate possible changes in thickness in the vaults. In this method, a sonic wave is generated on one surface of the vault, and an accelerometer is used to record the reflections of this wave on the same surface. Due to the multiple internal reflections of the wave, a profile of the construction of the vault through the thickness can be obtained. By inspection of holes in the vault adjacent to the point of investigation, the thickness of the vault at this location is known to be 32-33 cm. An important peak in the response at 3.4 kHz peak results from reflections at the insider surface of the vault, and corresponds to a wave propagation velocity of 2180 m/s. Using the further relationship that the square of the ratio between the modulus of elasticity and the density of a material is proportional to the propagation of *p*-waves, and the range of density of the bricks of 1700 kg/m^3 to 2000 kg/m^3, it is possible to determine that the modulus of elasticity of the vault material is approximately 9 GPa. Further investigation of the result of multiple investigations over the entire vault show that there are only minimal changes in thickness through the extent of the vault. This is consistent with the findings of the georadar testing of the vault construction and with the geometrical survey.

4.2. Dynamic Testing

The methods of experimental modal analysis have been used to determine the natural frequencies and the mode shapes of the vaults over nave bays 2 and 5. In these studies, an array of accelerometers has been placed on the vaults in 16 locations, and vibrations have been excited in the vaults by means of a controlled force impact hammer. The resulting signals from the accelerometers can be processed to determine the natural frequencies and vibration mode shapes of the vaults. The results are eventually used to compare to the results of analytical models for the purpose of assuring that the analytical model is an accurate representation of the condition of the structure.

4.3. Sonic Pulse Velocity Testing

Sonic pulse velocity tests are carried out to detect the presence of density variation in the walls and hence the presence of different connections in the depth of the wall or of defects and cracks. The sonic pulse velocity tests were carried out in three positions, as shown in Figure 4. Figure 4 also shows the crack pattern surveyed on the extrados of the vaults. If Figure 3 is taken into account the crack pattern can be explained with outward movements of the load bearing walls and pillars due to the thrust of the vaults (no tie rods are present) and the cracks are formed in the weakest points of connection.

Sonic tests applied to three areas were used to achieve qualitative information about the transversal wall between the second and the third span, over the extrados of the vaults of the nave.

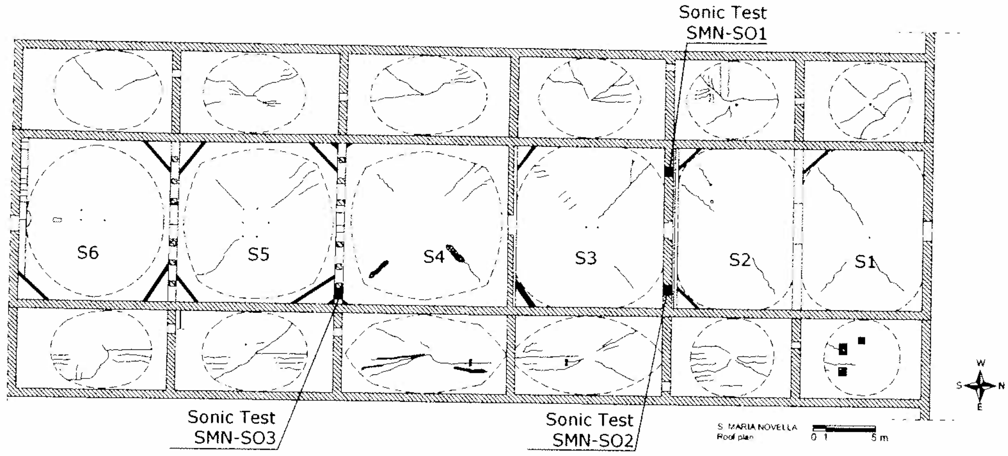

Figure 4. localization of the sonic tests performed in the roof level

Figure 5 shows the location of sonic tests on two grids positioned on the transversal wall. The crack patterns surveyed on this wall and on the other transversal ones, all affected by similar cracks confirms the settlement of the vertical walls and of the pillars due to the vault thrust. The same position of the grids was maintained also in the measurements at other spans.

An average rather uniformly distributed rather low velocity of 1,200m/s was measured while on the grid SMN-SO3 positioned on the transversal wall between the fourth and the fifth span is higher (2,200m/s), showing a probably better construction technology.

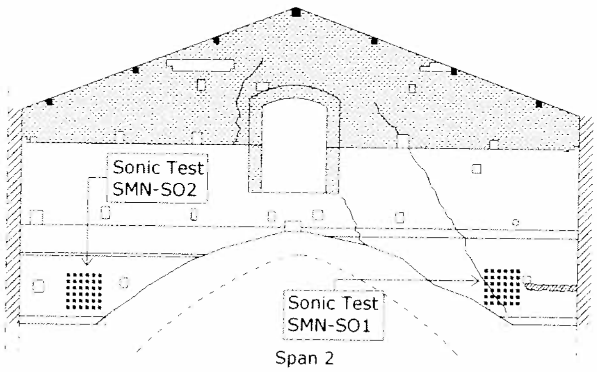

Figure 5. Sonic tests in the transversal wall between span 2 and span 3

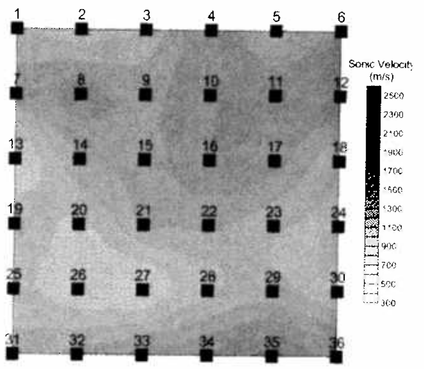

Figure 6. Test results on SMN-SO1 position

Sonic tests were also carried out on some pillars of the central nave made with sandstone. Here an average velocity of 2,800m/s at the base and of 1,500m/s at the level of 1.40m was measured showing a weakest material used in the upper part (Figure: 7).

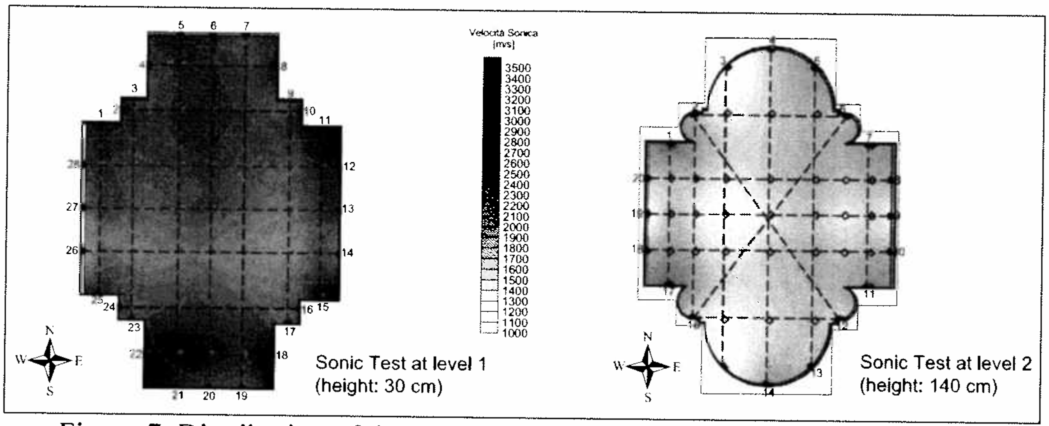

Figure 7. Distribution of the sonic velocity on the basement of pillar P3w

5. STRUCTURAL MODELING

A considerable effort has gone into the development of analytical structural models for the interpretation of the behavior of the vaults and their buttressing system. The modeling procedure has undergone a continuous development since the initial site visit in 2002. The findings of the analytical studies on these models are incorporated in a recently published article [2]. As a result of the comparisons of bay plans and vault geometries, it is evident that a square bay is better suited to a domical vault, while the rectangular bay is better utilized with even-level-crown vaults, and each pair has its own advantages and disadvantages. The transverse load distribution in Bay 2, a rectangular bay, is not as favorable as that of Bay-5, because the former is not perfectly square. Although a detailed stress analysis is not provided and the limited stress results do not perfectly match the cracks observed on site, the Bay-2 vault and Bay-5 walls are found analytically to be more susceptible to cracking, and this general observation is in accord with the condition of the structure.

6. CONCLUSIONS

The multidisciplinary research developed on the vaults of St. Maria Novella was an important help toward the goal of understanding why and how its gothic system has such a distinctive design. Furthermore it gave the opportunity of increasing the knowledge on the process of design and construction, identifying specific situations where builders made critical decisions regarding design and structure and also allowed to surveyed the present damage of the vault system.

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