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A modified corbelling theory for domes with horizontal layers

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HIGHLIGHTS

- Corbelling theory does not interpret structural behavior of "false domes."
- An extended model of corbelling theory is proposed.
- "Stability angle" is introduced in order to guarantee overturning balance.
- Closed form expression for stability angle is derived for cone-shaped dome.
- Insight on how the angle of stability varies as function of dome geometry.

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ABSTRACT

In the Mediterranean area, buildings with roofs arranged as corbelled domes comprise a widespread and valuable heritage that deserves protection and enhancement. Unfortunately, structural behavior of corbelled domes has been investigated only to a limited extent.

We compare results from the corbelling theory in the determination of intrados and extrados curves that attain limit balance conditions against evidences in two real cases of study. This shows that the theory is not able to capture the structural behavior of the corbelled domes. We thus propose a modified corbelling theory that emulates the actions along dome parallels through the collaboration among infinitesimal meridian wedges. Results obtained show that the proposed theory is able to correctly interpret the structural behavior of these domes.

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1. Introduction

Buildings covered by corbelled domes, made of purely horizontal layers slightly cantilevered toward the centre until meeting at the top, are still widespread in many Mediterranean countries. Despite its widespread presence, this kind of "false dome" received a limited interest from the scientific community, and it is not completely understood yet.

On the one hand, monumental buildings have been the subject of archaeological studies that highlighted their historical and social value [1–4], addressing construction techniques, links with territory and available technologies, relationships with social issues [5]. On the other hand, vernacular buildings with corbelled domes were for long time regarded as a deviation from "high" architecture, interpreted just as a poor expression of rural life, and thus not worth of scientific investigation. Yet, the history of building techniques tells that such structures might have preceded the true domes in many cultures [4,6], and this building tradition is still widely followed with a regional characterization, mainly depending on available materials, that separates two major Mediterranean areas: dry stone constructions in the north, and earthen constructions in the south. Where the stone material prevails, the distribution over the territory is strongly correlated with geomorphologic characteristics and with outcropping formations. Besides, the availability of clayey soils largely conditions the localization of earthen constructions.

Two relevant typologies of corbelled domes can be identified: the ancient hypogean constructions (with mound) and the buildings with a domed roof without mound. In the former type, Mycenaean *tholoi* (Greece, XIV century b.c.) provides a relevant example of constructive technique [5]. The same type of construction can be found with similar formal characteristics, though less impressive, at Populonia in Italy (Etruria, VII century b.c.), with notable examples in the tombs of the Granate and San Cerbone Necropolis [7]. The latter type, domes without mound, is widespread [8,9] in many European regions, including Italy, France, Spain, Germany, Slovenia, England, Croatia, and Switzerland. In many countries such buildings are mostly related to the development of rural life, associated with the need of shelters for sheep-breeding activity. In the Mediterranean area, some examples are characterized by significant architectural and visual impact, with notable constructive solutions, so that they can be considered

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almost as monuments, as the "Trulli" of Puglia (Italy), the great Sardinian monumental Nuraghes (1500 b.c.), or the cyclopean megalithic temples of Malta (3500 b.c.).

Corbelled domes without mound made of earthen material (adobe bricks and mud mortar) are widespread in the Near East (Turkey, Syria, Iraq and Iran), developing on a cultural tradition dating back to ancient times. This type of structures appears to be the result of a self-building process, but also the expression of a considerable constructive knowledge, handed down over time, linked to the land, and deeply rooted in the cultures of each country. Like many other artifacts that are expressive of minor constructive cultures but evidence of age-old wisdom [10–14], these buildings comprise a heritage that deserves investigation so as to provide guidance in protection and enhancement.

Structural behavior of corbelled domes was addressed in a limited literature. Since the 1980s, some works were focused on the analysis of Mycenaean *tholoi*, which are characterized by a big covering earth bank (mound). Following the contribution by various archeologists on the building technique [3] various works investigated on the structural behavior [15–18]. In [15], in-depth structural analysis on five Mycenaean *tholoi* is carried out by means of the so-called corbelling theory, which assumes that forces be transferred only along the vertical direction; according to this, equilibrium is imposed in a limit situation on an infinitesimal meridian wedge of dome, by equalizing the stabilizing and overturning moments produced by the overhanging masses at each level. In so doing, cooperation among stones along parallels due to interlocking and friction, cannot be taken into account. This yields a plane model, where equilibrium is determined only by the forces contained in the mid-plane of the infinitesimal meridian wedge, disregarding any static contribution provided by the horizontal ring of the structure. This is equivalent to regard the structure as a set of independent corbelled arches, without taking into account the 3D behavior of the whole structure.

Corbelling theory is applied in [19] to corbelled arches, *tholoi*, and corbelled domes without mound. In [20], the theory is applied to Catalane domes, whose profiles are almost straight and, for this reason, well approximated as cones; in this case, the assumption of a linear profile, the relation among thickness, span, and height is well captured through simple equations impose equilibrium on overturning forces.

The limits of corbelling theory are emphasized in [16] where the cooperation among stones in the horizontal rings is shown to be crucial for the interpretation of the mechanical behavior of corbelling domes: the opportunity of a "horizontal ring theory" is therefore advocated. Toward this aim, some preliminary technological considerations are provided to support the hypothesis of compression forces along parallels. In particular, it is observed how the stones are very tightly built so that they may be compressed along horizontal layers and overcome the tendency to fall inwards. This idea is recovered and developed in detail in [17,18], where it is shown that a membrane stress, and the consequent stress along parallels, is necessary to ensure equilibrium in the case study of Atreo's Treasure.

In this paper, the structural behavior of corbelled domes without mound is investigated with reference to two real case studies, addressing a dry stone and an adobe building (Section 2). In the first part (Section 3.1), the limits of corbelling theory are highlighted by comparing results on intrados and extrados curves attaining limit balance conditions against real evidence. In the second part (Section 3.2), a modified corbelling theory is proposed so as to emulate the actions along dome parallels through the collaboration among infinitesimal meridian wedges. Results obtained in the two cases of study show that the structural behavior of the dome is correctly captured by the proposed theory. A parametric closed formulation is also provided for the special case of almost cone-shaped domes, allowing evaluation of stability limits with respect to shape proportions (Section 4).

2. Two case studies: an earthen dome and a dry stone dome

Two different constructions were addressed in the study: an adobe (earth brick) dome, which comprises a typical coverage of inhabited dwellings in the many villages in the neighborhood of Aleppo (Syria); and a dry stone dome, typical of "Trulli" buildings of the Valle d'Itria in Puglia (Italy).

The Syrian case is a dwelling in the village of Alrahib, close to the salty lake of Jabboul south-east of Aleppo (Fig. 1) [21]. The building consists of two adjacent square cells, connected through an arch, each covered by a dome, according to a typical pattern widespread in the area (Fig. 2). The dome is built by progressive superimposition of jutting rings made of earthen bricks and earthen mortar. Thickness coincides with the largest dimension of a single brick, i.e. 35–40 cm; the height of bricks is 5–6 cm, about a half of that of the bricks used in the supporting walls (around 10–12 cm). The use of thinner bricks enables better control on the curvature by limiting the extension of juts between superimposed layers. As a salient trait, bricks are not laid on separated horizontal rings but rather along a sloped continuous spiral, which increases the interlocking between bricks and avoids the need of closing each single ring.

The Italian case is the corbelled dome of a "Trullo" in Castellana, a village close to Bari in Puglia (Italy) (Fig. 3), which effectively represents the typical roofing of houses in the Itria valley (Fig. 4). The dome is built on a squared room made of irregular stones, by laying subsequent separate jutting rings of stones, without usage of mortar, with a corbelling that progressively increases from 5 to 15 cm. The average size of dome stones is about $30 \times 10 \times 15$ cm. Ashlars are fairly irregular, but they are cut slantwise along the intrados face so as to obtain a continuous surface at the inner side of the dome. Special care is dedicated to achieve continuity of the ring brick-work, filling gaps between blocks through little pieces of stones. Flaked stones, of size about $30 \times 10 \times 3$ cm, are subsequently layered along the slope of the dome extrados to protect the internal structure.

For both the cases, surveys carried out "in situ" and interviews of masons experienced in traditional building techniques (a Syrian "Maalem" and an Italian "Trullaro") highlighted a major aim in achieving the best possible continuity along parallel rings. In the Syrian case, the earth material allows to create a sort of conglomerate providing cohesion, both during the building process and at its conclusion: mortar and bricks are made of the same earth, able to join completely when wet, and their spiral arrangement further increases interlocking of the wall texture. Besides, in the Italian case, but more generally in the construction with dry stone, horizontal rings are layered with the aim of minimizing empty spaces and constructive discontinuities. This is achieved through squared ashlars placed along a regular laying surface, and through the insertion of ad hoc shaped stones into remaining gaps between adjacent ashlars. Through this procedure, horizontal rings of stones are able to bear compression along parallels, and thus resist inward overturning forces. This ability is fully deployed when the ring is enclosed, but it helps to some extent also when the ring is not completed thanks to the friction between ashlars lateral surfaces. For both the cases, a practical evidence of the effectiveness of employed constructive techniques is provided by domes where a meridian wedge is still able to stand after partial collapses (Fig. 5).

A geometrical survey was made for each of the two cases, in order to identify intrados and extrados curves relevant for the subsequent structural analysis. In the Syrian case, the survey was obtained through a laser-scanner device [22]. In the Italian case,

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