Stability and consolidation of an ashlar barrel vault with great deformations: the church of Guimarei

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Abstract

The seventeenth century ashlar vault of the church of Guimarei presents severe cracking and large deformations that caused great concern. An account is given of a report on the stability of the church previous to the restoration. The report tried to find out the causes and date of the cracking, the actual measure of the stability, and the possible means of consolidation. Of special interest is the influence of "great deformations" and particularly an upper value for the limit deformation was calculated.

1 Introduction

Santa María de Guimarei is a little parish church located around 20 km from Lugo, in Galicia (North of Spain). The church consists of a square presbytery and a single rectangular nave; the nave presents an elevated choir at the end. The presbytery was built around 1650 in late-gothic style and is covered by a light ribbed cross vault. The nave was finished in 1699 (the date of completion appeared on the straight arch before the elevated choir), and is covered by a heavy barrel vault divided in three bays by transverse arches.

The nave has caused concern since its completion. Only a year after, in 1700, the Bishop, on a travel of inspection, reported on the bad state of the nave and the necessity of calling a commission of experts to propose a subsequent consolidation: "... that the church should be consolidated... and that expert architects inspect the vault of the nave, and that repairs be made to avoid the collapse...".[1]

In 1995, some unimportant earthquakes aroused the alarm of the people who attended the church. It was said that new cracks have appeared and that the church was on the point of collapse. Religious services were interrupted and the church closed. We were requested by the Regional Government (Dirección Xeral do Patrimonio Cultural, Consellería de Cultura e Comunicación Social. Xunta de Galicia) to make a report to know the origin of the pathologies, to assess the safety of the church and to suggest, if necessary, means of consolidation.

2 Theoretical frame: limit analysis

Along the study we have made use of the ideas, principles and theorems of limit analysis of masonry structures, developed mainly by Prof. J. Heyman in the last 25 years.[2] We have supposed, then, that masonry has no tensile strength, that compressive strength is infinite (the material is rigid-unilateral) and that sliding is impossible. For such a rigid-unilateral material the three fundamental theorems of Limit Analysis could be proved.

In the context of an expertise, it is paricularly important the "lower-bound" or "safe" theorem: If we could find a trajectory of the internal forces (a thrust line or surface) in equilibrium of external loads, within the structure, then this structure is safe. The power of the theorem lies in the fact that this thrust line need not be the actual thrust line; any thrust line in equilibrium with the external loads will suffice to demonstrate that the structure is safe. Finally, the degree of safety could be measured "geometrically" from the relative distance of the thrust line to the surfaces which limit the masonry.[3]

3 Study of the pathologies

A masonry structure (made of a rigid-unilateral material) cannot deform without cracking. It is of interest to investigate what kind of movements have produced the actual pattern of cracks; in this case it should also be investigated if movements and deformations are recent or have taken place after the completion and decentering of the vaults.

In Guimarei the cracking was due to a leaning outwards of the abutment system (walls plus counterforts) of the nave. The vault adapted itself with a "classical" pattern: a crack in the crown, directed inward, and two cracks in the haunches, directed outwards (see Figs. 2 and 6).

The presbytery wall, connected to the vault, tried to impede the movement and, not being able to resist the thrust, leaned also a little; the presbytery arch shows the corresponding cracking (the neighbouring zone of the ribbed vault was also slightly affected, see Fig. 5). In what follows we will concentrate only in the nave; in the original report a similar study was made also for the presbytery wall.

From inspection of the external ashlar facing it could be deduced that the four great counterforts, **B**, that support the central zone of the nave, and other four small, **A**, at the corners, were added after the completion of the church (see Fig. 1). Effectively, the horizontal stone courses present an evident discontinuity both in counterforts **A** and **B** (see Fig. 3); besides, the stones of the great buttresses in contact with the wall are not square, but present a slanted face just to fit with the wall's inclination. Moreover, the stone courses of the four great counterforts are perfectly horizontal. The conclusion is that counterforts **A** and **B** were added as a mean of consolidation after the lateral walls were already out of plumb.

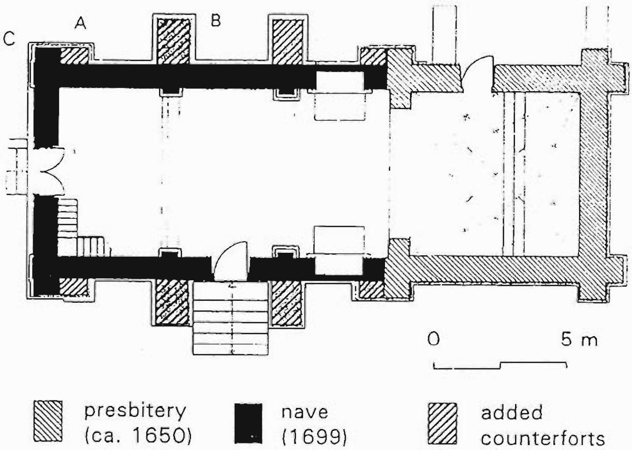


Figure 1: Plan of the church of Guimarei

Figure 2: Vault cracking

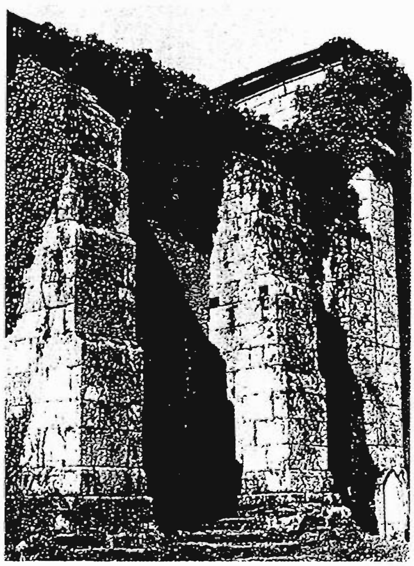


Figure 3: Added counterforts

3.1 Possible history of the damages

Most probably the original counterforts were too weak to support the thrust of the heavy barrel vault of the nave. It may be noted that the remaining original buttresses have the same dimensions as the gothic buttresses of the presbytery. Perhaps an ignorant builder wanted to continue the nave with the same buttressing of the already existing presbytery. This would not be so rare. Old masterbuilders used geometrical rules to determine the buttress for a vault of given span. Different structural types conduced to different rules, and it may be that the builder of the nave of Guimarei applied a gothic rule to a renaissance vault. In fact ribbed vaults were often constructed in Spain during the seventeenth and, even, the eighteenth century. In this long transition from one structural type to the other, many errors were committed that led sometimes to the collapse of the structure.

There exists contemporary evidence. Juan García de Berruguilla, a spanish eighteenth-century builder, commented in his treatise *On the true practice of geometry*[4] the different rules for vault abutments and stressed the contradiction between some of them. In Fig. 4 the so-called Blondel's rule, which is gothic and intended for gothic vaults, is compared with the renaissance rule of the third of the span.[5] The difference is evident and he concludes that this has led to many collapses: "Both rules are very old and the contradiction between them is before the eyes. And this is the origin of so many ruins that we are experiencing in the whole World...".[6] The drawing is explicit and, in fact, a barrel vault needs 30-40% more buttressing than a ribbed vault.

In Guimarei, it is very likely that after the decentering and subsequent settlement, the abutments would have leaned outwards, with gross deformations of the vault, the whole nave menacing collapse (maybe in this state saw the Bishop the church). The vault was shored and new buttresses added. The deformed vault was no longer semicircular; the increase of span and sagging of the crown, made the relationship height/ span of the barrel arch decrease from 0.5 to 0.43. The result is a slightly surbased vault which needs, more buttressing than the semicircular original geometry. Actually, the new buttress are 2/5 of the span instead of 1/3, 20% more; roughly an increasing proportional to the surbasement.

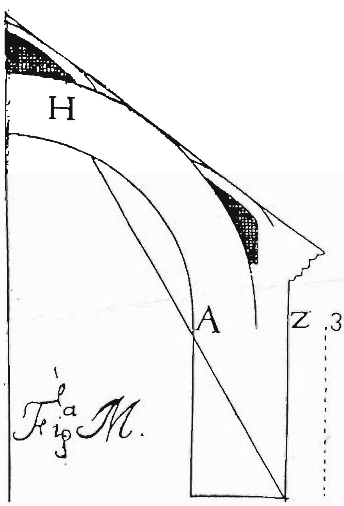


Figure 4: Comparison of structural rules: gothic" (AZ = span/4); "renaissance" (A3 = span/3)

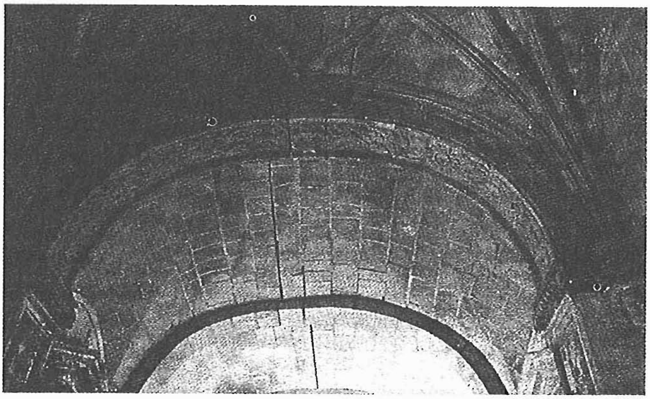


Figure 5

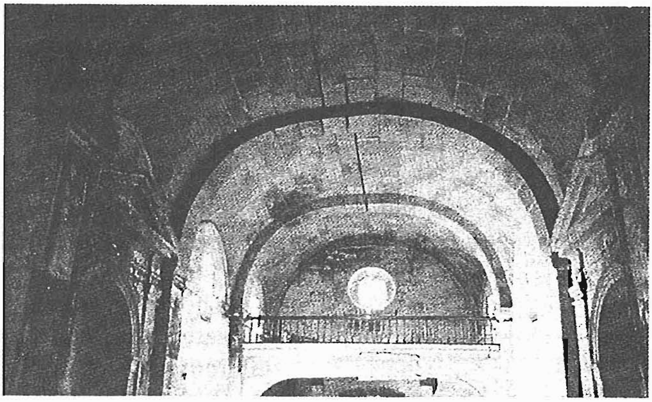


Figure 6

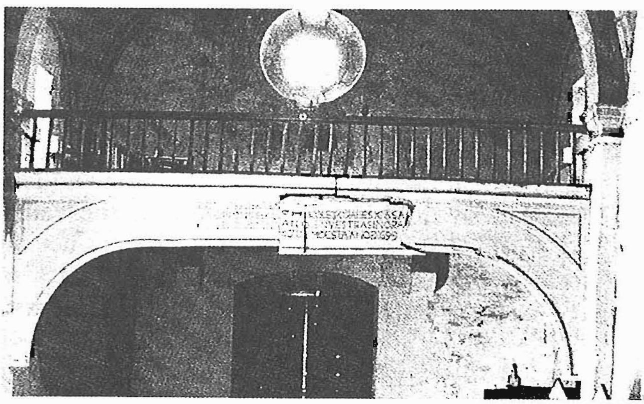


Figure 7

3.2 Cracking of the nave vault

As said before, all the damages are concentrated in the nave and in the presbytery arch, and are a consequence of the leaning of the original walls and counterforts. In Fig. 8 are represented both the original (counterforts are hypothetical) and the actual distorted geometry. Table 1 summarized the measurements made to obtain the inclination of the walls. The values of Table 2 have been calculated from Table 1 supposing rigid body movements around the hinges. Some of them were checked and showed a good agreement with the actual state.

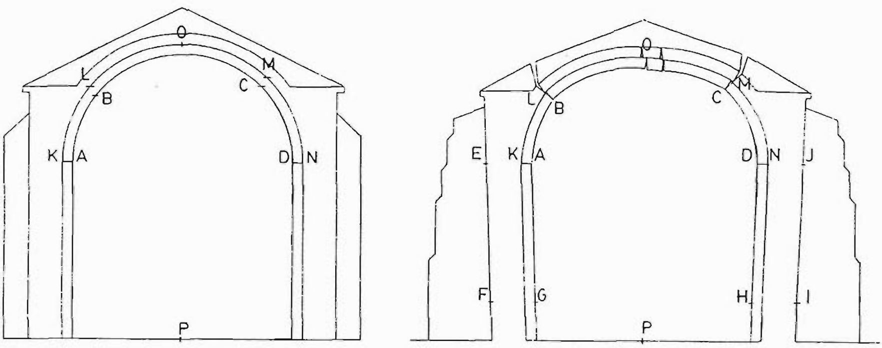


Figure 8: Original and actual deformed state (letters refer to the Tables)

		Distance (m)	Lean (m)	α (°)
walls	EF	3.77	0.135	2.05
	AG	3.77	0.095	1.45
	DH	3.77	0.100	1.52
	IJ	3.77	0.140	2.12

Table 1: Inside and outside inclination of the walls (α=inclination outwards)

		Original distance +	Increase =	Act. dist.
arch	AD	5.95	0.255	6.205
	BC	4.40	0.354	4.754
vault	KN	6.50	0.255	6.755
	LM	4.83	0.362	5.192
	OP	8.00	-0.325	7.675

T able 2. Original and actual distances (m)

It should be noted that the inclination of the walls is different inside and outside (greater). This difference of inclination have produced a separation of both faces (internal and external) of the wall, which afterwards moved independently.

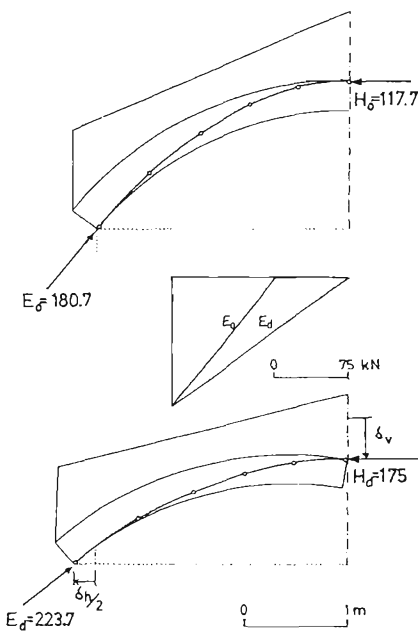
When the new counterforts were added, the deformation remained. The inside inclination governs the vault deformation. This has been verified calculating the crack width in the crown (57 mm) and comaparing this value with the actual width (55 mm).

4 Stability

Normally the deformations of a structure are so small that we suppose that the equilibrium equations before and after deformation are the same. This is not the case in Guimarei. The inclination of the walls has produced a notable distortion of the original geometry. Hence, in the analysis of the stability we had to use the actual distorted geometry. Trying to acquire more information about the possible origins of the pathologies, we have studied also the stability of the undeformed vault with the hypothetical original "gothic" buttresses.

In the analysis we have used well known thrust line techniques. Calculations were first analytically made (taking moments, etc.) and then we have used graphical statics to check the results. This graphical check was very useful; it allowed to discover some errors and, also, suggested new approximations to the problem. We have found, also, that the graphical method was sufficiently accurate in most cases.

4.1 The barrel vault



The vault is made of ashlar granite blocks. The roof consists of rafters that rest on a ridge and a wall plate. Nowadays, they rest also in the extrados of the vault. The covering is made of great slate pieces (around 0.60×0.60 m and 5 cm thick). After many years of reparations the void between the rafters and the extrados has disappeared and is full of slate fragments. Material weight of the granite was taken as 24 kN/m^3; for the roof we have taken 30% of this value, 7.2 kN/m^3.

Figure 10 summarizes the result of the calculations. Due to an increase of span at the level of the hinges of 36 cm, the crown of the vault has sagged 32 cm. Note the notable the change of direction and the increase of the thrust at the inferior hinges.

Figure 10: Thrust line in the vault: (a) undeformed geometry; (b) actual geometry

4.2 The buttress system

Precise and detailed information of the foundations would be required to make a complete study of the stability of the buttress system. In absence of a geotechnical report, we made a "guessing" of the situation. We had two indications: 1) the church is situated over a little granite hillock; some granite exposure could be seen only few meters from the church; 2) the perfect leveling of the stone courses of the great buttresses proves that no appreciate movement has taken place since its construction. Therefore, we have supposed that the church is founded on solid rock, i.e., that the foundations are rigid. We have considered the counterforts of solid granite ashlar masonry (24 kN/m^3); for the walls we have taken a reduced weigth of 19 kN/m^3.

The stability in the lowest joint of the buttress was determined. The position of the thrust in this joint will give a measure of the safety of the buttress system. As before, we have made two analysis: one for the undistorted original geometry with hypothetical "gothic" counterforts; the other for the actual distorted geometry. Figure 11 summarizes the results. The geometrical factor of safety results of dividing the total width of the joint with two times the distance of the thrust to the middle of the joint (x, in Fig. 11).[7]

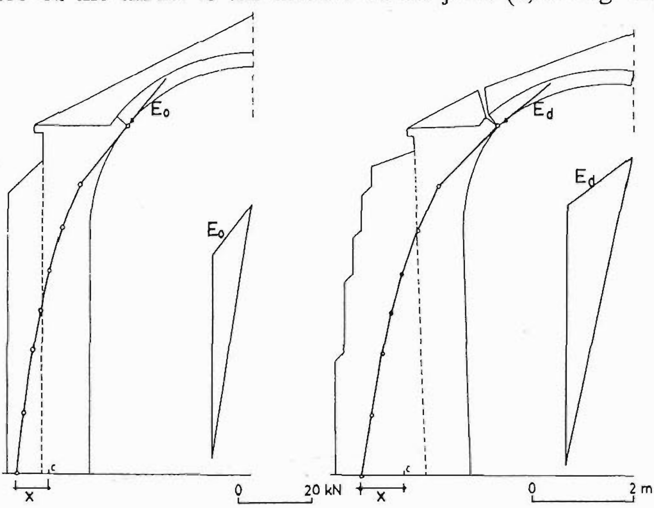


Figure 11: Stability of the abutment system: (a) undeformed geometry; (b) actual geometry

The safety factors are 1.2 for the "original" geometry and 1.58 for the actual geometry. It is evident that in the first case the stability was precarious and that a progressive inclination of the abutment system was likely to occur (indeed, that is precisely what happened).

An evaluation of the second factor is not so evident. If the counterforts were added around 1700, as points the historical evidence, it is a fact that the church has survived almost three hundred years in this situation and is therefore sufficiently safe. But if we compare this value with the factors usually considered adequate in the nineteenth century, it is very low. Rankine, for example, recommends for the buttress of buildings a geometrical factor of 3; a value of around 1.5 was only recommended for retaining walls, with no superincumbent structure affected by the deformations.[8]

4.2.1 Limit inclination of the abutments

The above considerations led us to investigate the safety in relation to the limit inclination of the abutments, that will cause the collapse of the vault. We have seen that the vault thrust grows very rapidly with the inclination of the walls (see Fig. 10 above). As the vault thrust grows the thrust position in the lowest joint of the buttresses approximates to the border. At the limit position unrestricted movement of the buttress will take place and the vault will collapse. However, the buttress itself will not collapse (being its limit inclination much greater) and will regain some verticality after the collapse of the vault. In the ruins of buildings we see often this situation: the vault has collapsed but walls and buttresses stand.

In Fig. 12 we have plotted the relative position of the thrust in the joint (the parameter d/2x is precisely the geometrical factor of safety) against a growing inclination of the buttress, α. Supposing that sliding is impossible and that the deformation is fairly symmetrical, the only unknown is the centre of rotation. We have tried both extremes of the joint and the worst situation was the centre of rotation located at the outer border (A) of the joint. (In a more detailed study intermediate points should also be checked.)

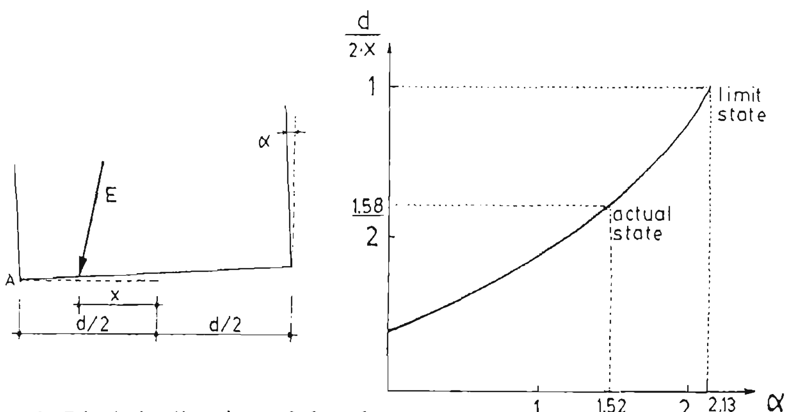


Figure 12: Limit inclination of the abutments

Dividing the limit inclination by the actual inclination we obtain a measure of the safety against inclination. The relation between thrust position and buttress inclination is non-linear and it turns out that the inclination "governs" the safety: we obtain a factor of 1.40, 15% lower than Heyman's geometrical factor.

5 Conclusion. Measures of consolidation

The defects and damages originated in an inadequate design of the original buttress. Most probably the church was consolidated just after its completion by adding new counterforts. Permanent deformations remained, but the church has survived almost three centuries in his actual distorted condition.

However, the safety factor of 1.4 in relation to new movements, appears to be a little low. It seemed prudent, then, to recommend measures that will stabilize the geometry. Therefore it was suggested to add steel ties at approximately two thirds of the vault's height, below the cracks. The analysis of the presbytery arch yielded similar values and it was also recommended to add a steel tie, this time embedded in the masonry above the keystone.

The solution of adding ties has several advantages: it is inexpensive, easy to execute, absolutely safe, reversible and, besides, it may transmit some "visual tranquility" to the brethren and visitors of the church.

The different leaning of internal and external facing of the wall suggests a crack in the wall's core; it was also recommended to make some stitching and grouting to consolidate the walls of the nave.

References

1. *Libro del año 1700, de los curas que hay en el obispado.* Lugo, Archivo del Obispado. (our translation) We thank Mr. J. M. Alonso Montero for this and other documentary information.
2. There two compilations of Prof. Heyman's writings: *Teoría, historia y restauración de estructuras de fábrica.* (Ed. by S. Huerta), Juan de Herrera/Cehopu, Madrid, 1995; *Arches, vaults and buttresses. Masonry structures and their engineering*, Variorum, Aldershot, 1996.
3. See Heyman, J. *The masonry arch*, Ellis Horwood, Chichester, 1982.
4. García Berruguilla, Juan. *Verdadera práctica de las resoluciones de la Geometría,* Madrid, 1747.
5. For a correct interpretation of this rule see, for example, Ungewitter, G. *Lehrbuch der gotischen Konstruktionen,* 3rd. ed., Leipzig, 1890, Vol. 1, pp. 273–6. For an inventary and discussion of empirical structural rules see: S. Huerta, *Diseño estructural de arcos, bóvedas y cúpulas ca. 1500- ca. 1800.* Ph. D. Diss. Universidad Politécnica de Madrid, 1990.
6. Berruguilla, op. cit. , p. 130. (our translation)
7. This is an application to buttresses of Heyman's geometrical factor for arches. Rankine used the same idea of "stability of position". See: Rankine W. J. M., *A Manual of Applied Mechanics,* London, 1858.
8. Rankine, op. cit., p. 227.