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Methodology and Evaluation of Large Deformations in Romanesque Pillars

By Josep Lluis I Ginovart, Cinta Lluis-Teruel & Mónica López-Piquer
Universitat Internacional de Catalunya

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I. Introduction

The churches of Val d'Aran are located at the Spanish Pyrenees and were built between the twelfth and thirteenth centuries. Large deformations have been found on these Romanesque buildings masonry and are one of the main characteristics of them. In the church of Santa Maria de Arties (XII-XIII), the most deformed building, some antifunicular shapes have been found at their arches and vaults (Lluis i Ginovart, et alli, 2021: 210-221). This funicular shape is the inverse of the natural shape of an arch since it is convex in relation to its centerline. The case-study of this paper focuses on the church of Santa Maria d'Arties, which is the most assessed building of the group. Its great deformations were identified during the restoration works of the 70's (Saez, 1976). Afterwards, José Luis i Villanueva noted the existence of funicular shapes (Villanueva, 1974) and, in 2009, the structure was studied by means of finite elements method (FEM) by the team of Joan Polo i Berroy (Polo, 2009).

The deformation presents a typical pattern leaning vertical elements towards the outside because of vaults thrust and settlement, which is the cause of the apparition of funicular shapes. One of the apparition of funicular shapes. One of the reasons of these deformations in Santa Eularia d'Unha, Santa Maria d'Arties and Era Purificacio de Bossost is the displacement of the pillars since they are the least rigid elements of the structure (figure 1).

The study of the deformation of the walls and the pillars was done through the transversal sections where the deformations parallel to the plane was analyzed. For this, it was necessary to measure the vertical deformation of walls and columns, as a vault and wall must work jointly to transmit the weight. The investigation focuses on the geometrical parametrization and on the evaluation of these movements. Previous investigations set the assessment of the overall structure to understand the stability conditions, revealing that masonry was working to its limit, with the maximum status of deformation, and this plus the displacements had their origin in the rigidity of the structure.

The assessment was based on a three-dimensional model obtained with a terrestrial laser scanner (TLS). Direct measurement techniques for architectural heritage surveying requires many resources and the use of massive data capture by terrestrial laser scanner (TLS) has recently become prominent. On the other hand, topographic documentation of the heritage is a keytool for its preservation. Current techniques of massive data capture (MDC), such as digital photogrammetry and terrestrial laser scanner, have become widespread and numerous investigations have tested their reliability proving their effectiveness to survey the building's geometry with high precision. Point clouds make it possible to detect and track degradation processes and formal anomalies. Other applications go from heritage documentation to delve in the history of buildings constructions (Dhonju,"et alli", 2017). The specific issue of deformation assessment is essential for architectural heritage conservation. Many studies have developed simple procedures to address the issue from the 3D topographical information of the point clouds, e.g., the Cathedral of St. Johannis in Meldorf (Sternberg, 2012), the Cathedral of Tortosa (Lluis i Ginovart, "et alli", 2016; 42-50), the churches of Santa Maria in Portonovo (Quagliarini "et alli", 2016).

Author α: Dean of School of Architecture Barcelona, Universitat Internacional de Catalunya. e-mail: jlluis@uic.es
Author σ: Associate professor and PhD Candidate at Universitat Internacional de Catalunya. e-mail: cintalluis@uic.es
Author ρ: PhD Candidate at Universitat Internacional de Catalunya. e-mail: mlopezp@uic.es

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Fig. 1: Deformation of the pillars: Santa Eularia d'Unha, Santa Maria d'Arties and Era Purificacio de Bossost

To analyze the deformations of the church of Santa Maria d'Arties (XII-XIII), we used the point cloud extract from the scanner Leica ScanStation P20, with a bandwidth of 808/658, class 1. The point cloud was processed with the software Cyclone and the program 3DReshaper version 2016, used to obtain the three-dimensional mesh with an average distance of points of 0.05 m as well as a measure of the triangle for detecting 0.1m holes. The model of the interior of the building has 80.582 points and 156.449 triangles, and the exterior has 314.650 points and 609.472 triangles (figure2a).

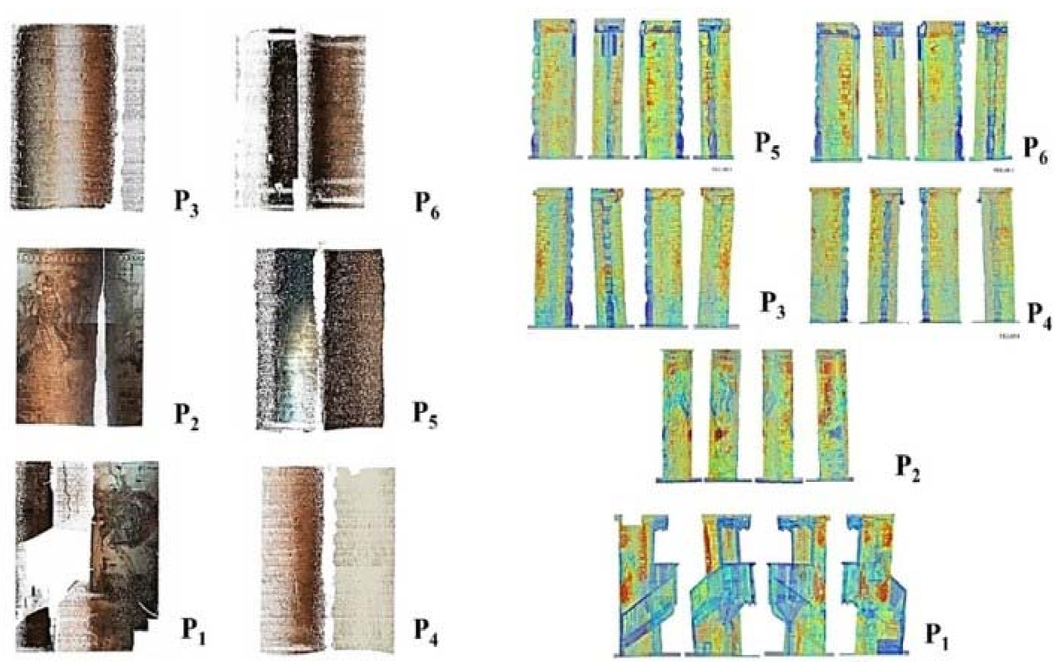

Fig. 2: Visualization of Santa María's pillars: a) Software Cyclone; b) Software Undet

The point cloud has been processed with the plugin Undet, of the software Google SketchUp version 2019. Nevertheless, in this occasion, the point cloud was not converted to a mesh because this plugin works with points, not with meshes. The models have a grid of points in coordinates (x, y, z) ranging from 0,06 to 0.09 m. (figure 2.b).

II. Methodology of the Geometrical Assessment of Pillars

The methodology of this study focuses on the assessment of the geometrical characteristics of the six pillars [P1…P6] of Santa Maria d'Arties with the objective of studying the displacements that they have suffered (figure 3). The pillars of the central nave have deformed in a specific way, namely, through the masonry joints (ns). These joints are perfectly visible on pillars P3, P4, P5 and P6, while they are more difficult to visualize on P1 and P2 since they are partially covered by mural paintings. The displacement of a particle in Cartesian coordinates (x, y, z) with its corresponding orthonormal base ($\hat{e}_1$, $\hat{e}_2$, $\hat{e}_3$) starts from a reference configuration Ω_0, where the position vector (X) of a particle G (corresponding to the center of gravity) in space is defined by the material coordinates; $X = X_1 \hat{e}_1 + X_2 \hat{e}_2 + X_3 \hat{e}_3 = X_i \hat{e}_i$; ($x_1$, x_2, x_3). When moving to the current configuration Ω_t, occupying spatial point G', the position vector (x) in spatial coordinates at a snapshot of time (t) will be given by $X' = X'_1 \hat{e}_1 + X'_2 \hat{e}_2 + X'_3 \hat{e}_3 = X_i \hat{e}_i$; ($x_1$, x_2, x_3). This change in position is represented by a displacement vector, $u_G = (u_{Gx}, u_{Gy}, u_{Gz})$ (figure 4).

The displacements can be assessed according to the coordinates of the centroid of each row (x_{ci}, y_{ci}, z_{ci}), and the point of reference is taken from the row of the floor plan, which is believed that it is nondeformable. This establishes the coordinates as (x_{ci}, y_{ci}, 0). These points allow defining a regression plane P_{ri} for each pillar. Thus, it is possible to define a vector of deformation contained on each plane [Pr1…Pr6]. Finally, this data allows to determine the general tendency of vaults' deformations (figure 5).

Fig. 3: Geometrical characteristics of the 6 pillars [P1…P6] of Santa Maria d'Arties

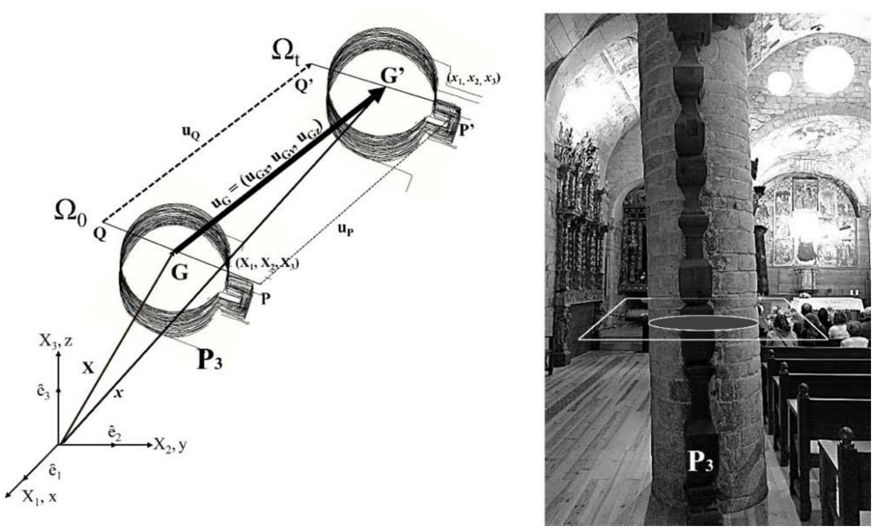

Fig. 4: Displacement of the center of gravity in the section of the pillar P3 of Santa Maria d'Arties

Fig. 5: Above is the example of single column image. Images must be of very high quality

The assessment of shapes can only be understood in three dimensions through an interval (a, b) which must impose the condition of equilibrium according to the elastic theory and the summation of the active thrusts (E_{ba}) of the vaults and the passive thrusts of the walls (Emp) and buttresses (E_{mc}) [1].

$$\sum_{b}^{a} F_{(x,y,z)}\left(E_{ba}+E_{mp}+E_{mc}\right)=0$$

$$\sum_{b}^{a} M_{(x,y,z)}\left(E_{ba}+E_{mp}+E_{mc}\right)=0. \qquad [1]$$

The forces caused by the vaults are transmitted to the vertical structural elements. The vaults of the central nave are supported by the walls over former arches which, at the same time, are supported by the pillars of the central nave. Thus, the elements can deform over the three planes, the pillars dfp (dfpx, dfpy, dfpz), and the perimeter walls dfm (dfmx, dfmy, dfmz). On the other hand, the deformations of the pillars are a function of their monolithic nature. Therefore, the deformations are directly related to the stone cutting of the pillar and the thrust Ep (Epx, Epy, Epz). According to the internal distribution of forces, the masonry stone cutting, the mortar (Epz1) and the irregular geometry of the vault (Epz2), the structure tends towards a state of equilibrium (Epz1- Epz2) or to the opposite state (Epz1+Epz2).

A monolithic, infinitely rigid pillar tends to rotate on its base. The upper part moves over the axis (x) towards the exterior, since the main horizontal thrust (Ex), with the consequence that there is also movement in the axis (y) since their extreme upper part declines. Finally, there is also movement over axis (z), due to Ebz, which defines the deformations dfp (dfpx, dfpy, dfpz).

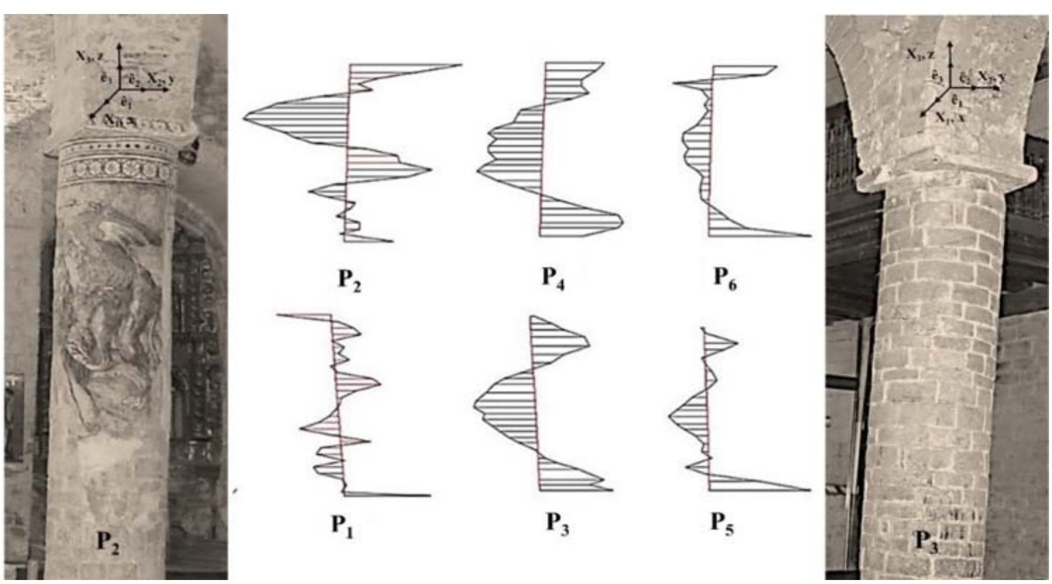

Fig. 6: Representation of displacements on the regression planes Pri over (y)

Pillars are not monolithic and are built with numerous joints, they tend to deform in the upper part so that there is no Δ dfpy. If we suppose that the extremes of the vaults have not suffered differential settlements and that the movement of these extremes is, thus, (Δz=0), then the deformations are dfp (dfpx, 0, dfpz) which is the hypothesis of the present case study. There can be a combination of rotations and translations, as a function of the stone cutting, so the general characterization of the displacements should be made through intervals I1; dfp (dfpx, dfpy, dfpz). Then, in I2, dfp (dfpx,0, dfpz) displacements (Δy>0) can occur because of the contact between mortar and stones or due to the friction between stones where there is no more mortar. The displacement of the pillar can be deduced through analysis of the displacement of the centroid of n sections (ns) of the pillar. Thus, coordinates (xci, yci, zci) are set for each section (ns). The centroid of reference (xc0, yc0, zc0) is set in the section of the floor plan since it would have not suffered any displacement (figure 6).

The reparation and containment of these deformations are the cause of the reinforcement of the perimeter walls by means of the construction of buttresses or strategical placement of bell towers, which are usually built in the opposite façade to the apse. The active thrusts (Eba) of the vaults over pillars and walls have been determined, but to understand the equilibrium of these constructions, it is essential to understand the passive thrusts of the buttressing elements, walls (Emp) and buttresses (Emc). Due to these thrusts, some vaults have deformed towards funicular shapes (figure 7).

Fig. 6: Passive thrusts of the buttressing elements, walls (Emp) and buttresses (Emc)

III. Data Treatment with the Software Cyclone

The use of the specific software Cyclone to process the data enables to visualize the obtained point-cloud and to process and join all the scanners done to convert the point-clouds to a mesh. This processing occurs through an automatic process with slight manual adjustments, so a complete-depurated point cloud and a triangular mesh are obtained.

The morphological features assessment of the pillars is made through the visible elements, such as the masonry joints. Non-visible elements are not considered. Thus, data is obtained according to the centroids of each visible row. Thus, pillars have following rows: (P1 =26), (P2=26), (P3= 27), (P4= 25), (P5= 23) and (P6= 23). Rows are numbered from bottom to top the identification of pillars' joints was made by means of a manual measurement system because the graphical capacity of the software Cyclone and the program 3DResheaper do not allow to specify pillar's joints because it constructs them three-dimensionally (Lluis I Ginovart, "et alli", 2017).

The greatest displacement is found in pillar P1, with a range of displacement on each row of [0.270, 0.001]. This displacement is followed by that in pillar P3, with a range of [0.190 – 0.001]. The range of displacements of the rest of the pillars is as follows: P2 [0.108 – 0.002], P4 [0.109 – 0.002], P5 [0.101 – 0.001], and, finally, the least deformed pillar, P6 [0.065 – 0.001].

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Thus, pillars P1, P3 and P5 have greater deformations than the others. None of the regression planes Pri is perpendicular to the axis of the central vault. Each one is moderately sloped. The angle in P1 is 85.466º, so (ω φ) < 90º). It is also the most inclined pillar (0.270 m) and is the highest (4.170 m). The rest of the pillars have angles (ω φ) > 90º with a range [103.893º - 126.169º]; [P2; 103.893º], [P3; 108.,665º], [P4; 117.245º], [P5; 112.066º] and [P6; 126.169º] (figure 8).

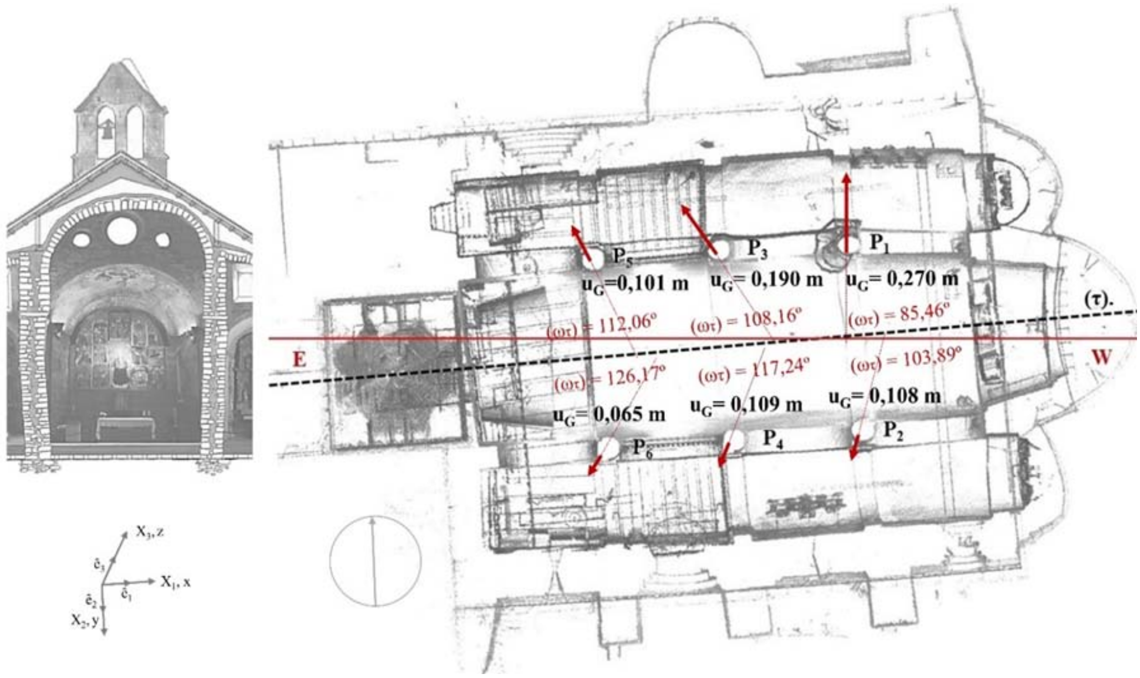

Fig. 8: Characterization of the regression planes Pri from Cyclone (2016)

IV. Data Treatment with the Plugin Undet for Google Sketchup

Using the plugin Undet for Google SketchUp 2019, the identification of pillar's joints was made directly with the image of the software. Undet is a plugin that combines individual scan stations into groups and point-clouds from a wide range of scanners. In this case, we have used the data extracted from the Massive Data Capture (MDC) of the Leica ScanStation P20 scanner. What we have experienced with this plugin is that the management of the point-clouds is more efficient and quicker than with the software Cyclone.

Undet for SketchUp 2019 has interactive coloring and density management so it let us to adjust transparency, change point-cloud and points size and, the most important thing for our research, we can see the point cloud colored by planes or heights. This function lets us see pillar's joints in detail so, from now on, we will be able to check the manual measurement previously done and to express that the joints measured with Undet range from 0.007 m to 0.015 m of width. We have also analyzed the regression planes Pri from the pillars, which, like the previous results obtained from the software Cyclone, are also non-perpendicular to the axis of the central vault.

We observed that there are little differences between the other results and these ones, being the deformation of P2 the biggest difference (2.599º less) and the one of P3 the smallest (0.003º less). The angle in P1 is 85.474º, so (ω φ) < 90º, and it is also the most inclined pillar (0.206 m). The rest of the pillars have angles (ω φ) > 90º, as we have previously seen, with a range [101.291º - 124.756º]: [P2: 103,893º], [P3: 108.657º], [P4: 119.417º], [P5: 124.756º] and [P6: 110.553º] (figure 9).

We have also seen that the deformations of P4 and P5 are bigger in the middle of pillars height than at the top of it. With Cyclone we did not find those deformations. The obtained results from both methods used are very similar to determine deformations in Romanesque masonry buildings, where the interest of the displacements is more qualitative than a quantitative order of magnitude. The graphic precision of the plugin Undet for Google SketchUp 2019 should be noticed, since it is higher and, therefore, allows the identification of the masonry joints of the pillars that each point composing the point-cloud extracts from the Terrestrial Laser Scanner (TLS). To work with this plugin, there is no need to have a computer with a lot of graphic capacity, and the point-cloud can be sectioned in few seconds. Regarding to its precision, in a section of 0.005 m, the error is about 0.006 m (0.030%), unlike the one obtained from the software Cyclone (2016), which was 0.03m.

Otherwise, the vectorization of the displacements of each row, deduced from the regression plane, makes it possible to parametrize the leaning of each pillar. In addition, two deformation modes were identified, so the displacements of the pillars are not uniform. Moreover, on pillars (P2, P3, P5), the displacements are variable and appear to be negative displacements on (y) in relation to the vertical, and the deformation of pillars (P1, P5, P6) is biggest in the middle of their height than in their extremes.

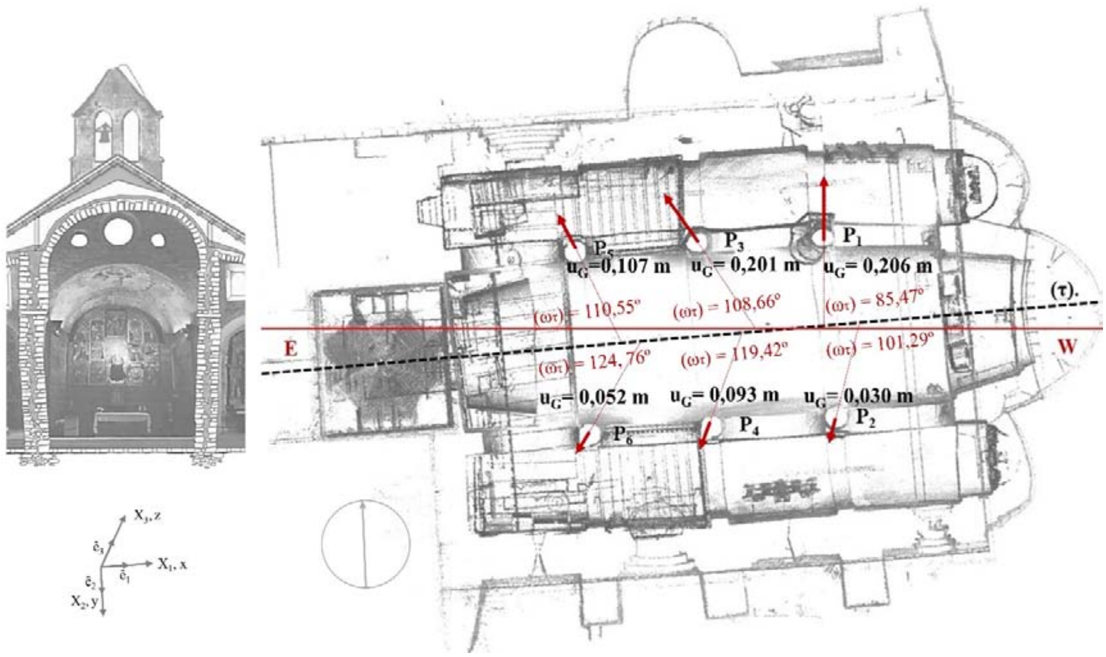

Fig. 9: Characterization of the regression planes Pri from the plugin Undet

V. Conclusions

The obtained regression planes Pri, which contain the deformations dfp (dfpx, dfpy, dfpz) for each pillar, tend to have the direction of the thrust over the pillar Pi. These displacements are the result of the active thrusts of vaults 〖(E〗 _ba) and the passive thrusts of the buttressing system, walls 〖(E〗 _mp) and buttresses (E〗 _mc). This study revealed that the direction of the displacements of the six pillars Pi is not perpendicular to the central axis of the church φ1, since (ω φ) ≠ 90º. This result proves the hypothesis that the thrusts of the vaults are not perpendicular to the axis of the church, as was the case of Roman vaults, which Choisy (1873) [27] defined with regular geometry and stone cutting. The direction of displacements is caused by the irregular geometry of the vaults of Santa Maria d'Arties as well as the masonry stone cutting and the above-mentioned passive thrusts of the walls and buttresses. The last ones were placed to maintain equilibrium during the last millennium (figure 10).

The displacement of the five pillars (P2…P5), where (ω φ) > 90º, tends to the opposite façade of the apse. In addition, pillars P5 and P6, built during the twelfth century on that façade, are the least deformed pillars because of two subsequent transformations: the construction of the bell tower over the center of the façade (XIII-XIV) and the wood choir (XVIII). These elements have a stiffening function. Pillar P1 is the most deformed of Santa Maria d'Arties and has (ω φ) < 90º over the main axis. The displacement tends to the apse. This pillar, together with pillar P3, where (ω φ) > 90º, have achieved a great balancing through the passive thrust of the walls (Emp) and buttresses (Emc). For a specific weight of more than 24 kN/m3, the buttressing system weights 3144,96 kN. It is here where funicular shapes and inverted arches have appeared, therefore: ff''(x) > 0. Pillars deformations dfp (dfpx, dfpy, dfpz) tend to have the same direction of the thrust over pillars Pi, so regression planes Pri, which contain these deformations, are essential to define any intervention over these masonry buildings because they show the direction for possible preventive actions. The ranges of heights where great deformations occur have also been identified and are: P1; [1.50 – 2.00 m], P2; [3.00 – 3.50 m], P3; [2.00 – 3.00 m], P4; [1.50 – 2.50 m], P5; [2.00 – 3.00 m] and P6; [1.00 – 2.50 m]. There is a difference between the height of the base pillars too due to the inclination of the church floor, being P1 and P2 of the same height from their base center, and P3 of the same height of P4, but beginning 0.047 m upper than P1 and P2, and, finally, P5 is 0.0577 m upper than P1 and 0.019 lower than P6. These points are extremely important to determine the appropriate actions that need to be taken for intervention on these buildings to preserve the Romanesque architectural heritage.

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Fig. 10: Vectorization of the displacements of each row from the regression plane

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