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Computer Analysis of the Church of Notre-Dame de Lamourguier

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Abstract

For more than a hundred years, art and architectural historians, architects, and engineers interested in structure have attempted to interpret Gothic architecture, one of the most technologically complex and sophisticated structural systems in history. Indigenous Gothic, however, such as non-vaulted Gothic in the Lower Languedoc region of southern France, has been largely ignored. This study intends to analyze the Gothic non-vaulted *nef unique* (aisleless) structures of Lower Languedoc which have 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 computer analysis, a selected example of an existing building. The church of Notre-Dame de Lamourguier, the earliest surviving example of a Gothic *nef unique* with wide-span diaphragm arches in Lower Languedoc, is selected. Thus, hypothetical models of diaphragm arch buildings and an existing building as a complete structural system were scientifically analyzed in order to provide a comprehensive explanation of how the non-vaulted *nef unique* system works. The result of the analysis, allows us better to understand the structural behavior of this type of masonry arcuated system and the processes involved in the design and construction of medieval buildings.

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

1. INTRODUCTION

At the end of the twelfth century, a new architectural movement began to develop rapidly in the Ile-de-France area of France. This new movement differed from its antecedents in its structural innovations as well as in its stylistic and spatial characteristics. The new movement, which came to be called Gothic, is characterized by the rib vault, the pointed arch, a complex plan, a multi-storied elevation, and the flying buttress. This new style would have a profound impact on and transform local, traditional styles throughout Western Europe.

During the thirteenth century, a separate interpretation of this movement began to develop in the Languedoc region of Southern France.[1] Gothic architecture in Languedoc was characterized most frequently by an aisleless plan, a simple paneled sanctuary, a one or two storied elevation, and chapels constructed between massive exterior wall buttresses, all of which were based on local constructional and aesthetic traditions. Languedocien builders, given the evidence of their buildings, were particularly interested in spacious, light-weight construction and a systematized skeletal framework. In this respect, it was the non-vaulted Languedocien formula, the aisleless structure with a wooden roof resting on diaphragm arches, which most completely satisfied their needs [*Figures* 1, 2].

It has been suggested that as Languedocien builders began to build wider and wider spans, certain structural adjustments had to be made in order to ensure the structural stability of their buildings. They flattened and reduced the height of the gable at its peak, which would lessen the total amount of masonry per arch and shift the concentration of masonry from the apex toward the haunches of the arch where it could act as haunch loading. Although the arch thickness did not noticeably change with wider spans, longer arches alone would have increased the amount of masonry and the load and necessitated structural compensation. Builders consistently used the pointed arch, which would cause the thrust line to fall in a more vertical, more efficient trajectory. Most important, however, the wall buttresses that were positioned in the line of the diaphragm arches were deepened in response to increase in nave width and corresponding load, and the thrust line of arch was altered whenever the springing level of the arch was raised.[2] These statements, however, have been based solely on intuition and on the evidence suggested by existing buildings. They have never been tested scientifically. In this paper, thus, a selected example of an existing building,

[1] Languedoc is divided into two regions, following the natural geographical division established by the directions in which the major rivers flow. Upper Languedoc, directed toward the West by the flow of the Garonne, finds Toulouse as its center, and comprises most of the present *départements* of Haute-Garonne, Tarn, and portions of Tarn-et-Garonne. Not surprisingly, during much of its history, Upper Languedoc was more closely aligned artistically with the lands to the West, with Gascony and Gironde, than with Lower Languedoc. Lower Languedoc faces the Mediterranean, and was thus more open to influences from that direction. In response to these geographical circumstances, two different but closely related versions of the Gothic Languedocien *nef unique* formula developed. In Upper Languedoc (or the Toulousain), the *nefs uniques* were commonly rib-vaulted. In Lower (or Mediterranean) Languedoc, rib vaulting was at first confined only to sanctuaries and to chapels between the massive exterior wall buttresses. The central space was covered by a wooden roof resting directly on gabled diaphragm arches. The development of both variants, and the shift from Romanesque to Gothic in the region, was prompted by a conflict between two opposing tendencies: an interest in vaulting and an even more basic insistence on the construction of wide spacious interiors. For more information, see V. Paul, "The *Nef unique* in the Origins and First Developments of Gothic Architecture in Languedoc," Ph.D. diss., University of California, Berkeley, (1975).

[2] V. Paul, the Beginnings of Gothic Architecture in Languedoc, *Art Bulletin*, 70, (1988): 116-117.

the church of Notre-Dame de Lamourguier, is tested in order to examine the role of structural considerations as determinants of architectural form in the non-vaulted *nef unique* with diaphragm arches. For this study, a computer modeling technique (PATRAN and ABAQUS: a general-purpose finite-element program), known as finite element analysis will be used. Not only is the overall efficiency of finite element modeling generally greater than other methods of analysis, but it provides complete information concerning the stress distribution in masonry structures.

Figure 1. Carcassonne, St. Vincent, nave to east. Many buildings including St. Vincent were covered with false rib vaults in the nineteenth century.

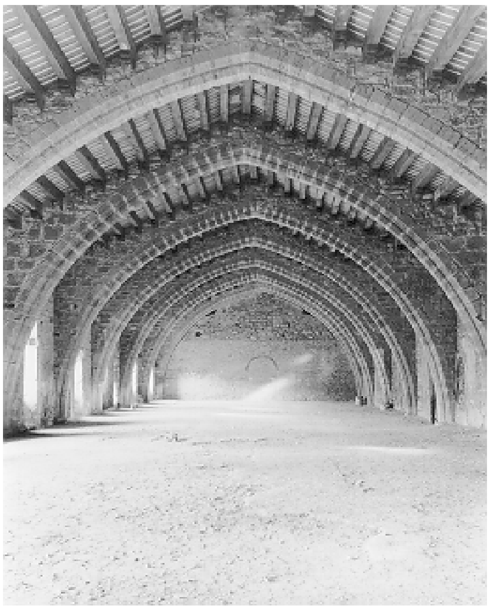

Figure 2. Lagrasse, refectory with a wooden roof resting on diaphragm arches.

2. THE CHURCH OF NOTRE DAME DE LAMOURGUIER IN NARBONNE

The nave of the church of Notre-Dame de Lamourguier in Narbonne, which dates to the first half of the thirteenth century, offers an excellent opportunity to examine the theoretical study concerning the non-vaulted Languedocien formula. First, it is the earliest surviving example of a Gothic *nef unique* with wide-span diaphragm arches in Lower Languedoc. Second, it is in relatively good condition, and the present configuration of the diaphragm arches is likely to reflect that of the thirteenth century arches quite closely. Third, it is the building for which the most accurate dimensions are available, enabling us to provide specific measurements for the analysis. Fourth, there are some specific questions concerning Lamourguier that a finite element analysis may help to answer.[3] In addition, there are two features that set Lamourguier apart from other buildings in Lower Languedoc with diaphragm arches: first, the fact that the diaphragm arches continue down the inside surface of the nave wall and second, that a passage way cuts through the arches above the level of the chapels built between the buttresses.[4]

Figure 3. Narbonne, Notre-Dame de Lamourguier, interior nave to east.

[3] There are some questions, for instance, as to the date of the existing diaphragm arches and the format of the building at the time they were built.

[4] According to V. Paul, ("The *Nef unique*"), shifts in the masonry coursing in the buttresses of Lamourguier indicate that the buttresses have clearly been strengthened, that is, they have been made deeper than they were originally. She believes that this occurred during the thirteenth century and that the diaphragm arches were rebuilt at that time. She also believes that the passageway is likely to date from that period. As to the preceding building, she suggests two possibilities: either it was thin-walled without diaphragm arches or it was thick-walled with diaphragm arches. She comes down in favor of the latter, but argues that in any case it was the combination of thin walls and wide-span diaphragm arches that necessitated the strengthening of the buttresses.

Before beginning the analysis of Lamourguier, three qualifications with reference to the building must be made. First, while Lamourguier was constructed with diaphragm arches during the thirteenth century, the existing arches may have been reconstructed at a later date. It is unlikely, however, that the basic form of the arches would have been altered, since the basic dimensions of the building were not changed. Second, the external wall of Lamourguier is pushed further toward the exterior with reference to the intrados of the arches and the half column on which they fall is the case with most diaphragm arch churches. This difference, given the basic interrelation of the parts, should not have an effect on the basic structure or the forces active within the structure, but the effect of changing the position of the wall will be tested. Third, the position of the wall at Lamourguier with reference to the arches provides sufficient space and room for the construction of a wall passage mid way in the elevation, above the vaults of the chapels. The wall passage cuts through the extension of the arches. This is unique in non-vaulted buildings with diaphragm arches, and the extent to which it affects the structure will be one of the major factors in the design of the building to be tested.

According to Bony, the wall passage has been considered one of the important characteristics of Norman and English Romanesque architecture. He showed how the passage through the thickness of a wall was first used in a restricted way in the mid-eleventh century and then spread throughout the elevations of Norman buildings during the next century, appearing in clerestories, towers, apses, west facades, and triforium.[5] When master masons decided to insert a wall passage into the clerestory of a church's elevation, they had to make both structural and formal choices involving the height and the covering of the passage, its relation to the windows in the outer wall. They also considered the type of arcade separating it from the interior of the building, and its relationship to the rest of the elevation and to the vault or roof. The resulting designs were surprisingly varied and did not follow any obvious progression toward more open or Gothic forms. [6] Thus, the wall passage in clerestory had not developed in the classic Gothic architecture in France.

Figure 4. Lessay, wall passages in clerestories.

3. COMPUTER ANALYSIS PROCEDURE OF NOTRE DAME DE LAMOURGUIER

(1) Analysis Procedure

In order to analyze the structural behavior of Lamourguier and hypothetical models, 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 5].

(2) Analysis Model

The major problem we faced when we attempted to apply finite element analysis to existing medieval buildings was a lack of documentation, including accurate measurements. Fortunately, a section [*Figure* 6] and a floor plan [*Figure* 7] of Lamourguier do exist, and from them the approximate measurements for the building can be obtained. Based on these measurements, two different groups of variables are selected to test and compare with test results from hypothetical models having different configurations [*Table* 1]. Group 1 consists of four different models (pseudo-Lamourguiers) without exterior buttresses. The first four models (diaph1, diaph2, diaph3, & diaph4 in *Table* 1) were selected for examining the variations in structural behavior in accordance with proportional

[5] J. Bony, "La technique normande du mur épais à l'époque romane," *Bmon*, XCVIII, (1939): 153-188. For Bony, the thick wall necessary to accommodate wall passages caused important structural and aesthetic changes in other parts of the elevation, and led eventually to a lightening and voiding of the wall important for the development of early Gothic architecture in the Ile-de-France. However, master masons had to face both formal and structural problems in combining the wall passage with windows in the outer plane of the wall and openings in the inner plane. They had to consider the number and size of windows, the number and size of the inner openings, the covering and height of the passage itself, the relationship of the clerestory to the rest of the elevation, and, in particular, its relationship to vaults and roof above. The solutions obviously vary from building to building. For more information, see R. Liess, *Der frühromanische Kirchenbau des 11. Jahrhunderts in der Normandie*, Munich, 1967; J. Bony, *French Gothic Architecture of the 12th & 13th Centuries*, Berkeley, (1983); P. Rolland, "La Technique normande du mur épais et l'architecture scaldienne," *Revue belge d'archeologie et d'histoire de l'art*, X, (1940).

[6] L. Hoey, "The Design of Romanesque Clerestories with Wall Passages in Normandy and England," *Gesta*, XXVIII/1,(1989): 78-101. Clearly, these first clerestory passages, built into the least important elevation in the church and articulated more plainly than the other parts of the building, were designed for purely functional and not aesthetic reasons. Of course the clerestory passage always retained its basic functional purpose of providing access to the upper windows and roof or vault. But it is unlikely that these considerations played a major role in its retention; after all, many other Romanesque clerestories (in Burgundy, for example) remained without such easy access (Ibid. 95).

increases in the thickness of the wall (0.6m each; 1.3, 1.9, 2.5, & 3.1 meters). The wall thickness in this case would include the projection formed by the diaphragm arch as it passes down the interior surface of the wall (a sort of "interior buttress"). Group 2 (diaph5 & diaph6 in *Table* 1) represents the same geometrical configuration as the existing building with and without a wall passage. The diaph6 in *Table* 1 which includes models that have the same configuration as the existing building will be used to analyze Lamourguier itself. These results will be compared with each other in order to examine the structural variations that occur in a building with and without a wall passage.

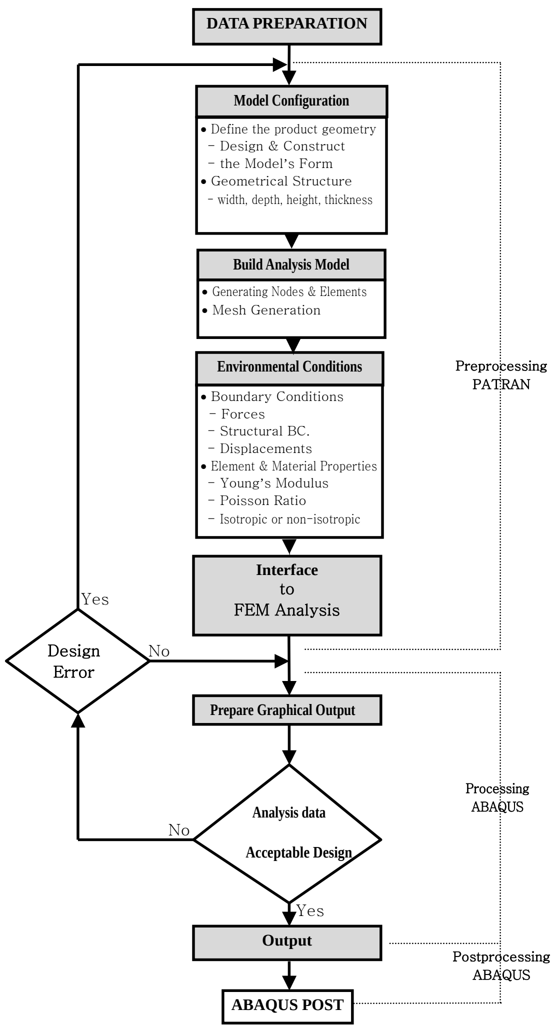

Figure 5. Outline for the finite element computer analysis procedure.

In order to analyze, Lamourguier and hypothetical models 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 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 the diaphragm arch analysis of Lamourguier.

Group	Diaphragm Arches	C (m)	AP	BT (m)	IB (m)	EB (m)	W
Lamourguier		**16.5**	**21.32°**	**1.15**	**1.3**	**2**	**yes**
Group1	Diaph1	16.5	21.32°	1.15	1.3	-	-
	Diaph2	16.5	21.32°	1.15	1.9	-	-
	Diaph3	16.5	21.32°	1.15	2.5	-	-
	Diaph4	16.5	21.32°	1.15	3.1	-	-
Group2	Diaph5	16.5	21.32°	1.15	1.3	2	-
	Diaph6	16.5	21.32°	1.15	1.3	2	yes

* C=clearspan, AP=angle of pitch, BT=buttress thickness, IB=interior buttress, EB=exterior buttress, W=wall passage.

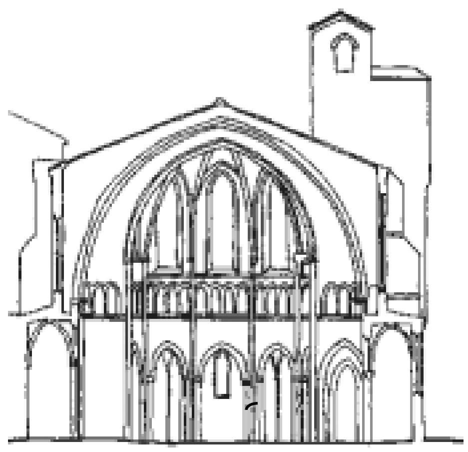

Figure 6. The section of Notre-Dame de Lamourguier, Narbonne.

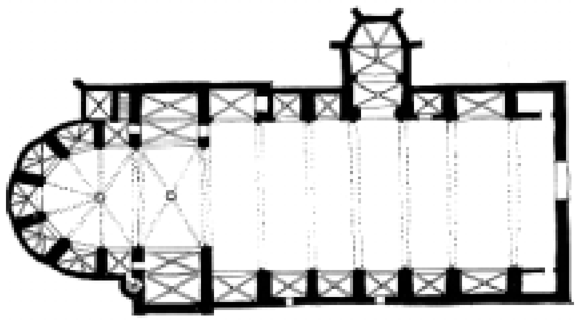

Figure 7. The plan of Notre-Dame de Lamourguier, Narbonne.

4. THE STRESS ANALYSIS OF A HYPOTHETICAL MODEL AND LAMOURGUIER

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.[7] However, if tensile stress were 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 to examine the stress behavior of the masonry structure under variable conditions.

(1) The Results of the Structural Analysis of Lamourguier

The result of a finite element stress analysis permit the following conclusions concerning the diaphragm arches at Lamourguier to be drawn:

a) First, *thick walls without exterior buttress*: Previous study suggests that the existing diaphragm arches replaced earlier arches, but that the walls of this earlier building would have been thick and would not have needed extensive exterior buttressing. In the existing nave of Lamourguier, the walls, including the interior buttress formed by the base of the diaphragm arch, are approximately two meters thick {interior buttress 1.3 m (the thickness of the wall: 0.5 m, the depth of the interior buttress: 0.8 m) and the depth of the pier: 0.7 m}. As shown in the results from the finite element analysis of diaph1, which has the same configuration as Lamourguier but without exterior buttresses, the area with the greatest magnitude of maximum principal tensile stresses is located on the flank of the wall, slightly above the point from which the arch springs (there are also tensile stresses concentrated at the apex of the arch). This suggests that the thickness of the wall should be increased in order to stabilize the building. As indicated by the analysis of the first group, in which the wall thickness was increased in increments of 0.6 meters, the greater the thickness of the wall, the smaller the magnitude of tensile stresses [*Figure* 8]. Moreover, tensile stresses concentrated at the flank of the wall disappear when the thickness of the wall reaches 2.5 meters. Thus, when there are no additional loads from the roof, the thickness of the wall buttress at Lamourguier (excluding the depth of the pier (0.7 m)) should be greater than 2.5 meters. Even though Lamourguier was assumed that the walls of the earlier building had been thick before the thirteenth century reconstruction and suggested that a roofing system in which the load was not directly transferred to the diaphragm arches might have been used, the thickness of the wall would have had to have been more than 3.2 meters (the depth of pier: 0.7 m, and the rest: 2.5 m) in order to stabilize the building.

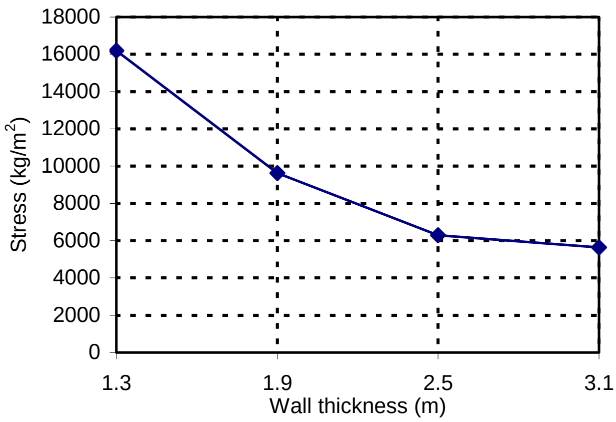

Figure 8. Comparison of the maximum principal stresses for wall thickness.

b) *The unique wall passage* cutting through the diaphragm arches at the base of the windows: Even though the intention behind the construction of the unique wall passage at Lamourguier cannot be determined, the structural rationality of its being there can be examined using structural analysis. In this study, the diaphragm arch models both with (diaph6) and without a wall passage (diaph5) were tested. As shown in *Figures* 9 & 10, the graphic contour indicating maximum principal stress is almost the same for each model, except in the area of the wall passage. In *Figure* 11, the magnitude of maximum principal tensile stress in the case of the model with the wall passage is greater than it is for the model without the wall passage.

Given these results, we can assume that it is unlikely that wide-span diaphragm arches existed at Lamourguier before the thirteenth century reconstruction. Without extensive buttressing, the building would not have been stable until the wall thickness was greater than 3.2 meters, even if there had been no applied load. If there had been diaphragm arches before the reconstruction, the clearspan of those arches would have had to have been less than that of the existing arches. For this to be true, however, one would have to presume that the earlier building had some form of internal supports and that the whole interior of the building was reconstructed in the thirteenth century. Alternatively, one would have to assume the presence of a timber truss system without diaphragm arches. Whatever the case, the construction of wide-span diaphragm arches at Lamourguier must have been part of the reconstruction of the thirteenth century. The result of the analysis also indicates that a building without a wall passage is more structurally stable than a building with a wall passage such

[7] 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 J. 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.

as that of Lamourguier and it may be that the presence of the wall passage explains the distortion in the form of the arches at the west end of the nave [*Figure* 11&12]. Problems with the arches may also be why Lower Languedocien builders did not use a wall passage in later buildings. Finally, the hypothetical model (diaph5 in *Figure* 11) that has the same configuration as Lamourguier, with the exception of the wall passage, represents the optimal solution among those models tested. It is the most structurally stable and the most efficient. In addition, the stepped *contrefort* used in some parts of the existing building is more efficient than the angled *contrefort*. [*Figure* 13] It would require less masonry and have the added aesthetic advantage of looking more stable (bigger and heavier at the bottom, smaller and lighter looking at the top).

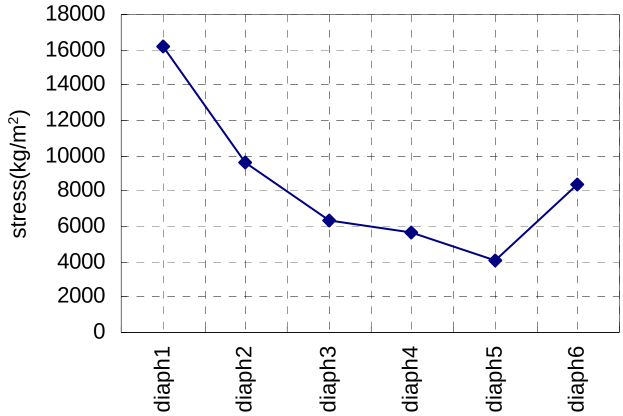

Figure 11. Comparison of the maximum principal tensile stresses for wall thickness.

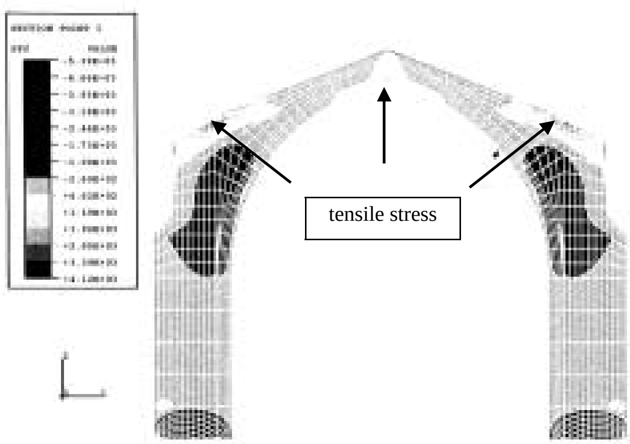

Figure 9. Principal stresses(SP_2): Lamourguier without the wall passage. (diaph5 in Table 1)

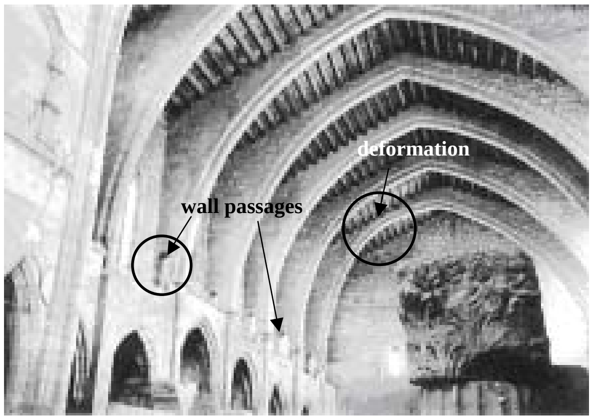

Figure 12. Narbonne, Notre-Dame de Lamourguier, interior nave to west.

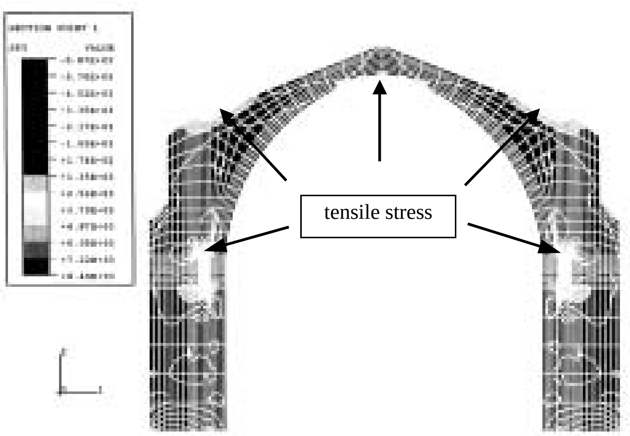

Figure 10. Principal stresses(SP_2): Lamourguier with the wall passage. (diaph6 in Table 1)

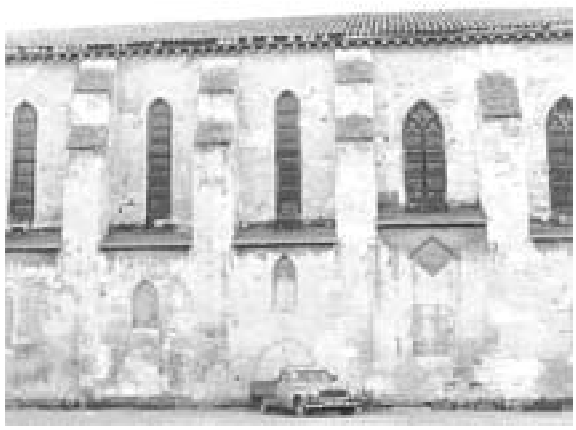

Figure 13. Narbonne, Notre-Dame de Lamourguier with stepped *contrefort*, exterior.

5. CONCLUSION

In this study, hypothetical models of diaphragm arch buildings and an existing building as a complete structural system were scientifically analyzed in order to provide a comprehensive explanation of how the non-vaulted *nef unique* system works. The result of the finite element analysis with a computer, allows us better to understand the structural behavior of this type of masonry arcuated system. In particular, two specific issues concerning Lamourguier were tested in this study: the theory that the building preceding the thirteenth century reconstruction might have had wide span diaphragm arches with thick walls, and the presence of a passage in the base of the diaphragm arches would have had any impact on the structure. As indicated by the analyses of hypothetical diaphragm arches, in order for a building the width of Lamourguier to have been constructed with thick walls without exterior buttressing, those walls would have had to be greater than 2.5 meters in depth (not including the depth of the pier), even without the addition of roof loads. Therefore we assumed that the preceding building did not have diaphragm arches because there is no evidence of the walls ever having been that thick. The result of the analysis also indicates that a building without a wall passage is more structurally stable than a building with a wall passage. Thus, the wall passage at Lamourguier is not structurally necessary. Quite the contrary, it is in fact detrimental to the stability of the structure and may have helped contribute to deformation of the arches in the west end of the nave. [*Figure* 12] This suggests that aesthetic or functional interests were more important than structural concerns, at least in the case of the passage at Lamourguier.

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