Vernacular Constructions in the Spanish Pyrenees: The deformation process of Vall d'Aran churches

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Abstract

Vall d'Aran is located on the North face of the Spanish Pyrenees. Here, we can find a set of Romanesque churches built during the 11th - 13th centuries with large deformations. Due to the isolation of the area, the construction systems of these churches are highly influenced by the vernacular knowledge of the builders.

This research examines the key measures and proportions of the main structural elements of the churches, together with their geometric deformations in relation to the construction systems used. This study is conducted with the cross sections of different churches. Several ground plans of the basilica churches were surveyed between 2014-21, using a Terrestrial Laser Scanner through diverse data campaigns, and subsequently analysed.

The paper concludes that the buildings with different construction phases and large deformations have been developed over six centuries, and have over 7% geometric deformations from their original shapes. The value of this research lies in the study of the geometric deformations of churches through statistical methods.

Keywords: Romanesque, strain vault, pillars, large deformations, Vall d'Aran

Introduction: Geographical, historical, and cultural contexts

Vall d'Aran is located on the *septentrional* gradient of the central Pyrenees, in the province of Lleida, Spain. It shares a North border with the French Department of Haute Garonne; on the South-west with the Aragonese region of Ribagorça, province of Huesca; and with the Catalan regions of Alta Ribagorça and the Pallars Jussà, province of Lleida, on the South and the East. It has an extension of 634 km² and 30% of its land is above an altitude of 2000 meters. The Garona River flows across the whole valley, arriving at the Southwest of France before plunging into the Atlantic Ocean (Fig.1). The geographic and political structure produces a unique vernacular architecture like in Xanthi, Greece (Sinamides 2017).

Fig. 1. The Aran Valley site in the mountain area of the Pyrenees
Source: Google Earth

Fig. 2. The Aran Valley and the Garonne River from the chapel of Sant Miquèu de Vilamòs.
Source: Author

However, in terms of the ecclesiastical organization, the region continued to be a part of the French diocese of *Comminges* until it disappeared. Then, it was annexed to the diocese of Urgell in 1804 to which it belongs today. Prominent ecclesiastical figures such as Bertrand de l'Isle (1083-1123) and Bertran de Gòt (1262-1314), who became Pope with the name Clement V (1305-1314) had occupied the cathedra. During this period, several churches were built, among which Josep Puig i Cadafalch (1867–1956) makes a distinction between the early architectural style inspired by foreign traditions and the later local adaptation (Fig 3).

Therefore, it has preserved a rich and varied natural and cultural heritage extremely concentrated along the 40-km-long valley. Here, 30 small villages can be found, grouped into nine municipalities located in the natural context of high landscapes. Vall d'Aran has an interesting ethnological heritage: the traditional livestock economy provides economic, social and political unity. The region also supports hydraulic flourmills, lime ovens, iron and zinc mines and, more recently, large hydroelectric projects. No less important is its cultural heritage, which is highlighted by the language, a variant of the Occitan language spoken in the Vall d' Aran, as well as a large number of feast days and traditions.

Fig. 3. Bell tower of Santa Maria de Unha
Source: Author

This article, however, focuses on Vall d'Aran's architectural heritage, which is extensive and unique. In Vall d'Aran we find an important group of more than 30 churches. Among them, they stand out as an ensemble of Romanesque churches built between the 11th and the 13th centuries. The buildings selected for the study are: Santa María de Cap d'Aràn de Tredós, Santa Eularia d'Unha, Sant Andreu de Salardú, Santa María d'Arties, Sant Félix de Vilac, Santa María de Vilamós and Era Purification de Bossost. Nowadays, most of these buildings have suffered deformations over 7% from their original shape (Fig.4).

Fig. 4. Deformations in the churches of Santa Eularia d'Unha and Santa Maria de Vilamós.
Source: Author

The remoteness of the region has led to vernacular architecture, specific to Vall d'Aran inhabitants, conditioned by the characteristics of the place. This heritage influenced the architecture of the buildings, the main characteristic of which nowadays is the deformation of their structures. (Fig.5)

The purpose of this paper is to study the constructive proportions of Vall d'Aran churches. We also quantify the geometric deformations concerning the vault construction systems they used. Finally, we value the standard vernacular model of construction and its evolution in these churches over nine centuries. Despite the constructive typology, the system of construction of the churches is not well defined, and its main characteristic is its low structural stiffness, which has caused large deformations through centuries.

Fig. 5. Large deformations in the church of Santa María d'Arties.
Source: Author

The aim of this research in understanding the structural behaviour of these churches will be to demonstrate how their geometrical and spatial form results from their structural characteristics. The study intends to demonstrate that the vernacular shape of these churches in Vall d'Aran comes from the efforts they suffer.

Review of Literature: Studies about architectural heritage in Vall d'Aran

The Romanesque churches have caught the attention of some important construction history researchers. This is the case of Emmanuel Viollet-leDuc (1814–1879), who visited Santa Maria de Bossost in 1883 and drew the apse of the church of Asuncion de Maria (Español 2013, 13–36). Later, the scientific visit of Lluís Domènech i Montaner (1850–1923) in 1905 (Granell, Ramon 2006 276-282) made people to take an interest in the Romanesque buildings of Vall d'Aran. A new historical archaeological expedition was carried out by the Catalan Institute of Studies in Vall d'Aran and Ribagorça (1907), directed by Josep Puig i Cadafalch (1867-1956). Consequently, the study named "The Romanesque churches with wooden roofs of the Valls De Bohí and Aran" (1908) has been undertaken and it established the hypothesis that the churches of Vall d'Aran were covered with wooden structures. He theorized that the wooden structures would be transformed with the construction of barrel vaults, thus conserving as supports, the initial pilasters of the circular section and non-monolithic construction. He documented the main differences between the churches of Boí and Vall d'Aran (Puig i Cadafalch 1908, 119-136) by examining this hypothesis.

The Lombard connection of Catalan Romanesque art was determined for the first time by Josep Puig i Cadafalch (1867-1956) at the Congrès Archéologique de la France in 1906 (Puig i Cadafalch 1906, 684-703). Subsequently, as a result of his brief visit to Vall d'Aran in 1908, he made his first synthesis and interpretation of the characteristics of Aranese Romanesque architecture. He also defined an initial School of Lombard tradition, which would be progressively replaced by their local identity (Puig i Cadafalch, 1909 79-86). In the 1960s, Marcel Durliat (1917-2006) identified the symbols of this identity through the sculptural elements (Durliat 1969). This gave way to the first major cataloguing in the 1970s by José Serrate Forga, who has determined a territorial classification of the Aranese Romanesque architecture, with drawings by Jesús Sarrate Boneu. Serrate classifies Romanesque architecture according to its location within the territory of the Vall d'Aran, distinguishing between Naut-Aran, Mig-Aran and Baix-Aran. This first inventory concludes with the Scheme of Aranese Romanesque Art (Serrate 1976: 54-63). Afterwards, the dissemination of the Romanesque art of the Valley has an encyclopaedic vision in the volume dedicated to the Vall d'Aran in Catalunya Romànica of 1987 (Pladevall 1987).

The construction period of these twenty-four Romanesque churches is established between the 11th century and the 13th century. In some cases, Gothic, Renaissance, Baroque and Neoclassical elements have been added later. The oldest group of these churches were built between the 11th and 12th centuries and belong to what Emmanuel Garland first (Garland 2012, 82-105) and Elisa Ros later called early Romanesque (Ros 2015, 33-64). The churches are: Santa Maria de Cap d'Aran, Sant Estèue de Tredòs, Santa Eulària d'Unha, the nave of Sant Pèir d'Escunhau, the apse and the remains of part of the walls of Santa Maria de Mijaran, Sant Joan d'Arròs, the north wall of the presbytery and the central part of the apse of Sant Ròc de Begòs, Sant Miquèu de Vilamòs, Sant Fabian d'Arres de Jos, the bell tower of Era Mair de Diu dera Purificacion de Bossòst, Sant Pèir de Betlan (Fig.6).

Fig. 6. Sample of the Early Romanesque churches of Vall d'Aran, built between 11th and 12th centuries
Source: Author

On the other hand, Juan Bassegoda Nonell (1930–2012) claimed during the presentation of the XVIII Congresso di Storia dell'Architettura, that the expressionistic aesthetic of the Lombard Romanesque architecture in Catalunya was a consequence of the formal and structural deformations of the churches (Bassegoda 1974, 33-64). He stated that the formal anomalies constitute one of the characteristics of the Romanesque architecture produced in Catalunya.

Thus, some of the churches of Vall d'Aran have different characteristics from other nearby examples, such as the constructions that can be found in the Vall de Boí. In this regard, some specific peculiarities were established as a characteristic of the geographic environment, hence the importance of the primitive churches of Vall d'Aran. The most studied church is Santa Maria de Arties. Its great formal alterations caused the appearance of funicular shapes in this vaults (Villanueva 1974, 145-158), which were already noticed and debated in the restoration undertaken in the 1970s by Joan Bassegoda i Nonell (Bassegoda 1972, 51). Finally, the main structural intervention was carried out by Joan Josep Polo i Berroy in 2009 (Polo 2009, 75-103).

The investigation presented regarding Vall d'Aran churches is based on the data obtained during the 2014–2020 surveying campaign, which was performed with a Terrestrial Laser Scanner (Leica ScanStation P20). This unprecedented topographical base, accurately registers the shapes of the buildings with great precision and in three dimensions. The common surveying procedure allows a comparative study of the Vall d'Aran churches (Fig.7).

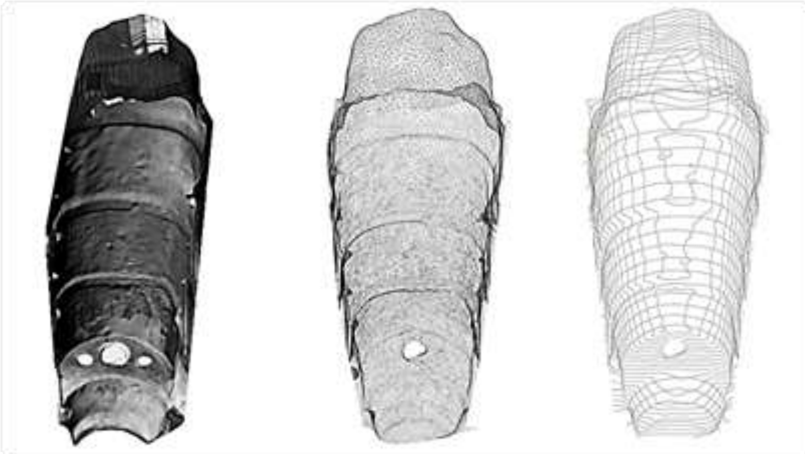


Fig. 7. Topographical study of the deformations of the vaults of the church of Santa María d'Arties.
Source: Author

Research Methodology

This research is based on a selection of the churches surveyed in the aforementioned campaigns (2014-2020). The research focuses on the study of key measures and proportions of the main structural elements to understand the different stability conditions through the dimensional relations. Initially for the study, they were selected as the main Romanesque churches in Vall d'Aran with a basilica ground plan: Santa María de Cap d'Aràn de Tredós (11th–12th c.) (Fig.8.a), Santa Eularia d'Unha (12th c.) (Fig.8.b) Sant Andreu de Salardú (13-16th c.) (Fig.7.c), Santa María d'Arties (12–13th c.) (Fig.8.d), Sant Félix de Vilac (12th–13th c.) (Fig.7.e), Santa María de Vilamós (10th–11th c.) (Fig.7.f) and Era Purification de Bossost (13th)) (Fig.8.g). While all of them have a Romanesque main body, they also have post-built elements, such as bell towers and wooden chorus. In addition, Sant Felix de Vilac and Santa María de Vilamós have extensions in the apse.

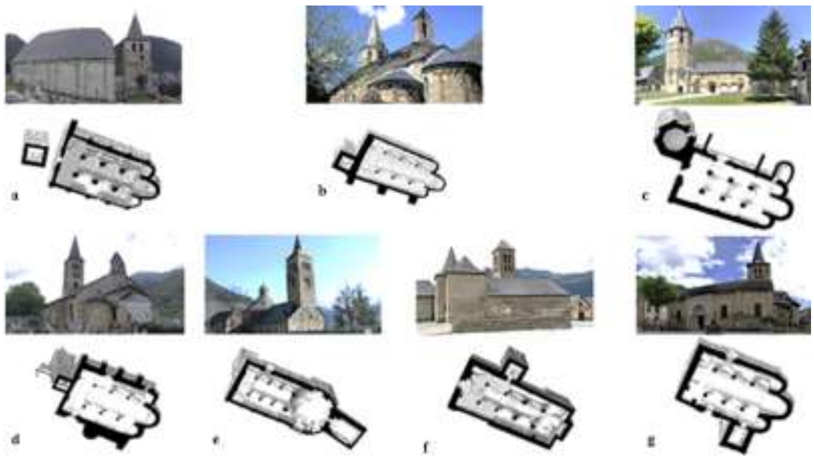


Fig. 8. Church Plan and section of studied church; a) Santa María de Cap d'Aràn de Tredós; b) Santa Eularia d'Unha; c) Sant Andreu de Salardú; d) Santa Maria d'Arties; e) Sant Félix de Vilàc; f) Santa Maria de Vilamós; g) Era Purification de Bossost.
Source: Author

The churches finally studied were Unha, Arties, Vilac, Vilamós and Bossost; the vaults in the church of Cap d'Aran de Tredós (Fig.9.a) which are not preserved, and the church of Sant Andreu de Salardú which has a central nave with gothic ribbed vaults (Fig. 9.b). The five churches have a basilica floor plan with a central vault and side aisles covered with half vaults. The exception is the church of Vilamos, where one of the side aisles is covered with a barrel vault. According to our observations, Santa Eularia d'Unha and Santa Maria d'Arties have segmental vaults, while Vilac, Vilamós and Bossost have barrel vaults.

Fig. 9. The churches: a) Santa María de Cap d'Aràn de Tredós; b) Sant Andreu de Salardú. Source: Author

The data for the study of the churches is based on the survey performed with a terrestrial laser scanner, model Leica ScanStation P20. The accuracy of the device was 3 mm at 50 m; 6 mm at 100m, with a lineal error equal to or less than 1 mm. The angular accuracy was 8" horizontal/8" vertical. The standard deviation in targets of accuracy was 2 mm at 50 m. The view rank was 360º horizontal / 270º vertical. The data was processed with the software Cyclone, which allows to set all the positions of the device in a common coordinate system, based on targets, and to generate a complete point cloud of each church.

Later, the point cloud is processed with the software 3DReshaper to generate a three-dimensional mesh. The same program is used to layout different cross sections. Thus, the dimensional study is based on an initial systematic sectioning to choose the most deformed section. A transverse section is made through every pair of pillars and another through the centre of every structural span between pillars. This procedure gave a total of 7 sections (3 sections through the pillars and 4 sections between them) from each church (Fig.10). Subsequently, the most deformed section is selected qualitatively by overlapping and comparing between all the sections. In addition, the main horizontal cross sections were defined at level zero and at the spring line.

Based on these topographical data, the typology of the vaults and the general measures and proportions are studied. It was assumed that a vault may become deformed due to the leaning of the supporting system. Thus, the out of plum of the vertical structural system is measured in the selected sections. Finally, the vault typology and the leaning of the vertical elements are discussed.

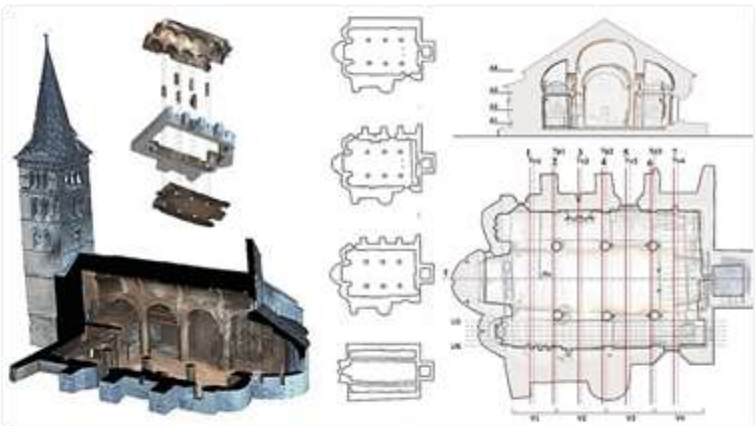


Fig. 10. Methodology for the study of deformations through sections of the church of Santa Maria d'Arties. Source: Author

Findings and the Analysis of the Typology of Vaults

The study focuses on the analysis of the central nave vaults. The vaults of Vall d'Aran churches are very deformed. Therefore, the study made some assumptions. The length of a theoretically non-deformed arch and the length of a deformed arch are the same, as long as there are no large cracks. In an ideal situation where the vault is an arch of circumference with a diameter of 1m, the proportion between the arch length (considered as half of the circumference) and diameter is equal to 1.57m. Thus, we calculated the relation between the vaults of all the churches: if the relation between the length of the cross section of the vault and the span (the diameter) is higher than 1.57, the arch is pointed. If the relation of the arch to the vault is similar to 1.57 m, the arch is a barrel vault based on a rounded arch; and if the relation between the arch and the vault is lower than 1.57m, then it is a segmental vault (Fig.11).

Fig. 11. Study of the typology of vaults. 1) Relation < 1.57; 2) Relation = 1.57; 3) Relation > 1.57.
Source: Author

The analysis of the relation between the length and the diameter is performed in the central nave vaults (Table I). According to the results, Unha and Arties have segmental vaults, while the other vaults are close to the rounded arch. These results are in conformity with the graphical study of the vaults, where in Unha and Arties, it is hardly possible to find a single arch of circumference that matches the section. In the other cases, a rounded arch allows a good approximation to the cross section of the vaults, and its centre is very close to the impost line. Bossost vaults are slightly pointed, as it can be seen also in the numerical results.

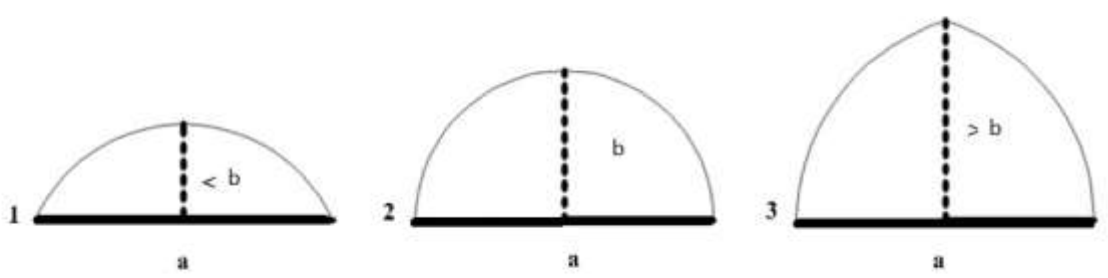
Table I: Study of vaults. Relation between cross section length and span.
Source: Author

(m)	Unha	Arties	Vilac	Vilamós	Bossost
Length	7.337	9.303	6.771	5.528	7.541
Span	4.849	6.101	4.274	3.444	4.661
Ratio	**1.512**	**1.524**	**1.584**	**1.605**	**1.617**

Another method to study the vault typology is to analyse the relation between the radius and the rise. If the church has a barrel vault, its radius is similar to the vault depth. If the church has a downloaded vault, the radius is higher than the depth; if the church has a pointed vault, the radius is less than the depth. The results of the analysis corroborate with previous conclusions (Table II).

Table II: Study of vaults. Relation between radius (a/2) and rise (b).
Source: Author

(m)	Unha	Arties	Vilac	Vilamós	Bossost
Radius	2.429	3.057	2.137	1.722	2.354
Rise	1.953	2.688	2.144	1.751	2.512
Ratio	**0.805**	**0.881**	**1.00**	**1.017**	**1.048**



Analysis of the proportion of churches

The proportions of the transversal sections of the churches of Unha, Arties, Vilac, Vilamós and Bossost (Fig.12), have a ratio, which is lower than the proportion of the equilateral triangle (0.86). The churches of Vilamós and Bossost have the same ratio (0.78), which is approximately ¾ the length of the ground plan. Arties has a similar proportion of 2/3 (0.66) of the plan (0.69), while Unha has a smaller ratio (0.58) (Table III).

Table III: General study of proportions.
Source: Author

(m)	Unha	Arties	Vilac	Vilamós	Bossost
Central height	6.041	9.356	9.18	7.428	8.425
Transverse width	10.414	13.536	11.061	9.425	10.751
Ratio	0.580	0.691	0.830	0.788	0.783

The proportion of the central nave shows that the churches of Vilamós and Vilac have a ratio that doubles the length of the floor plan. The rest of the churches of Unha, Bossost and Arties have a smaller ratio (1.247; 1.768; 1.532). The church of Unha has a proportion of 1+1/3. The church of Bossost has a proportion of 1+3/4 and the church of Arties has a proportion of 1+1/2 (Table IV).

Fig. 12. Central nave. a) Santa Maria d'Arties; b) Sant Félix de Vilàc; c) Santa Maria de Vilamós.
Source: Author

Table IV: Central space proportion study.
Source: Author

(m)	Unha	Arties	Vilac	Vilamós	Bossost
Central height	6.041	9.356	9.18	7.428	8.425
Span	4.849	6.106	4.591	3.685	4.764
Ratio	1.247	1.532	2.00	2.015	1.768

Out of plum analysis of walls and columns

The study of the leaning of the walls is done over the transversal sections. In this section, the horizontal displacement parallel to the section plane is studied (Fig. 13). Thus, it measures the position of the vertical element in the impost, related to the position at level 0 from the ground. The height of a vault is related to the height of a wall. A vault and wall must work jointly to transmit the weight. The size and shape of a vault determine the inclination of the weight vector. In that sense, the thrust of a pointed arch is lower than a segmental vault.

Fig. 13. Pillars leaning; a) Santa Maria d'Arties ; b)Sant Félix de Vilàc; c) Era Purification de Bossost.
Source: Author

The composition of the walls has not been determined; however, in the treatise of Vitruvius, the Roman wall is described through three layers, two of stone and one of timber or brick. The deformation of these three layers should be different, and therefore also the width of the walls, which was studied at the base and the height of their impost of the perimeter naves (Fig. 14).

Fig. 14. Ratio m2 masonry, mortar and density in the Aran Valley churches.
Source: Author

The right wall of the church of Arties exhibited a considerable width (0.234 m) which differs remarkably from the other cases because the exterior face moved independently from the inner face. The right wall of the church of Vilamós is the same case (0.114 m). The rest of the churches did not show any differences (between 0.017 m and 0.05 m). From those measurements, we can deduce that the interior-exterior facings are well fastened in these churches (Table V).

Table V: Wall thickness at Level 0 and at the Spring line
Source: Author

(m)	Unha	Arties	Vilac	Vilamós	Bossost
North Wall Level 0	0.947	1.862	1.784	1.444	1.302
North Wall Spring line	0.930	1.881	1.766	1.418	1.264
South Wall Level 0	0.924	4.054	1.809	1.566	1.426
South Wall Spring line	0.912	3.819	1.785	1.681	1.404

Most of the buildings show deformations in the columns and walls. Another key issue is the asymmetry of the displacements. The leaning was measured in degrees (α) from the wall or column base. Another measure was taken of the horizontal movement at the arch base (d) (Table VI).

Table VI: Leaning of walls
Source: Author

	Unha	Arties	Vilac	Vilamós	Bossost
α North Wall (º)	3.672	2.253	0.766	1.201	1.164
d North Wall (m)	0.215	0.107	0.035	0.110	0.0945
α South Wall (º)	2.350	3.553	0	0.659	2.913
d South Wall (m)	0.163	0.192	0	0.052	0.203

The width of the walls of the churches have a ratio inversely proportional to the leaning of the walls. The walls of Arties had a maximum width of 1.881m and a leaning of 0.107m in the same wall. The walls of Vilac had a width of 1.809 m and a leaning of 0.0 m; the walls of Salardú had a width of 1.564 m and a leaning of 0.044 m; the walls of Era Purification de Bossost had a maximum width of 1.426 m and a leaning of 0.203 m; the wall of Santa Maria de Vilamós had a maximum width of 1.681 m and a leaning of 0.052 m. However, the walls of Cap d'Arán de Tredós, which does not preserve its vaults, had a maximum width of 1.385 m and a leaning of 0.236 m; and the walls of Santa Eularia d'Unha had a maximum width of 0.947 m and a leaning of 0.215 m. The results showed that the North wall, South wall and inner columns all have different inclinations.

The purpose of studying the out of plumb of the columns was to understand their role in the process of deformation. The ratio between the width and the deformation was measured. It allowed us to deduce that the thickness of the columns keeps a ratio inversely proportional to the leaning—the larger the thickness, the less out of plumb it is. The pillars from Vilac are wider (1.052 m) and they had a maximum leaning of 0.080 m; the pillars of Bossost had a width of 1.045 m and a maximum leaning of 0.0 m; the pillars of Arties had a width of 0.918 m and a maximum leaning of 0.094 m while the pillars of Vilamós had a maximum width of 0.875 m and a leaning of 0.075 m. The columns of Unha had a width of 0.799 m and a leaning of 0.092. (Table VII).

Table VII: Column thickness at Level 0 and at the Spring line
Source: Author

(m)	Unha	Arties	Vilac	Vilamós	Bossost
North Column Level 0	0.799	0.905	0.947	0.815	1.007
North Column Spring line	0.777	0.937	0.906	0.837	1.045
South Column Level 0	0.753	0.740	1.052	0.825	0.971
South Column Spring line	0.744	0.918	0.966	0.875	1.092

The leaning in this case is not related to a geometric rule but rather due to material characteristics, since stereotomy of the walls is different to that of the columns. The studied church columns and walls leaning due to the effect of the vaults and the horizontal displacements are proportional to the vertical movements. The solution adopted to avoid this progression was the construction of buttresses (Fig. 15).

Fig. 15. Passive thrusts of the buttressing elements.
Source: Author

The Vall d'Aran churches employed buttresse constructions such as those found in the churches of Unha and Arties. Santa Maria de Arties has larger displacements, and the massive buttresses built have an area of 51 m². It had a leaning of over 0.148 m. Santa Eularia d'Unha had a 12.26 m² of buttress area with a leaning of 0.186 m (Table VIII).

Table VIII: Leaning of columns
Source: Author

	Unha	Arties	Vilac	Vilamós	Bossost
α North column (º)	1.286	1.711	0.359	0	0
d North column (m)	0.092	0.148	0.029	0	0
α South column (º)	2.991	1.050	0.080	0.875	1.914
d South column (m)	0.186	0.094	0.899	0.753	0.145

Discussion on the deformation and proportion of churches

When comparing the typology of the vaults with the leaning of the walls, the results show that the displacements are related to the typology of vaults (Table IX). We obtained some logical results from the ratio between the typology of vaults and the walls' horizontal deformation. The clearly lowered vaults of Unha and Arties had deformations of 0.225 m and 0.192 m respectively. The barrel vault of Vilac had a maximum deformation as little as 0.033 m. Santa Maria de Vilamós, with an adaption of the vaults to a certain height, had a horizontal deformation of 0.110 m. Era Purification de Bossost had a deformation of 0.203 m (Fig.16).

Table IX: Study of relation between vault typology and horizontal wall leaning
Source: Author

	Vault typology	**Max. Horit. leaning. (d)**
Unha	Segmental vault	0.225 (m)
Arties	Segmental vault	0.192 (m)
Vilamós	Barrel vault	0.110 (m)
Vilac	Barrel vault	0.033 (m)
Bossost	Barrel vault	0.203 (m)

Fig. 16. Church sections; a) Unha; b) Arties; c) Vilac; d) Vilamós; e) Bossost.
Source: Author

The relation between the width of the walls, the depth of the vault and the height of the vault difference is proportional. If the height of the vault difference is compared with the width of the walls and the deformation of the walls, they have an inverse proportional relation. Thus, the deformation also depended on the edge vaults. If the church had a high-height vault difference, there was less deformation, and if there was a low-height vault, there was more deformation (Table 10).

The general proportion was chosen to compare it with the maximum deformation of the transversal section. We observed that the proportion and the deformation maintained an inversely proportional relationship. It was noted that all sections studied maintained the same relation with the ground (located on an embankment). However, the church of Arties had some buttresses of a 1.719 m width in its right wall.

The central vault proportion and deformation were not related to the other data due to not having the same characteristics. The edge vault's strength spreads in one direction, while the central vault strength spreads in two opposite directions. When comparing the heights and widths of the churches with the maximum deformation, it was observed that a proportional relation exists between the width of the church and the horizontal movement.

The segmental vaults of Santa Eularia d'Unha and Santa Maria d'Arties had a wall leaning of 0.225 m and 0.192 m, respectively. The barrel vault of Sant Félix de Vilac had a maximum leaning of the wall of 0.033 m. In the case of Santa Maria de Vilamós, the adaption of the vaults to a certain height caused a horizontal displacement of 0.110 m. In the case of Era Purification de Bossost, there was a horizontal displacement of 0.203 m.

The ratio between the height and the width of the vault and the out-of-plumb maintained an inversely proportional ratio. The church of Unha maintained a very low ratio (0.58) and it is the one with the biggest deformation (0.657). Arties had an average ratio of 0.691 and a deformation of 0.541 m. Era Purification de Bossost and Santa Maria de Vilamós had a very similar ratios (0.783 and 0.788) and its deformation was also very similar (0.297 m and 0.235 m). The church of Vilac maintained a ratio close to the unity (0.83) and it was the least deformed (0.415 m). The width of the walls and columns maintained an inversely proportional ratio to the collapse of the walls (Table X).

Table X: Study of deformation-church proportion
Source: Author

	Unha	Arties	Vilac	Vilamós	Bossost
Ratio	0,580	0,691	0,83	0,788	0,783
Deformation	0,657	0,5419	0,145	0,235	0,297

Conclusions

The specific typological and formal characteristics of the constructions assessed and the little stiffness of the structural elements allowed the accommodation of the masonry through centuries, causing large deformations in some cases. The deformation rank is near 7%. Repairs to these churches have been carried out employing the concept of equilibrium, using counter-balances that produce passive thrusts, which in some cases have even produced funicular deformations in the vaults (Fig.17).

The buttressing elements added through centuries involves not only the construction of buttresses, but also massive bell towers and even wood choruses in the interiors. All these modifications, together with the large deformations have defined the current constructions, which are not the result of specific rules, related to a cultured architecture. The special characteristics of these churches has become a particular vernacular typology typical from the Vall d'Aran.

Fig. 17. Convex funicular vaults in Santa Eularia d'Unha, Santa Maria d'Arties and Era Purificacio de Bossost.
Source: Author

The extremes of these buildings are essential for the overall stability of the construction. The apses and façades with bell towers are stiffer elements and the near vaults tend to have smaller deformations. Regarding the apse, the curvature of the walls defines its stiffness, but that is not the case with the façade, where the bell towers have been built centuries later to serve as counterfort elements (Fig. 18).

Fig. 18. Bell towers of Bagergue, Salardú and Vilac
Source: author.

In future works carried out on these churches, structural characteristics must be carefully studied in order to avoid any misjudgement. Their characteristics are probably present in other vernacular buildings from other valleys in Pyrenees. All these studies help us to understand these buildings in order to assure their better use and conservation.

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