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Original article

Evolution of construction techniques in the Early Gothic: Comparative study of the stereotomy of European sexpartite vaults using new measurement systems

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ABSTRACT

Sexpartite vaults, built between the 12th and 13th centuries, stand out as the main feature of European Early Gothic, in a time of transition between the Romanesque and Gothic periods. The detailed study of sexpartite vaults provides an insight into how medieval construction systems evolved from the earliest times and facilitates our understanding of the knowledge and technical advances implemented through the stonemasons' lodges. Early examples show clumsy building solutions, which soon developed, however, new tools and different carving and erection techniques emerging together with intelligent building strategies that simplified the auxiliary wooden structures needed for construction. Sexpartite vaults did not evolve homogeneously across Europe, but rather in two radically different geographical areas, each developing in different stages. A new data-gathering procedure was used to define the vaults' components. This new system, together with key aspects of comparative analysis, helped us to establish how these structures developed. The master builders' knowledge was constantly changing and evolving at this time in history and therefore any qualitative leap in the technology used enables us to determine regional influences.

1. Introduction. Origin and expansion of European sexpartite vaults

Sexpartite vaults have diagonal ribs and an additional central rib that divides the vault into 6 severies. They also have six supports and two wall ribs on each side. This particular type of vault emerged from the need to solve the structural problems inherent in the large, square-based quadripartite vaults in the first Gothic cathedrals, where the diagonal ribs were enormous. The sexpartite vault offered a safer system that strengthened the structure thanks to the central rib, and it spread rapidly across the whole of Europe.

This type of vault was one of the most frequently used in France in the second half of the 12th century and can be found in the main French cathedrals. It was, however, ephemeral. From the 13th century onwards, it was considered to be obsolete in France while in the rest of Europe it was just beginning to spread and develop.

A total of 59 vaults in Western Europe have been studied [1], which are: Notre Dame de Paris, Bourges, Laon, Sens and Lyon Cathedrals and the Churches of Notre Dame de Dijon, Sainte Madeleine in Troyes and Saint Julien le Pauvre (France); Canterbury, Rochester and Lincoln Cathedrals (England); Limburg an der Lahn and Bremen Cathedrals and Maulbronn Monastery (Germany); Lausanne Cathedral (Switzerland); Piacenza Cathedral, Basilica of San Antonino in Piacenza and Certosa di Pavia Monastery (Italy). In Spain, all the sexpartite vaults that have been preserved have been studied, the most important being: Ávila, Cuenca and Sigüenza Cathedrals, the Monasteries of Santa María de Huerta, Las Huelgas Reales in Burgos and Roncesvalles and the Church of San Saturnino in Pamplona.

Although the sexpartite vault has been studied in terms of the disciplines of history, art and archaeology, there is no research into the characteristics of its construction or the technology used. Exceptionally, there are some occasional references, such as the 19th century works of Viollet Le Duc and Auguste Choisy, but they present theoretical models of this type of vault that do not reflect the actual construction characteristics [2–7].

2. Research aim

The main aim of this research is to reveal the knowledge of the master builders and the evolution of medieval technical

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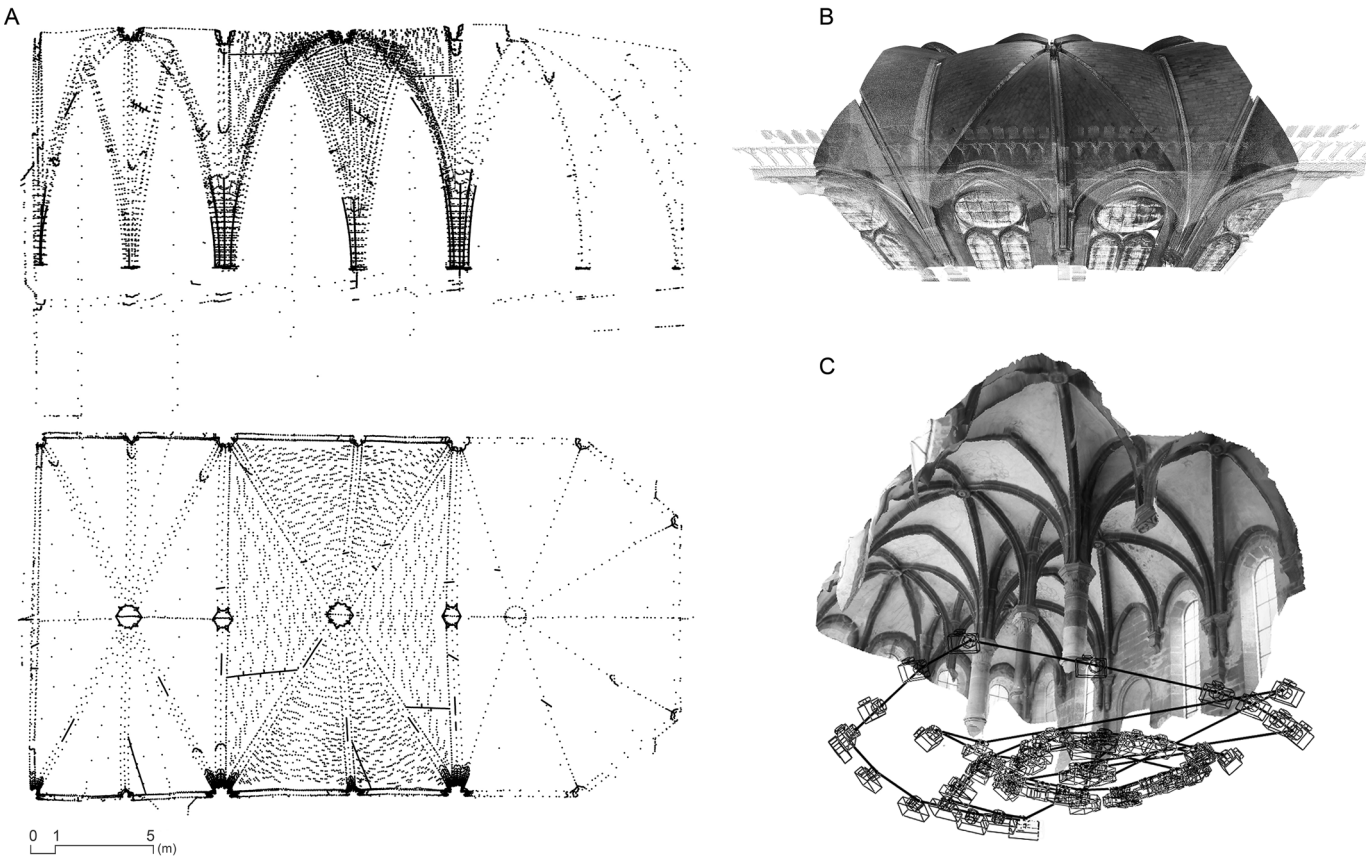

Fig. 1. Different surveying methodologies: a: laser total station, Church of San Saturnino (Spain); b: laser scanner, Cathedral of Notre Dame de Paris; c: photogrammetry, Monastery of Maulbronn (Germany).

solutions in Europe between the 12th and 13th centuries, and through comparative analysis determine the influences of the different geographical regions. In order to do this, European sexpartite vaults, the unquestionable protagonists of Early Gothic, were analysed, scrutinising each one of their constituent parts, namely: voussoirs, keystones, *tas-de-charges* and severies, as well as their bonding arrangements and layout. A further objective was to find a new way of gathering data and carrying out surveys using new high-precision survey equipment enabling previously impossible construction studies to be undertaken [8].

3. Methods

3.1. Use of new measuring devices and establishment of new analysis methodologies

New measurement technologies developed in recent decades, including laser scanner, total station and photogrammety, allow highly-accurate data to be collected for architectural heritage research. However, each methodology has its advantages and disadvantages when measuring, managing and interpreting the data and enables different information to be extracted [9]. Before beginning our research, we had to clarify the differences between measurement technologies and describe the way in which to approach the analysis of the data measured to formulate objective hypotheses.

The vaults studied in Spain were surveyed using total station (Models Leica TCR1105 and TCR805ultra) (Fig. 1a). In the rest of Europe, a laser scanner (Fig. 1b) or photogrammetry (Fig. 1c) was used for surveys.

Total station is the only laser scanning equipment that can be used for analysis *in situ* at short distances, using a magnification eyepiece to 42×. An actual exploded view of vaults can be generated element by element, discerning information that is not relevant. While this is the preferred method of analysis, it is not always practical since too much time is needed to capture data. Laser scanner or photogrammetry has been used to survey vaults located outside Spain because there are so many. These systems can shorten data-capture times and obtain accurate 3D models, although they cannot be used to generate an exploded view of the structures.[1] As a means of obtaining this information, a system of analysis was devised to generate an exploded view by using complementary photographic information based on data extracted from Spanish vaults.

The first step was to identify the most relevant factors in order to analyse the construction of the vaults: the geometry of each rib (Fig. 2a) and the cross-section of each of the pieces that form the vault were defined (Fig. 2b).

The best survey methodology to define the exploded view was later determined using the total station based on sets of points measured. Each element is surveyed from different perspectives in order to obtain the complete shape. The voussoirs of the ribs are defined, together with their beds, based on three points (one on the intrados and two on the extrados of the rib) (Fig. 2b) and the shape of their cross-section is subsequently established (Fig. 3a). In order to know which tools were used for carving, it is necessary to know whether the pieces are curved or straight, which requires a great number of measurement points along the longitudinal axis

[1] Some photogrammetric software can generate an exploded view, however the results are based on a computer-generated model, not the actual vault, and are therefore less accurate.

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