Tension Ring in Masonry Domes

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ABSTRACT: Masonry domes are historically built in the form of rings without centring and remain stable mainly due to compression in hoop and meridional direction. The lower portion of the dome, during and after construction has tendency to bulge out which imparts hoop tension. This hoop tension can be either resisted as observed in domes constructed in Europe and Rome or allowed to relive by cracking in meridional direction leaving series of arches with top portion as common key stone as observed in dome of Gol Gumbaz, Bijapur. Dome stability with reference to provision of tension ring is discussed in the paper.

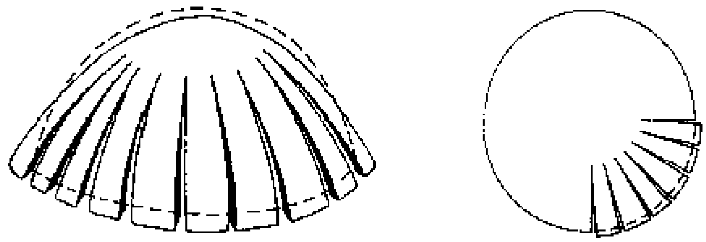
Grand Pagoda is the largest span masonry dome and is under construction at Mumbai. The approximate calculations are presented for comparison amongst available solutions on tension ring. The intricacies involved in calculating forces in tension ring are discussed.

1 INTRODUCTION:

The structures built by our ancestors in masonry are standing in good condition for centuries, where as structures built recently using modern material like steel and reinforced or prestress concrete are failing to serve for a period of fifty to hundred years. This durability of masonry is unrivalled. Masonry when constructed in shell form is a unique combination of durability and spanning capacity. It is a well-known fact that the nature has maximized the capacity in shell structure to span over larger area with minimum thickness; the shell of egg is an impressive example of shell structure.

Historically domes are constructed in concrete and masonry in form of rings without centering (Either in horizontal or radial layers); these domes remain stable mainly due to compression in hoop and meridional direction. Spherical dome in specific and also for other shapes, the lower portion is subject to hoop tension during construction (at an angle of about 51.80 degrees from axis of axial symmetry, in spherical dome of uniform thickness loaded with self-weight) [14]. Due to outward horizontal thrust resulting from hoop tension; the dome tries to bulge out resulting in cracking in the meridional direction as shown in fig 1.

The Dome remains stable even after these cracks. In that case the lower portion of dome where hoop tension prevails, acts like a series of arches with upper portion of dome in hoop compression serving as common keystone [12]. The stability and serviceability are the factors to be considered:



(a) View (b) Plan

Fig. 1 Spherical masonry domes without hoop tension carrying mechanism.

Stability: As shown in figure 1, the dome remains stable even after the cracks in the meridional direction. The provision of tension resisting mechanism is an add-on to the stability.

Serviceability: It creates the feeling of insecurity in the minds of inhabitants and hence should be considered as failure against serviceability.

Paper discusses historical masonry domes with reference to (alternative arrangements provided for resisting tension) provision of tension ring, and alternative materials. Approximate calculations for tension ring for Grand Pagoda is presented. Grand Pagoda is a masonry dome under construction in Mumbai, India. Limitation of calculation methods presently available and their effects are discussed.

2 HISTORY: MASONRY DOME

The masonry domes in Europe and Rome are found to be practicing (the provision) with metal tension rings, like in Pantheon and St-Peter in Rome, St-Paul in London. A different concept of tension resistance is practiced in the construction of the dome of Hagia-Sophia, where small domes around the main dome are used to dissipate the hoop directional forces, it is relying more on geometry of structure than material properties. These are the examples of tension resisting mechanism in hoop direction.

The dome without tension ring stands as series of arches, remarkable example of this type is Gol Gumbaz of Bijapur. The Gol Gumbaz is a spherical dome standing for more than 350 years and can now be visualised as series of arches without tension ring. This is example of tension reviling instead of resisting for stability of dome.

Some of the historical structures are referred and noted below in table (1) with reference to tension mechanism provided.

Pantheon of Rome:-

The Pantheon of Rome has the biggest span of the dome structures till today [9]. It was first constructed in 27 BC and then rebuilt in 118-128 AD. It is a coffered dome with 28 vertical and 5 horizontal ribs. The diameter of the dome is 44 m and its height is nearly 45 meters. The structural material used for the construction of the dome was a kind of concrete, which consisted of three parts namely hydrated lime, volcanic pozzolanic cement and pieces of fish sized rocks and was termed as ‘Roman Concrete’ [6].

Table 1 Different historical structure showing their technique of resisting hoop tension.

Structure	Diameter*	Construction*	Material	Tension ring provisions
Pantheon Rome	44 m.[9]	118-125 AD[6]	Concrete [6]	7 stepped rings covered with lead plates are placed at the base of the dome [6]
St.-Peter Rome[9]	41.60 m	1546-1591 AD	Stone and Brick Masonry	Iron chains have been added at different times to prevent spreading
Hagia Sophia Istanbul[4]	32.60 m	532-567 AD	Stone and Brick Masonry	No tension rings instead 4 big arches and 2semi-domes are provided to support the dome
St.-Paul London[9]	30.70 m	1675-1710 AD	Stone	A double chain on the outer shell supports the heavy lantern.
Gol Gumbaz, Bijapur, India[3]	37m	1627- 1656 AD	Masonry	No provision. Constructed with centering

*Approximate data is quoted for comparison purpose only; different values are given at different references.

The relative thickness of the dome reduces from 5.9 meters at the base to nearly 1.5 meters at the “oculus” on top. Oculus is the large opening in the center of the dome. It acts as a compression ring having a diameter of 5.9 meters and thickness of 1.4 meters. This ring distributes the compression forces at top of dome and work like keystone. The ring is made of 3 horizontal layers of tile. These tiles are covered with bronze plate; some of the plates are later removed and replaced by lead plates. (There is small discrepancy in details available regarding Pantheon; the details are interpreted from reference 9 and 6)

On the outside surface of the dome, there is a series of 7 rings from springing to half way up the dome and the profile is stepped. Location of tension rings as interpreted by author are shown in figure 2. Dome line changes into a circular line after the top most of the rings up to oculus. Along with this on the inner surface of the dome there is a series of 5 bands made of waffle-like depressions called coffers. There are 140 coffers which required special forming for the waffle shape. At mid-point on the outer surface of the dome, contour changes from these coffers to a circular line. Probably designer has provided these coffers to reduce the weight of masonry.

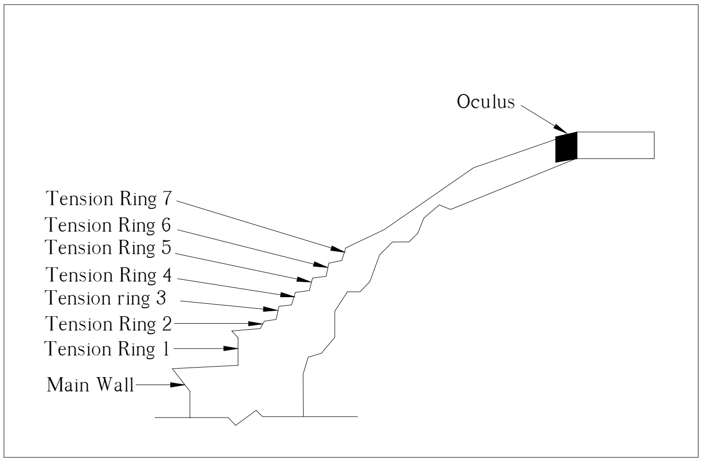


Fig. 2 Tension Ring in Pantheon

St. Peter's Rome:-

It was first constructed in 314-349 AD and then repaired/reconstructed in 1546-1591 AD, the dome span is 41.60 m, and its crown is 117.60 m above floor level [9]. Dome is constructed in two skins of brick masonry. Four iron chains have been added to the dome, at different times since its construction, to prevent its spreading at the base. (Rome, Italy)[9]

There is interesting story about St. Peter Basilica.; structure at Vatican City, Italy; span of 42m. This structure was completed in 1626. "To support such a giant dome, builders placed three iron rings within the masonry of dome. But even the rings couldn't hold back the outward thrust of tension; significant cracks eventually developed around the dome's base. By the early 18th century, the cracks became serious enough for Vatican engineers to add several more tension rings as an emergency fix. Fortunately, this solution has stood the taste of time." [5] This clearly shows the complex behaviour of masonry structure with reference to tension rings. This indicates that the dome is either stable with these cracks due to hoop tension or at least the failure due to hoop tension cracks is not sudden.

Hagia Sophia Istanbul:-

Originally it was known as the Great church and later named as Hagia Sophia. At first it was constructed in 360 AD, had a timber roof. The church had been destroyed in a great fire and then rebuilt in 532 AD in stone and brick with a difference of diameters in X and Y direction [in plan]. The diameter in the X direction is 30.37 m and in Y direction is 31.87 m. The dome is buttressed on the outside by 40 closely spaced short ribs built in brick. The thrust in the dome was high and to resist this thrust 4 big arches and 2 semi-domes in north and south are built to support the dome. It is the first dome in the world made in frame construction.[4,9]

St. Paul's Cathedral:-

This dome is the largest Cathedral of England. The period of construction required was from 1675 to 1710, the diameter of the dome is 30.7 m and its height is 67.33 m. It replaced the old St. Paul's which was destroyed in the Great Fire of 1666. It is a complex structure consisting of an outer shell, intermediate brick cone strengthened with a massive double chain embedded in large Portland Stone around the base of the inner brick, which supported the heavy lantern, and an inner shell. (London, England).[9]

Gol Gumbaz

'Gol Gumbaz' was built in 1627 to 1656. This is India's largest dome [1]. The total height of structure is 54 m. Diameter of dome is 37m [3]. The Dome is standing with number of meridional cracks [due to hoop tension]. Tension ring or other such arrangement is not made for this dome. It was repaired in 1936–37 by using a method of guiniting to help tie the cracked segments of the dome together.

3 GRAND PAGODA:

Grand Pagoda is masonry dome under construction at Gorai Creek, in Mumbai, India. It is a massive stone masonry structure being constructed in Jodhpur (Sand stone) and black basalt stones. It is a complete replica of the "Swedogoan Pagoda" only for the fact that Swedogoan is a solid masonry structure and "Grand Pagoda" is a masonry dome as shown in figure (4). The dome rests directly on the ground with a height of 26.3m from plinth level and diameter in plan at plinth level is 84.4m [about twice of present largest span in this type– Pantheon].

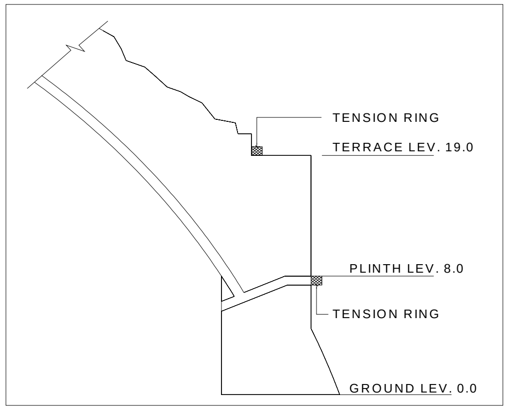


Figure (3): Elaborated view of Base in section

The plinth level of the structure is 8m above GL, wherein the first metal tension ring is proposed and second at terrace level as shown in figure (3). The rings are required in order to avoid any cracks or their propagating in meridional direction. Proposed height of Grand Pagoda is 89.72meter from plinth level; it is compared in figure (4) with Pantheon and Hagia Sophia.

There are two small Pagoda proposed around Grand Pagoda with the height of 23.93 meter and inner diameter of dome in plan at springing point is 14.19 meter. One of these Small Pagoda is already standing on site which is scaled down model of main Pagoda. The dome and arches are constructed without centering; and same is practiced for the construction of Grand Pagoda. Authors believe that the construction of masonry dome with centering as in case of Gol Gumbaz and without centering as in case of Grand Pagoda changes the structural behaviour of domes.

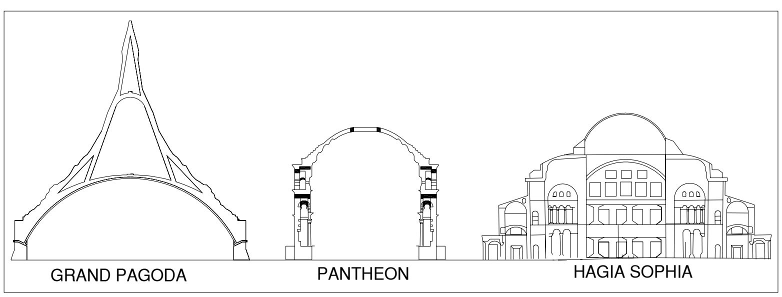


Figure (4): Comparative section of Pagoda with Historical Landmarks

4 CALCULATION FOR TENSION RING:-

Meridional stresses in dome are compressive throughout, whereas the hoop stress are compressive from crown to the circumferential line which remain unchanged in length,[15] and there after it develops hoop tension up to the base of the dome. In case of spherical dome subjected to self-weight with uniform thickness; the hoop tension occurs in lower portion at an angle of 51.8^{o} from axis of axial symmetry. Normally the tension resisting ring is provided at the base to carry the horizontal thrust resulted from the hoop tension. The calculation of horizontal thrust with assumption of rigid support is sometimes used to provide the tension ring in masonry dome [15].

The tension resisting ring provided do not work as rigid support and the strain compatibility equations are required to calculate the forces developed in the tension ring. Stress and strain developed in masonry dome are small and using strain compatibility, the stresses in tension ring corresponding to tensile strain are small. This necessarily induces the tension in masonry. The requirement of cross sectional area to avoid the tension in masonry to exceed the permissible limit becomes too large and non practicable. The alternative to this is to provide the pre tension in the ring.

Apart from strain compatibility, there are some other effects that makes calculation more complex. Dome constructed with and without centering will produce different stress distribution [stage construction effect]. In addition to this, the joints perpendicular to meridional direction are thinner in dome constructed without centering as mortar squeezes from joint due to gravity. The joint perpendiculars to hoop direction are likely to remain thicker. It is also observed that lacunas in workmanship adds into the thickness of joints in the meridional direction. This reduces the relative stiffness of joints perpendicular to hoop direction in comparison to joints perpendicular to meridional direction.

The masonry without tongue and grove [interlock masonry] should not be accounted for resistance to the tension. The analysis carried out should set zero stiffness for masonry in direction of tension. This tensile stress, depending on the stiffness and cross sectional area provided to the tension ring, will be distributed into:

a) Tension in 'Tension Ring'

b) The dome will stand as assembly of arches with the cracks produced in meridional direction as shown in figure (1). The forces will be re-distributed from hoop direction to meridional direction.

These complexities are collectively not found addressed anywhere in the literature and work in this direction is expected to be done. There are few simplified methods also, used in practice. Maini has used the arch analysis for design of domes [13]. His designs are based on philosophy that "If arch or vaults are stable, domes of the same section will necessarily be stable. But opposite is not necessarily true". Maini has constructed the dome [Dhyanlingam Temple, near Coimbatore, India] in mud brick masonry with the span 22.16 meter with the thickness varying from

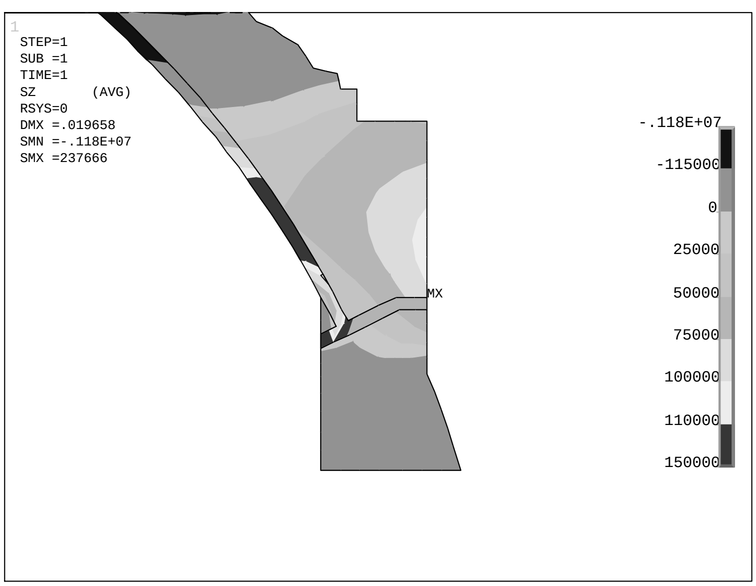


Figure (5): Hoop Stress in Grand Pagoda

0.53 meter at springing to 0.21 meter at crown.

For Grand Pagoda the axisymetric finite element analysis is carried out without modeling tension ring. The product of tensile stress in hoop direction as shown in figure (5) and corresponding area is used for design of tension ring for comparison purpose. Force calculated in tension ring is 2238 KN. Different materials that can be used for tension ring are worked out for resisting this force and their merits are discussed.

5 MATERIALS FOR TENSION RING

The metal rings are found practiced in Europe and Rome like in dome of St. Peter and St. Paul cathedral. Metal is a ductile material with viable strength to cost ratio [Mild Steel]. Metal is readily available and it can be fabricated in desired shape. Corrosion is only the problem with the metal. Stainless steel or other metal can be use to offset this problem, but then the cost may become prohibitive factor. Relative cost of mild steel tension ring with corrosion resistive coating is 0.70 [with some tensioning in the steel for better utilization].

In Hagia Sophia the geometrical shapes [adjacent small domes and arches] are utilized to reduce the lateral thrust transferred on supporting walls. The other possible options, which can be used for tension rings, are Reinforced Cement Concrete [R.C.C.] or Prestress concrete. Relative cost of Prestress concrete ring is 0.23. Prestress is difficult for detailing at expansion or contraction joints and for circular Prestressing. The lower cost is mainly due to use of high strength steel.

The stone masonry is weak in carrying tension due to the presence of mortar joints. This can be offset by providing tongue and grove masonry joint as shown in figure (6) below. Stone and specifically igneous rock has good tensile strength [long term i.e. over the centuries, behaviour of stone under persistent tensile stress need to be investigated]. This kind of joint is more recommendable to use within masonry where small magnitude of tension may occur.

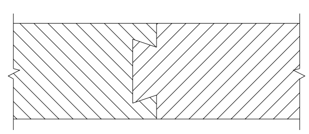
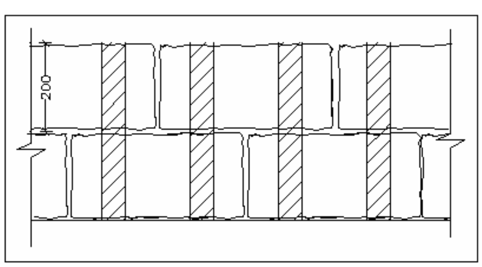


Figure (6): Tongue and Grove Masonry



a) Section through Tension Ring

b) Photo

Figure (7): Tongue and Grove Masonry Tension Ring

The stone when used as tension ring from outside as shown in figure (7) with pins made of stone are subject to shear. The stress in stone ring depends on strain compatibility; no pretension is possible in this case. This makes the stone ring to remain underutilized. Relative cost of masonry tension ring is 1.0 [Basis for cost comparison]. Stone is a brittle material; and using stones as external ring can lead to sudden failure in case of under estimation of the tensile stress. Stone masonry ring is likely to add more elegance to the structure as compared to other materials.

6 CONCLUSION:-

The masonry is known to have negligible strength in tension; in this case the provision of hoop tension resisting ring becomes necessary for serviceability requirements. The calculation of tension in tension ring is required to consider following effects:

1. Strain compatibility.
2. Stage construction effect
3. Different stiffness in hoop and meridional direction.
4. Zero stiffness in masonry in tension.

In historical structures this tension is mainly resisted by providing metal rings. There are many possible arrangements of tension resisting mechanisms. Amongst which some are discussed in the paper. The metal is more viable option for higher diameter domes [20 meter and above], where as for diameter up to 20 meter, the reinforced concrete or even stone ring can be provided.

Hoop tension ring is required for serviceability reasons and not for stability. The Dome of Gol Gumbaz is stable even after 350 years without any tension ring as series of arches.

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