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# Computer Analysis of Non-vaulted *Nef Unique* System

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**Abstract**

Ever since Viollet-le-Duc began to examine Gothic structural elements using his method of geometrical analysis in the nineteenth century, art and architectural historians and a few engineers have periodically attempted to ascertain the structural advantages of the various characteristic features of Gothic architecture. In none of these studies, however, has the way forces work within the lightweight and spacious masonry Gothic buildings been precisely interpreted. The approach taken by art and architectural historians has therefore tended to be primarily descriptive and to be based on intuitive assumptions. This study intend to analyze the Gothic non-vaulted nef unique(aisleless) structures of Lower Languedoc which has never been scientifically tested, and to provide as comprehensive an explanation as possible of the way in which these non-vaulted buildings work. In order to achieve this goal, this paper is to examine, by means of finite element analysis, the links between the width of non-vaulted aisleless structures, the configuration of the arches, diaphragm arch, and the buttress. Finite element analysis with a computer provides a more accurate analysis than the methods of analysis that have been heretofore applied to Gothic structures, as well as permits us to visualize the global stress behavior of the structure. Combined with traditional methods of studying historical buildings, therefore, finite element analysis inevitably give us a broader understanding of the processes involved in the design and construction of medieval buildings.

*Keywords: gothic architecture, Languedoc, aisleless(nef unique), FEM*

## 1. INTRODUCTION

Tall, rib vaulted, multi-storied Gothic buildings such as Amiens Cathedral have always attracted attention, and the techniques of computer finite-element analysis have provided modern scholars with a better understanding of the structural problems involved in their construction. The many indigenous forms of Gothic architecture that do not conform to this familiar northern French formula, however, have been largely ignored. This is particularly true of the non-vaulted Gothic buildings in the Lower Languedoc region of southern France.

The non-vaulted variant of Languedocien Gothic is characterized by an aisleless nave, a paneled sanctuary that is smaller than the nave, a timber roof in which the purlins rest directly on the backs of gabled, pointed diaphragm arches, and external wall buttresses that rise along the exterior elevation. [1] This type evolved out of the indigenous traditions of the region, and it has been suggested that changes over time reflected an increasing desire for spaciousness and lightness. It has been further suggested that while aisleless spans of less than 8 meter were not difficult to build, spans greater than 8 meter implied that builders were willing to confront more difficult problems of construction for the sake of aesthetic preferences. The extent, however, to which changes in span would have affected the configuration of major structural components and by extension reflected the relationship between aesthetic and structural concerns in the design of non-vaulted Languedocien Gothic has never been scientifically tested. Therefore, the purpose of this paper is to examine, by means of finite element analysis, the links between the width of non-vaulted aisleless structures, the configuration of the arches, diaphragm arch, and the buttress.

### (1) Background

Scholars have generally used three different approaches to explore Gothic architecture: the first is stylistic or archeological, the second is iconographical, and the last is structural. Stylistic analysis or archeological analysis provides us with information concerning campaigns of construction, reconstruction programs, and repair or restoration. It can be based on a review of the primary textual sources, comparison of existing buildings, or excavations. An iconographical analysis in the context of architecture is the study of the symbolism of churches and it conveys a meaning of the visual pattern of the structure and religious implications. These have been the approaches, generally, of historians. On the other hand, structural analysis explores the nature of structural forces and the behavior of medieval building systems. Until recently this approach has been that taken primarily by engineers.

Even though medieval building systems have been examined by art and architectural historians since the nineteenth century, we still do not entirely understand either the medieval builder's constructional techniques and structural knowledge or the *raison d'être* of the different medieval architectural elements. Prior to the fifteenth century contemporaneous written documentation concerning design methods and constructional techniques

[1] For more information concerning Southern Gothic architecture, See Vivian Paul, "The *Nef unique* in the Origins and First Developments of Gothic Architecture in Languedoc," (Ph.D. diss., University Of California, Berkeley, 1975): Vivian Paul, "The Beginnings of Gothic Architecture in Languedoc," *Art Bulletin* 70 (1988).

of medieval architecture is scarce. [2] Given this circumstance, modern methods of structural analysis provide the best method for analyzing complex medieval building systems and for providing conclusive solutions to what have been only descriptive technical arguments.

Within the past twenty years, several experimental techniques have been developed for analyzing complicated structural behavior and solving the practical problems of design and construction in contemporary structures. One major technique has been a photoelastic modeling method that is a widely used experimental stress analysis.[3] Robert Mark introduced this technique to the field of medieval architectural history and has applied it to studies of complex Gothic structural systems. However, this method is best suited to homogenous elastic materials and is difficult to apply to masonry structures, because stresses can be measured for only a limited number of loading cases.

Another important modern method of experimental stress analysis that has been applied to medieval architecture is the use of electric resistance strain gauges.[4] This method can accurately measure the change of local deformation in structures, but, like photoelastic method, it is difficult to apply to masonry structures. The number of gauges is necessarily limited and because of this, the gauges provide only local information and measure the strain only at the points where the gauges are mounted.

For analyzing complex medieval structural systems, a computer modeling technique, known as finite element analysis is better suited and will be used in this study. Not only is the overall efficiency of finite element modeling greater generally, but more complete information concerning the stress distribution in masonry structures can be discovered with finite element modeling than with the other two experimental methods. For this study, finite-element computer modeling methods (PATRAN and ABAQUS) will be used to examine the non-vaulted Gothic nef unique system. These programs will be able to handle the complex geometry of Gothic structural systems and can be used to study the structural behavior of these complex masonry buildings under any type of load without difficulty.

## 2. ANALYSIS PROCEDURE AND MODEL

### (1) Analysis Procedure

In order to analyze the structural behavior of non-vaulted Gothic buildings, the process of finite element analysis will be executed according to the following three steps: designing the finite element analysis model (Preprocessing: Patran), the actual analysis (processing: ABAQUS), and output (postprocessing: ABAQUS), as shown in [Figure 1].

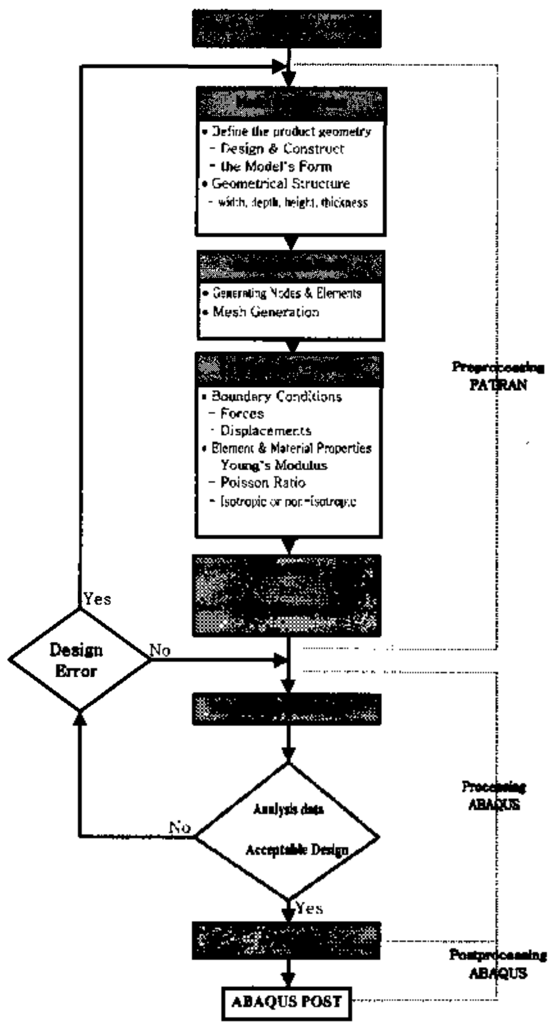



Figure 1. Outline for the finite element computer analysis procedure.

### (2) Analysis Model

In order to analyze hypothetical arch, the various conditions of each sample (arch, roofing, and support system) will be designed and constructed as part of the computer model's form. The analysis model will be constructed by generating nodes and modeling finite elements. In this study, quadrilateral eight node elements

[2] Before the late Middle Ages, only two major documentations on Medieval construction have been found. The one is the Abbot Suger's of Saint-Denis nontechnical treatise, and the other is Villard de Honnecourt's Sketch Book in which he drew Gothic buildings and commented on the use of geometry in designing. However, questions as to the real artist of the note book still remain. For more information about these documents, see Otto von Simson, *The Gothic Cathedral* (Princeton, 1974), *Abbot Suger on the Abbey Church of Saint-Denis and Its Art Treasures*, ed. E. Panofsky (Princeton, 1946), F. Bucher, *Villard de Honnecourt: Architector, the Lodge Books and Sketchbooks of Medieval Architects* (New York, 1979), and H. Hahnloser, *Villard de Honnecourt: Kritische Gesamtausgabe des Bauhuttenbuches ms, fr 19093 der Pariser Nationbibliothek* (Wien, 1935).

[3] See Joe McKinley, *Fundamentals of Stress Analysis* (Portland, 1979): 489-513

[4] See Yunsheng Huang, "Westminster Hall and the Hammer-Beam Roof, a New Structural Interpretation," (Ph.D. Diss., Princeton University, 1987) 52-53.

will be used for mesh generation of two dimensional analysis. This gives more accurate results than the use of triangular (three or six nodes) and quadrilateral four node elements. After the analysis model is built, a simulated environment that includes loads, boundary conditions (forces, displacement), and element and material properties will be created. For effectively visualizing the global stress behavior of the arch, the analysis model will be the perfect bond and the joints between voussoirs will be not considered.

In this study, the distributed load will be applied in the negative direction (downward) along the structure. The distributed loads will be derived from the structure's own weight based on the density of the material(limestone). We will not consider the horizontal force provided by wind loading, because the buildings to be studied are not tall and thus are not overly affected by lateral winds.

Table 1: Variables and constants for arch analysis

| Group | Arch | Clearspan (m) | Springing (m) | Depth (m) | Width (m) |
|---|---|---|---|---|---|
| Group1 | semicircular | 4-20 | 4 | 0.3 | 0.6 |
| | three point | 4-20 | 4 | 0.3 | 0.6 |
| | four point | 4-20 | 4 | 0.3 | 0.6 |
| | five point | 4-20 | 4 | 0.3 | 0.6 |
| Group2 | three point | 8 | 4-10 | 0.3-1.2 | 0.6 |
| | four point | 8 | 4-10 | 0.3-1.2 | 0.6 |
| | five point | 8 | 4-10 | 0.3-1.2 | 0.6 |
| | semicircular | 10 | 4 | 0.3 | 0.6 |
| Group3 | three point | 10 | 4 | 0.3 | 0.6 |
| | four point | 10 | 4 | 0.3 | 0.6 |
| | five point | 10 | 4 | 0.3 | 0.6 |

## 3. THE STRESS ANALYSIS OF A HYPOTHETICAL NON-VAULTED BUILDING

In a stress analysis, it is very important to determine the maximum stress in each member, and whether or not the material is strong enough to withstand the loads applied to it. In the analysis of masonry structure, it is assumed that the masonry material has no tensile capacity.[5] However, if tensile stress is indicated by the finite element analysis, it would lead to radial cracking. Therefore, the main objectives of this study are to determine whether there are any tensile stresses in the masonry structure and the maximum principal tensile stresses exceed the strength of material properties (limestone), and to examine the stress behavior of the masonry structure under variable conditions.

### (1) Masonry Arch Analysis and Results

The basic element of non-vaulted Gothic is the arch. Therefore the first step in the analysis of this structural type is to analyze masonry arches and their different variables (arch type, clearspan, thickness, depth, and spring point), with special focus on clearspans greater than 8 meters.

In medieval architecture, there are generally four basic forms of arches: the semicircular arch, three pointed arch, four pointed arch, and the five pointed arch. For the purpose of this study, these types will be organized into three different groups as shown in table 1.

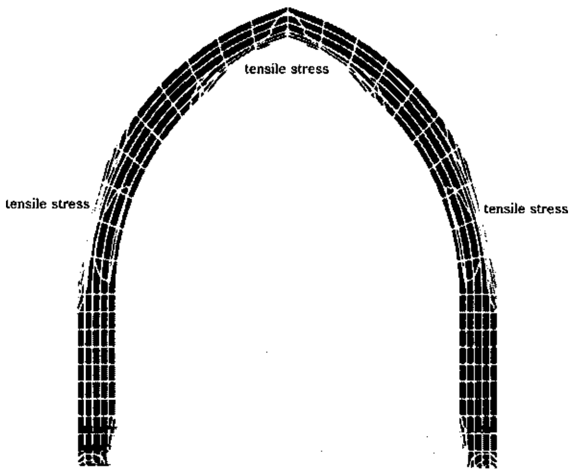



Figure 3: Three areas of critical tensile stresses in pointed arch

The common graphic output of the arches by finite element computer analysis yields three areas of critical tensile stresses [Figure 3]. Using these results, we can suggest the kinds of adjustments that need to be made in order to obtain an optimal shape for a masonry arch as follows:

*reduce the clearspan of arch*: Tensile stresses are augmented by increasing the clearspan, as indicated in figure 4. The amount of maximum principal tensile stresses dramatically increase in spans over 8 meters,

[5] 1. Sliding failure between blocks at the joints cannot occur. 2. There is no tensile strength across the joints between voussoirs. Although stone has a definite tensile strength, no tensile forces can be transmitted within a mass of masonry, because the joints may be dry or made with weak mortar. 3. Masonry has an infinite compressive strength. This assumption implies that there is no danger of crushing of the material. For more information, see Jacques Heyman, *Equilibrium of Shell Structures* (Oxford, 1977), 70; *The Masonry Arch* (New York, 1982), 28-48. Further studies for this theory, T. Boothby, "Stability of Masonry Piers and Arches," *Journal of Engineering Mechanics* 118 (1992), 367-382. Vilnay and Cheung, "Stability of Masonry Arches," *Journal of Structural Engineering* 112 (1986) 2185-2199.

indicating that some kind of structural adjustment will be needed whenever the internal space exceeds 8 meters.

*increase the arch thickness* (that is, the distance between the intrados and the extrados of the arch): As indicated by the analysis of group two arches, the greater the depth of the arch, the smaller the tensile stress effects [Figure 5]. In figure 5, even though the depth of arch was increased proportionately for the analysis, the increase in tensile stress is greater between 0.3 meters and 0.6 meters than at any other point. Therefore, if the span of arch is to exceed 8 meters, an arch greater than 0.6 meters should be used.

*use the pointed arch*: Pointed arches produce less tensile stress than semicircular arches [Figure 6]. Of the three different pointed arches formulae tested, the three pointed arch is more efficient than the others, especially when a distributed load is applied, because it is steeper than the others. A two pointed arch should be even more efficient.

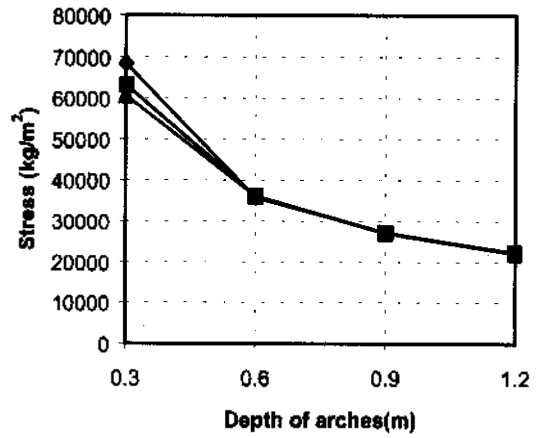



Figure 5. Comparison of the pointed arches with maximum principal tensile stresses. (arch clearspan: 8.0 m, springing: 4.0 m)

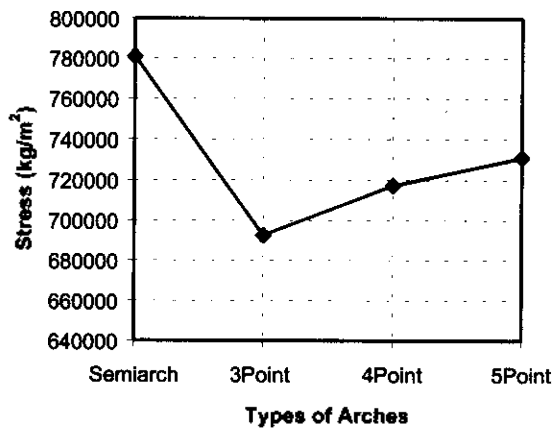
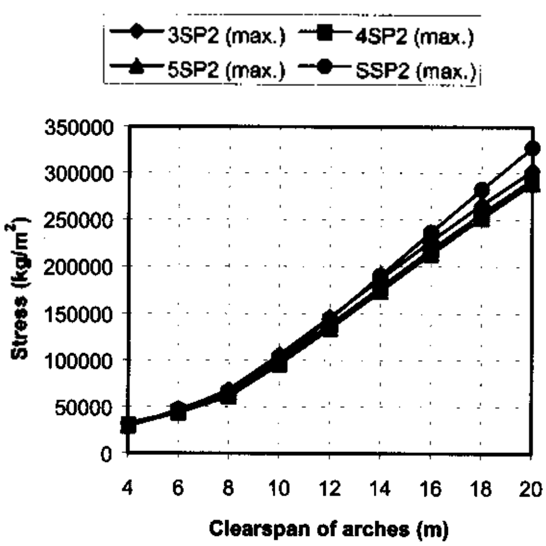



Figure 6. Comparison of arches with maximum principal tensile stresses. (arch clearspan: 8.0 m, arch depth: 0.3 m, springing: 4.0 m)




(3SP2: three pointed arch, 4SP2: four pointed arch, 5SP2: five pointed arch, and SSP2: semicircular arch)

Figure 4. Comparison of the pointed arches and semicircular arches with maximum principal tensile stresses. (arch depth: 0.3 m, springing: 4.0 m)

(2) The Diaphragm Arch

Diaphragm arches, which may be defined most simply as arches carrying masonry walls and spanning a major interior space, are the most essential and characteristic component of the non-vaulted Gothic formula in Languedoc[Figures 7,8]. In order to examine the structural behavior of diaphragm arches, eight different variants have been selected, specifically with reference to the roofline [Table 2].

A finite element computer analysis of diaphragm arches provides us with an understanding of the structural behavior of this types of arch. First, diaphragm arches have three areas of critical tensile stresses as shown in our

Figure 7. Narbonne, Notre-Dame de Lamourguier, interior nave to east

Figure 8. Narbonne, Notre-Dame de Lamourguier, interior nave to west

Table 2: Variables and constants for diaphragm arch analyses.

| Diaphragm Arches | Clearspan (m) | Springing (m) | Arch depth (m) | Wall depth (m) | Angle of Roofline |
|---|---|---|---|---|---|
| Type1 | 16 | 8 | 0.3 | 0.6 | 20° |
| Type2 | 16 | 8 | 0.3 | 0.6 | 30° |
| Type3 | 16 | 8 | 0.3 | 0.9 | 20° |
| Type4 | 16 | 8 | 0.3 | 0.9 | 30° |
| Type5 | 16 | 8 | 0.6 | 0.6 | 20° |
| Type6 | 16 | 8 | 0.6 | 0.6 | 30° |
| Type7 | 16 | 8 | 0.6 | 0.9 | 20° |
| Type8 | 16 | 8 | 0.6 | 0.9 | 30° |

arch analysis, and their maximum principal stresses are exceeded the strength of material properties of limestone. Therefore, wall buttresses must be placed in such a way as to control the stresses and to stabilize the building [Figure 9]. Second, given the same wall height and arch departure, a roof pitch of 30 degrees produces less tensile stress than a pitch of 20 degrees, because the depth of the arch at its thinnest point is greater. However, the difference in the margin of stresses is not greater, so that in fact, a 20 degree roof would be less expensive considering that the amount of material needed for its construction would be less.

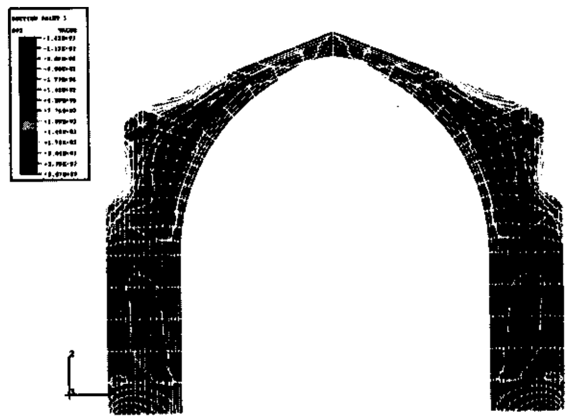


Figure 9. Principal Stresses: $SP_2$ (diaphragm arch).

## 4. CONCLUSION

Finite element analysis with a computer provides a more accurate analysis than the methods of analysis that have been heretofore applied to Gothic structures, whether it is used to analyze complex Gothic buildings like Amiens or a simpler structural system like the non vaulted Gothic buildings of Languedoc. Finite element analysis, first of simple arches provides us with a more through understanding of the stresses active within the different forms of arches used in the medieval period, and permitted us to identify changes that would provide an optimum arch configuration. Then, using our understanding of the stresses active within an arch, we added a wall to the arch to create a diaphragm arch. Analysis of the diaphragm arch supported our original assumptions that arches over 8 meters in span were more difficult to build, would require specific adjustments to the structural system (as for instance in the buttressing) and reflects a deliberate decision to build wider spaces despite the difficulties involved. This suggests that aesthetic interests were more important than structural concerns.

But these hypotheses would not have been provable without the use of finite element analysis. Finite element analysis can be applied to any type of architecture, including arcuated masonry buildings under varying conditions. Finite element analysis permits us to go beyond a limited understanding of forces and static equilibrium, and to visualize the global stress behavior of the structure. Combined with traditional methods of studying historical buildings, finite element analysis will inevitably give us a broader understanding of the processes involved in the design and construction of medieval buildings.

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