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CONTACT

Luis Palmero Iglesias
Phone: +34 963879451
Fax: +34 963879129
Email: lpalmero@csa.upv.es

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Evaluation of the Structural Stability of an Octagonal Dome with Meridional Cracks. Case Study: Temple of Santa Lucia, Ambalema, Colombia

Jorge Olmedo Montoya[1] , Olimpia Niglio[2], Karol Brigith Romero[1]

[1] *Universidad de Ibagué, Colombia*
[2] *Pontificia Università Teologica Marianum, ISSR, Varicano*

ABSTRACT

This work performed a comparative analysis between the construction process carried out when building the dome at the Temple of Santa Lucía, in Ambalema-Colombia and the typical process of an octagonal dome. Additionally, the structural stability of the dome is assessed in the case studyagainst service and dynamic loads. To compare with the case study, known domes were taken as examples from structures in Italy and Spain. The analysis includes a study on the dome's geometry and the constructive errors found. Methodology: The dome's stability was evaluated through structural analysis software for which the dome was simplified into a system of four articulated arches. Conclusions: As a result, it was found that the dome of the temple of Santa Lucía does not have a system to counteract lateral thrusts (a drum or its equivalent), which permitted the appearance and widening of meridional cracks. These cracks propagate from the base to the crown, but do not compromise the structure's stability for service loads. The analysis for seismic loads indicates that the dome is at risk of collapse upon seismic events, even of moderate magnitudes. Originality: The study is aimed at architects and engineers interested in the theme of restoration of historical structures.

KEYWORDS

Ambalema, Colombia, Temple of Santa Lucía, Dome, Historical Heritage, Structural Stability

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1. INTRODUCTION

Masonry structures (i.e., set of lime material with stone, brick, or adobe) emerge with the birth of civilization upon the desire for such constructions to withstand the passage of time. Constructions formerly consisted in supporting tree trunks on stone walls; however, the need to cover all the spaces with masonry led to the birth of the arch, which was invented in Mesopotamia or Egypt some 6,000 years ago, with it being a natural technique to bridge openings (Huerta, 2004). Arches are composed of equal, wedge-shaped keystones constructed over auxiliary scaffolding (Heyman, 1999, p. 39). It must be guaranteed that each keystone thrusts its adjacent keystones in such a way that thrusts counteract each other. Besides, the elements of the springers must be supported on abutments that resist the thrust transmitted by the keystones (Huerta, 2004). All the aforementioned with the purpose of each of the arch's keystones to work in compressive manner (Figure 1). From arches we get the creation of domes, which are differentiated by having lower thicknesses, supported on a drum in charge of restricting the displacements of each element. In addition, domes top off in lantern towers, in charge of generating stability to the structure, guaranteeing work under compressive stress.

Domes are vaults, which when divided into meridians behave as funicular arches, hence, resistant to load systems without developing bending tensions under certain levels of magnitudes.

The domes have parallels that restrict their lateral displacement, developing tensions in rings that permit membrane behavior (Ignacio Requena Ruiz, n.d.). The forces on rings that restrict movement of the wedges out of the plane are compressive in the upper zone and tension in the lower zone. The transition from the compression zone to the tension zone occurs between 45 and 60 degrees with respect to the dome's vertical axis (Pavlovic, Reccia, & Cecchi, n.d.) (Figure 2). Tensions in the lower part are not present in atypical cases of domes with flat crown and heavy lantern tower and the effect of the ring forces is more pronounced in a dome's upper region, where the circular compression rings tend to maintain equilibrium (Hall, Lindsay, & Krayenhoff, 2012).

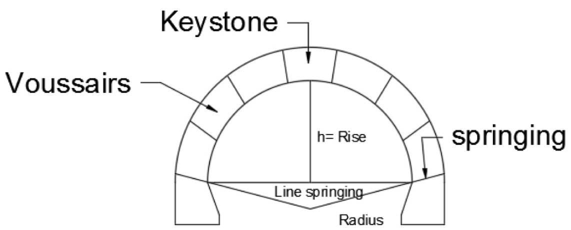

Figure 1.

Parts of an arch
Source: by the authors

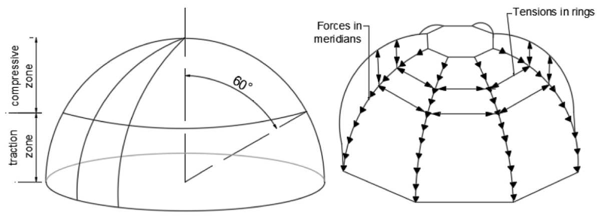

Figure 2.

Forces and stress upon the domes.
Source: by the authors

Investigations of different ancient contructions around the world evidence typical components of octagonal and circular domes. In Spain, the Ermitorio de San Marcos and the Church Arciprestal San Jaime show important characteristics to highlight like, for example, the elevation of the central dome over a drum that counteracts thrusts in both constructions. The outer plant in both domes is octagonal and the outer sheet is consistent with a cambered geometry of two partitioned leafs. The Ermitorio de San Marcos has an eight-arch supplement of variable width that converge by forming an upper crown, unlike the Church Arciprestal San Jaime, which has eight ribs formed by aristas coinciding with the diagonals from the drum (Soler-Verdú & Soler-Estrela, 2015). In Italy, the santuary Basílica de la Virgen de la Humanidad and the cathedral of Florence have octagonal masonry domes with ring and rib system, light lantern towers, and large drums (Foraboschi, 2014). Regarding the circular domes, the domes of the 35 temples of the province of Alicant (Spain) are characterized for being 97.37% of circular plant because they are easier to construct and geometrically the center of the supports coincides with that of the springer circumference of the domes, all are supported on drums or rings that comply with the minimum height and thickness parameters proposed by García (Pérez-Sánchez & Pie de Causa-García, 2015). These drums are in charge of counteracting the thrust produced by the domes (Gema López Manzanares, n.d.). The way to counteract thrusts in the absence of a drum is through the construction of adjacent vaults (López Mozo, 2013).

The domes of the ancient structures referenced all have a drum and lantern tower, indicating that these elements play a fundamental role in contributing to stability. The structural labor of the drum, besides counteracting thrusts, is to keep the dome from presenting a rotation mechanism. Drums require adequate thickness to fulfill their structural function. Mostly, these must be of considerable thickness and if not so, they need circumferential reinforcement elements. The lantern tower, on its part, is a joint mechanism that belongs to the load resistance system. The heavier the lantern tower is, greater force will be exerted by the drum. Hence, to prevent its aperture the drum must be thick (Foraboschi, 2014).

The shape of the domes determines the conditions of equilibrium. These conditions stem from the hypothesis of absence of friction between the keystones to guarantee that the trajectory of forces is perpendicular to the contact surface (Gómez de Cózar, 2001). In a study conducted in 2000, German López Manzanares concluded that “concave and conical shapes are always stable due to the dome’s capacity to develop compressive stress, the opposite occurs with convex shapes that have defects in maintaining a constant thickness”.

Construction processes used for ancient domes, arches, and walls are based on empirical techniques and knowledge of the nature of masonry structures, that is, these kept in mind laws of proportion more than resistance criteria, looking for geometry to provide an adequate transmission of stress in the material. A design was created in which all the elements would work under compression, without admission of another type of stress (Hurtado Valdez, n.d.).

The stability of an arch depends on the possibility of drawing a line of thrust within the central third of its thickness (Rankine 1858, Huerta Fernández, 2005). Thus, is how the theorem establishes: “if it is possible to find a system of internal stress in equilibrium with loads that comply with the limit condition, that is, that the materials are working at compressive stress, the arch is considered stable” (Heyman, 1998, Huerta Fernández, 2005). However, stability may also be determined through structural analysis programs.

Figure 3.
The ancient Temple of Santa Lucía in Ambalema (Colombia)
Source: by the authors

This last method evaluated the dome's stability of the ancient temple of Santa Lucía in Ambalema (Figure 3). The ancient temple of Santa Lucía located in Ambalema – a municipality in the department of Tolima, Colombia, is a relatively new structure, given that anamnesis concluded that the current structure dates from early to middle 20th century: this structure is part of the historical center of Ambalema (site declared historical heritage of humanity), the temple is mostly constructed in masonry; however, wooden and reinforced concrete elements are found. This structure has an octagonal dome in masonry that presents meridional cracks; due to this, a study was conducted on stability against service loads and seismic loads through a spectral modal analysis.

2. METHODOLOGY

To conduct this study, the geometric characterization of the temple was performed; to determine the dome's geometry, photogrammetric estimates were made. The photographs were taken from the inside and outside (Figures 4 and 5).

Samples of the materials used in the construction were extracted to obtain the mechanical behavior of each. Characterization of these materials was done through laboratory tests and correlations suggested in NSR-10 (Colombian Association of Seismic Engineering AIS, 2012) and Eurocode 6 (Comité Européen de Normalisation CEN, 2005).

The software SAP 2000 was used for the dome's structural stability analysis. The analysis included mechanical characteristics of the materials. It was made through macro-modelling, taking the mortar-brick set to obtain a single composite material. The model's geometry initially consisted in defining the elements via a distribution through pre-meshing (Muñoz, 2000).

Due to the meridional cracks present between the caskets of the dome, membrane tensions become compressive stress and the structure starts to behave as a series of concentric arches along the meridians (Pavlovic, Reccia, & Cecchi, n.d.). Thereby, four arches were considered for analysis, taking as an arch, the figured formed by two caskets one in front of the other. found; this can be done because the vertical cracking transforms the structure from bi-dimensional to unidimensional (Foraboschi, 2014).

The analysis encompasses the behavior against service loads, as well as a spectral modal analysis. Beam-

Figure 4.
Inner view of the dome of the temple of Santa Lucía
Source: by the authors

Figure 5.
Exterior view of the dome of the temple of Santa Lucía
Source: by the authors

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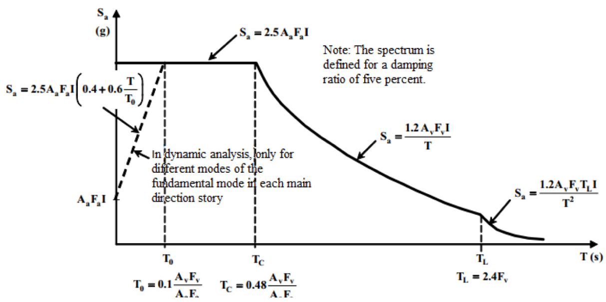
type and wall-type elements that support the dome were considered. To include the lantern tower in the analysis, it was assigned as a point load representing its own weight over the crown of each arch.

A modal analysis was performed, for which the temple's frontal structure was modeled. This analysis was carried out to evaluate the dome's stability against seismic loads, which was conducted by determining the vibration periods belonging to the modal forms, followed by the elastic acceleration spectrum for damping at 5% established by NSR-10. Lastly, occurrence of seismic forces was defined in two directions (X and Y), bearing in mind the load combinations (Table 1).

COMBINATION	PERCENTAGE OF PARTICIPAION
C1	*100%X 30%Y*
C3	*100%X 30%Y*

Table 1.
Load combinations used in the dynamic analysis
Source: by the authors

On site data, an acceleration coefficient (Aa) of 0.25 and an effective peak acceleration (Av) of 0.2 were taken. Regarding soil data, a short-period amplification coefficient, Fa = 1.4, was used, along with an intermediate-period amplification coefficient, Fv = 2.0



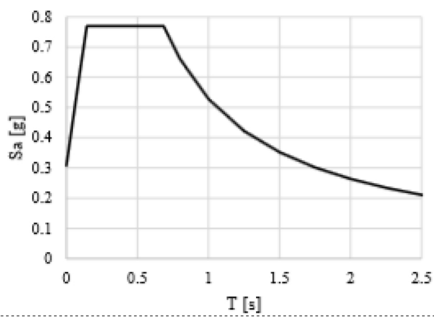


Figure 6.
Elastic spectra of analysis: a). Elastic acceleration spectrum design (NSR-10); b). Elastic acceleration spectrum of determined design.
Source: By the authors

3. RESULTS

The height from the base to the dome's crown was measured at 18.9 m. It is an octagonal dome of internal diameter and external diameter equal to 4.12 and 4.3 m, respectively. The thickness of the whole dome is constant at 0.09 m. Its total height is 2.03 m and it is hemispherical flattened at the crown, where a concrete lantern tower rests with a diameter of 0.6 m (Figure 7).

For the case study, the dome is supported on six reinforced concrete beams: two are parallel to the tower walls and the rest form a 45-degree angle with respect to the lateral walls; all the beams are of rectangular transversal section with 0.4 m in height and 0.3 m width and the tower walls have equal thickness at 0.24 m (Figure 8). The two other supports correspond to brick walls, which go to the foundation.

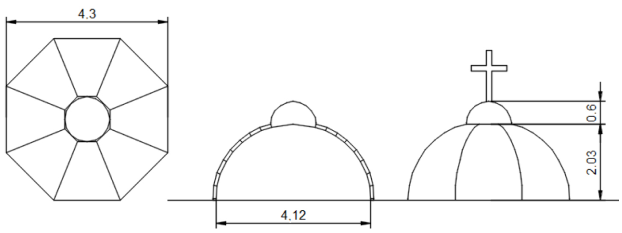


Figure 7.
Dome dimensions in meters
Source: By the authors

The span between the lateral walls and the dome was covered by low-resistance concrete slabs (between 10 and 12 MPa) on wood falsework still evident from a lower view.
The dome of the temple of Santa Lucía is hemispherical single leaf with eight caskets constructed in solid brick and mortar. The caskets show cracks of great consideration between them (some reaching 3 cm), indicating the independent work each one undertakes and the tension stress present. However, the dome is stable against service loads due to the union provided by the lantern tower topping it off.

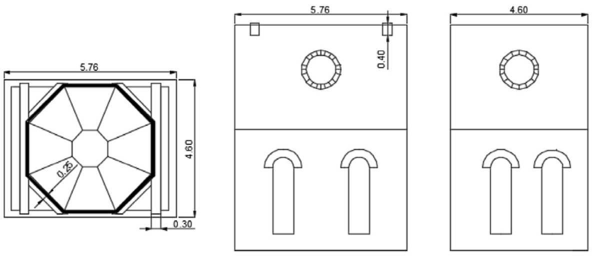


Figure 8.
Dimensions in meters of the dome's supports.
Source: by the authors

Analysis of the dome's constructive system permits determining its behavior upon loads and its current state. The meridional cracking between caskets presented by the temple's dome is a phenomenon that does not directly compromise the dome's structural behavior. In typical cases, the cracks commonly start in the springer and expand toward the crown without reaching it and descend through the drum; however, the lack of a drum present in the dome of the temple made it easier for total cracking from the springers to the crown.
Construction of the dome consisted, first, in the disposition of the elements to support it, which are of different transversal section and of different materials, specifically, two of the caskets rest on the tower walls and the other six on reinforced concrete beams; that is, they do not have support elements of equal rigidity. The caskets were constructed independently; it was possible to determine through photographic inspection that the bricks were not interlocked continuously around the whole perimeter of the dome – which was a common practice in the construction of these types of domes; the rows were erected independently for each casket and these were then joined with mortar.

Figure 9.
Fissures on caskets of the dome of the temple of Santa Lucía.
Source: by the authors

Construction of the first rows, seen from inside the dome, shows that the beddings are completely horizontal during the first six rows for which falsework was not needed. Row number seven is the high row, from there an inclination appears, generating a simple radial form to the dome. In addition, the caskets have rope interlocking in which the bricks were joined with mortar of variable thickness (between 1 and 2.5 cm), which indicates that the thrusts among bricks are not transmitted homogeneously; the opposite occurs between the union of the rows, showing more or less constant mortar thickness among all.
Construction of octagonal domes may be done without falsework (Santiago Huerta Fernández, n.d.); this occurs when the interlocking of the bricks is conducted surrounding the perimeter of the support holding it. The dome of the temple of Santa Lucía was not constructed in this manner; there was need for falsework as of the high row, a consequence of the

independent interlocking for each casket. The dome's thickness complies with the minimum thickness of 1/100 of the curvature radius proposed by Huerta (Huerta, 2004); this has a value of 1/22.55 of the curvature radius. Additionally, it is not supported on a drum in spite of presenting horizontal rows. These rows need to have a minimum thickness of 1/7.14 and a height of 1/3.34 of the dome's diameter (García Jara, 2008) to be considered drum.

The stability analysis for the service loads shows that the four arches present similar stress distribution. The presence of tensile stress is evident in all the arches. These stress values are noted in keystones 2, 3, and 8 (Figure 10), the maximum values of tension stress the arches are subjected to are 150 and 340 kPa for diagonal and normal arches, respectively. The zones subjected to compression presented maximum stress of 270 and 320 kPa.

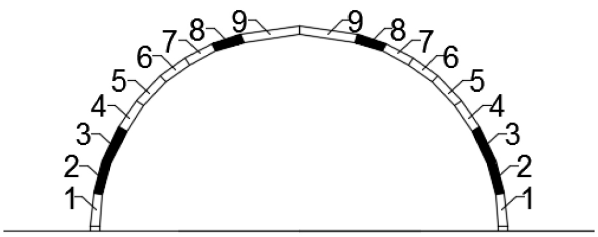


Figure 10.
Numbering of the keystones
Source: by the authors

Upon modal analysis, the structure presents a fundamental period of 0.2184 seconds. The compressive and tensile stress generated after the dynamic analysis exceed the masonry's maximum resistance stress (Table 2).

4. DISCUSSION OF RESULTS

The results obtained from comparing among the different buildings and the dome of the ancient Temple of Santa Lucía permits attributing the fissures among the caskets to the lack of uniformity in supports and to the absence of a drum. The fissures stem from the dome itself, that is, no records exist that the elements that support it present structural problems, and hence, fissures are attributed to the absence of a drum. The presence of a drum is not indispensable in the construction of domes, but it provides stability by counteracting the thrusts produced by its own weight and the service loads, avoiding the presence of tension stress. Lastly, the absence of interlocking between contiguous caskets did not permit guaranteeing transmission of monolithic forces, which facilitated the fissures being present in the brick-mortar union.

The tensile stress on the four arches occurs as of 60 degrees with respect to the vertical axis from the center of the dome, thus, complying with that proposed by (Pavlovic, Reccia, & Cecchi, n.d.) (Figure 11), reiterating the dome's stability against service loads.

Regarding the analysis for service loads, the stress obtained do not compromise dome stability, given that the mechanical characteristics of the brick-mortar set has a maximum average resistance of 570 kPa for tension and 5700 kPa in compression. With respect to seismic loads, the arches present more critical stress with the combination involving 100% of the earthquake in X direction and 30% of the earthquake in Y direction; additionally, the maximum concentration

Table 2.
Maximum stress on arches, according to types of loads.
Source: by the authors

Arches	Stress (MPa)	service	C1	C3
Normal	Comprensile	0.32	10.95	8.43
	Tensile	0.34	10.95	8.43
Diagonal	Comprensile	0.27	13.06	7.18
	Comprensile	0.15	13.06	7.18

of stress from combinations (C1 and C3) is generated in the springers of each casket. The compressive and tensile stress endured by the four arches are in a higher range than that of the resistance stress.

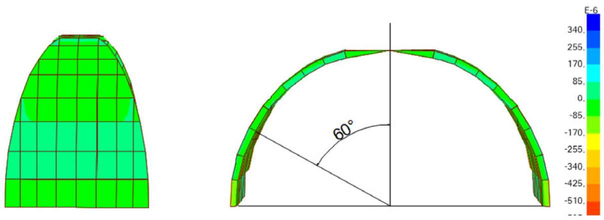


Figure 11.
Stress, in kPa, on arch 1.
Source: by the authors

5. CONCLUSIONS

The comparative analysis performed allowed to determining that the dome's construction process is not very different from those used in typical structures. From the support elements, independent caskets were constructed with falsework as of the seventh row. Although the dome has adequate geometry, it lacks an element to counteract lateral thrusts: the drum; which made the cracks between the caskets to propagate from the support to the lantern tower perimeter. Even though the concrete beams partially surround the dome, they are a failed drum attempt, given that they do not comply with the minimum heights and thicknesses required to be considered as such. The lantern tower is the only element keeping together the joints between the caskets because it is a solid lantern tower; if this were not so, the dome would have collapsed due to lack of internal equilibrium.

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