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P.B. Lourenço, P. Roca, C. Modena, S. Agrawal (Eds.)

Tension Ring in Masonry Domes

M.N. Varma
Director, Nandadeep Building Centre, Aurangabad

R.S. Jangid
Professor, Civil Engineering Department, IIT Bombay

V.G. Achwal
Professor, Civil Engineering Department, Jawaharlal Nehru Engineering College, Aurangabad

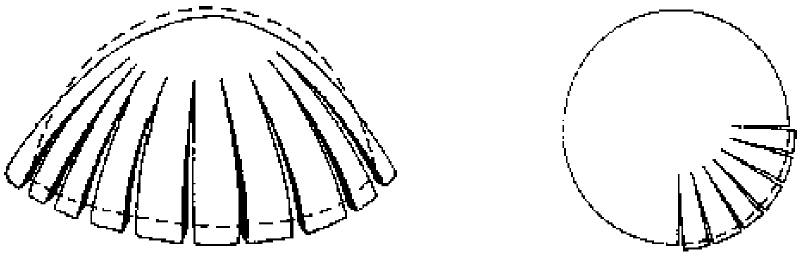
ABSTRACT: Masonry domes are historically built in the form of rings without centring and remain stable mainly due to compression in hoop and meridional direction. The lower portion of the dome, during and after construction has tendency to bulge out which imparts hoop tension. This hoop tension can be 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 with reference to Grand Pagoda. 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) (Timoshenko 1969). 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 (Santiago Huerta 2001). The stability and serviceability are the factors to be considered:



(a) View (b) Plan

Figure 1 : Spherical masonry domes without hoop tension carrying mechanism.

Stability: As shown in Fig. 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 (Ref 5, Ref 6). Different effects to be considered in calculation of tension in ring are discussed.

2 HISTORY: MASONRY DOME

The masonry domes in Europe and Rome are found with the provision of 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 relieve 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.

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

Structure	Diameter*	Construction*	Material	Tension ring provisions
Pantheon Rome	44 m (Mujde Altin 2001)	118-125 AD (Ref 4)	Concrete (Ref 4)	Seven stepped rings covered with lead plates are placed at the base of the dome (Ref 4)
St.-Peter Rome (Mujde Altin 2001)	41.60 m	1546-1591 AD	Stone and Brick Masonry	Iron chains have been added at different times to prevent spreading
Hagia Sophia Istanbul (Ref 4)	32.60 m	532-567 AD	Stone and Brick Masonry	No tension rings instead 4 big arches and 2 semi-domes are provided to support the dome
St.-Paul London (Mujde Altin 2001)	30.70 m	1675-1710 AD	Stone	A double chain on the outer shell supports the heavy lantern.
Gol Gumbaz, Bijapur, India (Ref 1, Ref 2)	37 m	1627- 1656 AD	Masonry	No provision. Constructed with centering

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

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 Fig. 2. The dome rests directly on the ground with a height of 26.3 m from plinth level and diameter in plan at plinth level is 84.4 m (about twice of present largest span in this type – Pantheon).

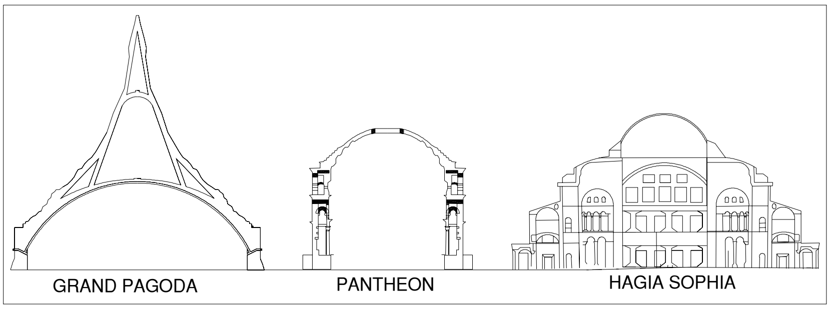


Figure 2 : Comparative section of Pagoda with Historical Landmarks.

The plinth level of the structure is 8 m above ground level. The first metal tension ring is proposed at plinth level and second at terrace level as shown in Fig. 3. The rings are required in order to avoid any cracks or their propagating in meridional direction. Proposed height of Grand Pagoda is 89.72 m from plinth level; it is compared in Fig. 2 with Pantheon and Hagia Sophia.

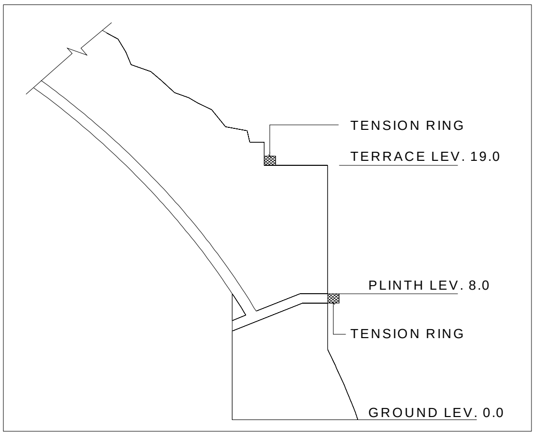


Figure 3 : Elaborated view of Base in section.

There are two small Pagoda (Photo 1 b) proposed around Grand Pagoda (Photo 1 a) with the height of 23.93 m and inner diameter of dome in plan at springing point is 14.19 m. One of these Small Pagodas is constructed on site and is scale down model of main Pagoda. The dome and arches of small Pagoda are constructed without centering; and it is practiced for the construction of Grand Pagoda as well. Authors believe that the construction of masonry dome with centering and without centering (Stage construction effect) as in case of Grand Pagoda changes the structural behaviour of domes.

Photo 1 : Construction of Grand Pagoda in July 2005. Examples of (a) Dome of Grand Pagoda under construction and (b) Small pagoda.

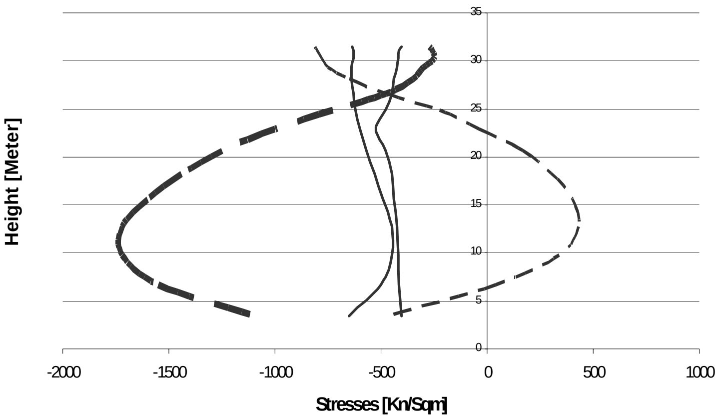
4 STAGE CONSTRUCTION:

Domes can be constructed with centering or without centering as discussed below:

1. Construction of dome with centering and removal of centering only after completion of dome.

2. Domes when constructed without centering are built in ring form. Each stone in a ring rests on a temporary support in the process of construction. As the ring is complete, these supports are removed. The stones on removal of support tend to slide inside the dome; which makes face-to-face contact of adjacent stones. The dome remains stable mainly due to the hoop compression in the rings completed.

Analysis is carried out for both the above cases for main dome of Grand Pagoda to study the effect of stage construction and is compiled in Graph 1. Meridional stresses at inner and outer face of the dome (X axis) are plotted against the height of dome (Y direction). Dotted lines represent the meridional stress in dome constructed without centering and full lines represent the meridional stress in dome constructed with centering.



Graph 1 : Meridional Stress due to stage construction.

The construction of dome without centering can be idealized as incomplete arch with spring supports due to hoop compression in the ring as shown in Fig. 4. The deformation in these rings produces bending and may subsequently lead to meridional tension on outer side of the arch. This tension is relieved with the horizontal cracks. These cracks are observed in the construction of Grand Pagoda; which subsequently disappeared. The meridional tension disappears with the increase in stiffness in the hoop direction.

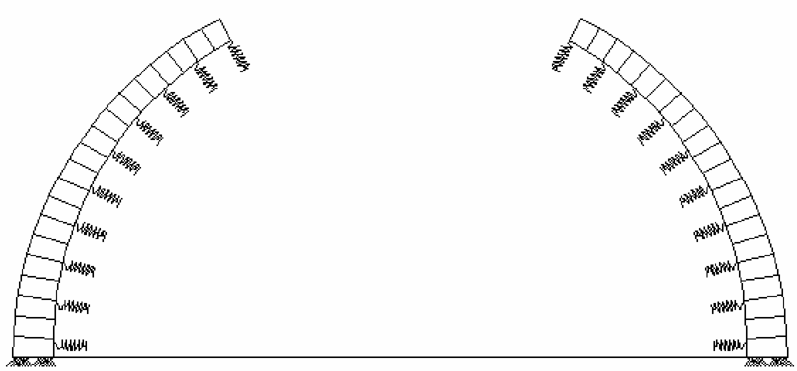


Figure 4 : Stage construction effect.

5 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 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 51.8PoP from axis of axial symmetry. Normally the tension-resisting ring is provided in tension zone to carry the horizontal thrust resulting 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.

The tension-resisting rings 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. The requirement of cross sectional area of tension ring such that tension induced in the masonry does not exceed the permissible limit becomes too large and non practicable. The alternative is to provide the pre tension in the ring or to allow cracking of masonry to relieve the tension to some extend.

The masonry without tongue and groove (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: tension in ‘Tension Ring’.

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

These complexities are collectively not found addressed in the referred literature. There are few simplified methods also, used in practice. Maini has used the arch analysis for design of domes (Satprem Maini 2003). 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 of 22.16 m with the thickness varying from 0.53 m at springing to 0.21 m at crown.

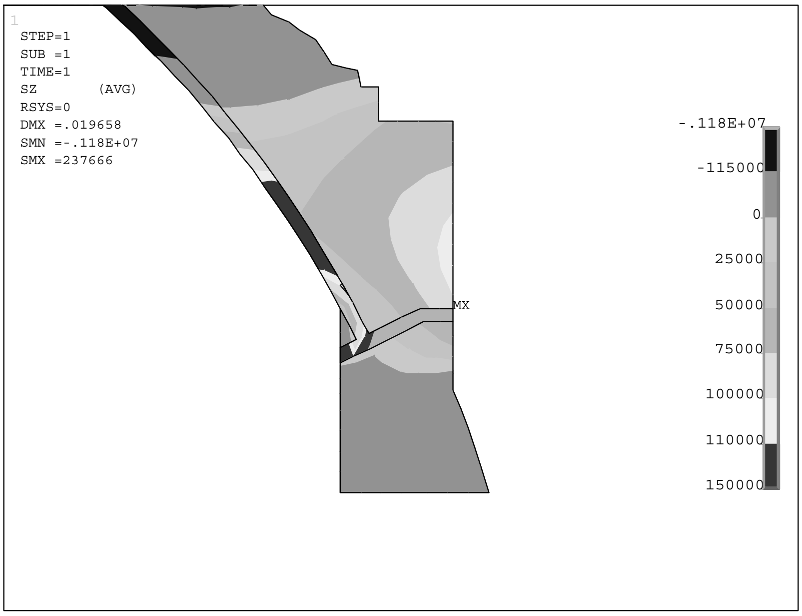


Figure 5 : Hoop Stress in Grand Pagoda.

Analysis of Grand Pagoda using axisymetric finite element is carried out without modelling tension ring. The product of tensile stress in hoop direction as shown in Fig. 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.

6 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 used to offset this problem, but then the cost may become prohibitive. 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. Providing tongue and groove masonry joint as shown in Fig. 6 below can impart the tensile strength in masonry. 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.

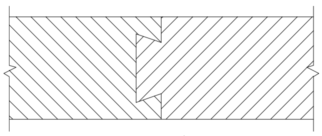
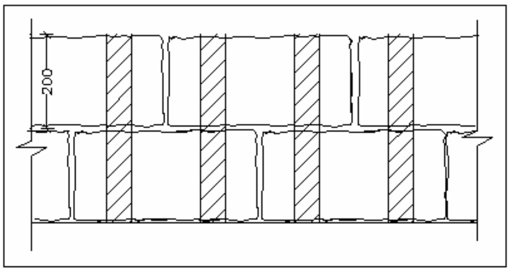


Figure 6 : Tongue and Grove Masonry.



(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 Fig. 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.

7 CONCLUSIONS

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:

- Strain compatibility.
- Stage construction effect.
- 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 m and above), where as for diameter up to 20 m, 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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