STRUCTURAL ASSESSMENT AND STRENGTHENING OF MULTI-TIERED MASONRY TOWERS

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ABSTRACT

The gopuram, a multi-tiered entrance gateway, is a representative structural form in South Indian temples introduced by Pandya rulers in 14th c. AD to confer architectural status to ancient shrines. The gopuram, typically rectangular in plan, rises as a truncated pyramid, crowned by a structure resembling the Buddhist chaitya with finials over its ridge. Such a historical 7-tiered tower at Kalahasti, in South India collapsed on 26 May 2010. The ground storey of the 41.4 m high tower was constructed in three-leaf granite stone masonry, while the upper stories had brick masonry walls, with a Madras terrace flooring system. Reasons for collapse of the tower at Kalahasti explain the need for structural strengthening of such heritage structures. Visual screening of ancient gopurams was carried out to identify structural damage and to prepare an abacus of common distresses with possible explanations. The most critical damage observed was in the Madras terrace floors, including the structural timber supporting the floor. Failure of these in turn leads to excessive deflections of the masonry walls, owing to inadequate tying of walls at the floor levels. A prototype gopuram was considered for structural assessment and development of strengthening strategies. Details of Finite Element models created to investigate the effects of diaphragm flexibility are discussed in the paper. The repair solution is evolved with due consideration to the historical value of these structures, reversibility of interventions and structural safety.

Keywords: South Indian temples, Gopuram, Masonry towers, Madras terrace roof, Safety

1. INTRODUCTION

1.1. History and Evolution of Temple Forms in South India

The configuration of the Hindu temple can be traced to the early Buddhist rock-cut structures (chaitya) and monasteries (vihara), seen in Ajanta (2nd c. BC) for instance, while the earliest structural temples belong to the Gupta (e.g. Vishnu temple at Deogarh in stone, 500 AD; brick temple at Bhitargaon, 550 AD) and the Chalukya periods from 6th c. AD (e.g. Lad Khan and Durga temples, Aihole). The distinct architectural style of temple construction in different parts was a result of geographical, climatic, ethnic, racial, historical and linguistic diversities. Ancient Indian temples are classified in three broad types based on their architectural styles: (1) Nagarag or the northern style, (2) Dravida or the southern style and (3) Vesara or the mixed style. The Dravidian style, identified by the vimana, a stepped pyramidal structure ending in a dome over the garba griha or sanctum sanctorum, evolved in South India under the Pallava, Chola, Pandya, Vijayanagara and Nayaka dynasties until 18th c. AD. The multi-tiered archetypal entrance gateway in the Dravidian temple, the gopuram, was a feature introduced by the Pandyas in 14th c. AD in order to confer architectural status to structurally insignificant ancient shrines [1, 2]. A gopuram rises as a truncated pyramid, crowned by a structure resembling the Buddhist chaitya with finials.

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over its ridge. Structures such as the gopuram of Meenakshi Temple in Madurai (1600 AD), Ranganathaswamy Temple in Srirangam (17th c. AD) and Ekambareswar Temple in Kancheepuram, built by Vijayanagara rulers in 16th c. AD, are ubiquitous and representative of the highly evolved Dravidian temple architecture (see Fig. 1).

Temple construction was classically carried out by the Stapathy, a hereditary temple architect-cum-builder. Factors influencing the size, elegance and significance of a temple were availability of material, religious custom, social and cultural life of the people of the region and above all the economic status of the king. Almost all ancient Indian temples are still in use and many of them are in UNESCO’s world heritage list (e.g. Mamallapuram group of monuments; Kailashnath temple, Kancheepuram; Pattadakal group of temples, Brihadeswara temple, Thanjavur).

Fig. 1 Typical gopurams of South India: (a) Raja Gopuram of Sri Narasimhaswamy Temple, Mangalagiri Andhra Pradesh; (b) Raja Gopuram of the Ekambareswar Temple, Kancheepuram, Tamil Nadu

1.2. Description of the Gopuram

Earliest Dravidian temples had tower-like structures above the sanctuaries, called vimana (or shikara), marking the sanctum. During the rule of the Pallavas in Tamil Nadu, some temples had incipient forms of gopurams, relatively smaller than the vimanas. Even in 10th c. AD, during the reign of Cholas,

Fig. 2 (a) Typical details of Madras terrace floor construction (BIS 2119, 1980) (b) View of a Madras terrace floor slab (photo courtesy: K. Kalpana)

the trend continued. Subsequently, under the Pandyas and then the Vijayanagar and Nayak rulers, the gopuram gained prominence in a temple. Among several gopurams in a temple, the tallest is referred to as the Raja Gopuram, or the king among the gopurams. The structure serves as a landmark that can
be sighted from great distances. The gopuram serves as prominent entrance gateways to the temple complex in the four cardinal directions. Essentially a masonry tower with an odd number of stories, it is similar in structural configuration to a bell tower or a minaret.

A gopuram is rectangular in plan, with floor area reducing along the height. Internal staircases provide access to upper stories. The foundation is typically not more than 3 m deep, composed mainly of irregular stone masonry. Load-bearing walls of the ground storey, known as kalkaram, are of multi-leaf stone masonry with lime mortar, typically with granite blocks and rubble masonry core. Upper stories are made up of single-leaf burnt clay brick masonry in lime mortar.

Floor slabs are of the Madras terrace system [3], which consists of closely spaced wooden rafters spanning the walls, supporting bricks-on-edge arranged diagonally, topped with brick bats and lime mortar (see Fig. 2). Smaller gopurams may have timber flooring on timber joists. This system is rather flexible diaphragm under lateral loads. Gopurams constructed in the modern era have reinforced concrete (RC) slabs instead of Madras terrace or timber flooring, while the granite kalkaram and upper brick masonry stories are still common, albeit in cement mortar. The exterior of the gopuram is decorated with sculptures derived from Hindu mythology, made with reinforced mortar.

2. TYPICAL DISTRESS OBSERVED IN GOPURAMS

2.1. General

Most prominent gopurams in South India are at least a few hundred years old. Several of these structures show signs of material deterioration and structural distress over the years and have undergone repairs. Repointing of mortar joints and repair of Madras terrace slabs, including replacement of timber joists, rafters, and entire slabs with RC slabs are typical interventions. In order to build an abacus of common damages encountered in gopurams, the authors conducted a visual survey of a number of ancient gopurams in the states of Tamil Nadu and Andhra Pradesh.

2.2. Abacus of structural damage in Gopurams

Common structural distresses under normal loading conditions (i.e. no seismic or accidental loads) observed in gopurams during the visual screening process are the following (see Fig. 3):

1. **Deterioration of masonry joints:** Deterioration of lime mortar in masonry joints due to weathering and ageing effects (Fig. 3a);
2. **Bulging of multi-leaf wall:** Deterioration and settlement of the poor infill material, typically composed of rubble stone masonry, brick bats, lime or mud mortar, and subsequent debonding with facing stone blocks, results in lateral pressure on the facing blocks. Bulging of the multi-leaf wall (Fig. 3c), cracking and delamination of granite blocks due to excess bulging (Fig. 3d), widening of mortar joints (Fig. 3e), and in extreme cases seepage of infill core material to the exterior after heavy rains can be observed. Differential settlement could also lead to widening of mortar joints (as in Fig. 3f).
3. **Crack formation in stone:** Vertical and sub-vertical cracks in granite blocks of the multi-leaf walls occur due to extreme compression (see Fig. 3b). Flexural tension cracks (see Fig. 3g) are seen in flexural elements such as beams and slabs, normally found in the ground storey and shear cracks are noticed in wide column capitals of the columns. Often cracks can be noticed along natural fissure planes in granite; however, these are typically confined to single blocks of granite and should not be expected to be extending to the entire wall.
4. **Cracks in the brick masonry walls:** Vertical or diagonal cracks in brick masonry walls may be seen (Fig. h-i). However, these are rare and expected in cases of severe structural distress.
5. **Deterioration of the timber joists and rafters:** Termite attack or fungal attack is frequently encountered (Fig. j-k). Ingress of rainwater through openings at different levels of the gopuram, stagnation on the floors and eventual seepage through the floor slab is common. Alternate wetting and drying of the timber structural members accelerates the decay process. In extreme cases sagging of timber joists and rafters and separation from brick-lime concrete slab of the Madras terrace floor can be seen. Chemicals from bat droppings, in the presence of moisture, have detrimental effects on untreated timber.
6. **Sagging of Madras terrace slab:** Excess deflection of deteriorated timber joists and rafters leads to spalling of lime plaster from the brick-lime concrete slab of the Madras terrace floor, detachment and spalling of bricks (Fig. k). Prominent sag of floor slab can be observed in extreme cases leading to the need for removal of the floor slabs (see Fig. 4).
Fig. 3 Abacus of structural damage in gopurams: (a) Deterioration of mortar joints; (b) Cracking and spalling in granite; (c) Bulging of multi-leaf walls; (d) Delamination and cracking of granite wall due to excess bulging; (e-f) Widening of mortar joints; (g) Flexural crack in granite beam; (h-i) Cracks in brick masonry walls; (j) Deterioration of timber joists due to termite, fungal attacks and exposure to moisture and debonding of brick units; (k) Sagging of timber rafters; (l) Cracking along natural fissures in granite blocks

Fig. 4 (a) Interior view of gopuram with floor slabs removed; (b) Building with Madras terrace slab dismantled
3. LESSONS FROM THE COLLAPSE OF A HISTORICAL GOPURAM

3.1. Salient features of the temple structure
The original shrine of Srikalahasteeswara, located near River Swarnamukhi, 36 km from Tirupathi in Andhra Pradesh, dates back to 5th c. AD; Pallavas and Cholas built it in the 12th c. AD. The Vijayagopuram (or victory tower), situated outside the temple precinct, was completed in 1516 AD by King Krishnadevaraya of the Vijayanagar Empire as a symbol of his victory. The 7-storied structure rose to a height of 41.4 m. Each storey had masonry walls with a plank and joist floor system. In the ground storey, the three leaf masonry wall had inner and outer granite fascia blocks, and the core filled with brick bats in lime mortar. Stone masonry walls at the ground storey were reportedly 3m thick. In the upper storeys (up to the pinnacle), the masonry walls were made of burnt-clay bricks.

3.2. Observations prior to and post collapse
A prominent vertical crack was noticed along the height of the structure on the north-eastern and north-western sides, through masonry wall thickness, and widest in the top five stories (see Fig. 5a). Heavy rains lashed the region around 20 May 2010 (storm “Laila”). The structure totally collapsed on 26 May 2010 at 20:05 hours. Amateur video recording showed initiation of collapse of brick masonry between 3rd and 4th stories on the western side. Total progressive collapse occurred and the debris was heaped (see Fig. 5b). During inspection preceding the collapse, wet patches were noticed in the masonry at the 3rd and 4th stories. Sand in the infill material had washed out from between stones through the crack in the 2nd storey. The masonry appeared to bulge in the north-east corner of the 2nd and 3rd stories. Few granite columns in the central portion showed delamination and vertical cracks. Granite beams seemed displaced; gaps were evident between elements. The wide vertical crack observed a few days before collapse was present and growing over a rather long period of time. A photograph dated 21 February 2009, taken from the eastern side shows the presence of the crack on the north-eastern side, extending over at least two stories.

3.3. Inferences from post-collapse investigations
3.3.1. Laboratory tests on historic masonry
Lab tests on historic masonry samples retrieved from the debris were revealing. The samples do represent better quality masonry from the distressed structure, as they have survived within the collapsed structure. All lab tests (water absorption, compression/bending tests on units, compression

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5 http://www.youtube.com/watch?v=KvK-Fs0DAY&feature=related
6 http://en.wikipedia.org/wiki/Srikalahasti
test on masonry prisms as shown in Fig. 6b, UPV test on prisms and chemical analysis of mortar) point to a material, well within the expected strength profile of historic masonry. Compressive strength of masonry was 4.05-4.85 MPa, and elastic modulus was 977-1400 MPa. Hence, if the entire structure were to be made of material close to the one tested, failure should not be expected. Some portions of the structure possibly had suffered significant local strength deterioration due to moisture ingress. Video footage of the initial moments of collapse validates this.

![Image](image_url)

**Fig. 6** (a) Delamination in granite blocks prior to collapse (central passage, northern block); (b) Strain-controlled uniaxial compression test on masonry prism instrumented with strain gauges, LVDT and load cell.

### 3.3.2. Possibility of creep failure

The original cause may not be long-term compressive loading (creep), as compressive failure is accompanied by distributed vertical and sub-vertical cracks, absent here. The pre-existing vertical crack in the structure was sharp and concentrated. Also, the material strengths in intact portions of the structure (§ 3.3.1) suggest that the collapse cannot be due to material deterioration under creep effects. The rapid progress in the widening of the vertical crack could have possibly resulted in vertical detachment of the north-western and north-eastern portions of the tower from the rest of the structure, inducing eccentric forces on the supporting granite storey, which can explain delamination in granite blocks as a result of excessive compressive stress in the extreme fibres (see Fig. 6a). A large quantity of sand was seen in the debris (see Fig. 5c), indicating that it was a major ingredient of the infill in the three-leaf granite masonry. Typically, infill material is composed of brick bats, lime mortar and sand, which must have deteriorated considerably over time due to ingress of rainwater. Consequently, the gravity loads may have been carried only by the outer and inner fascia of the granite masonry.

### 3.3.3. Possibility of soil and foundation distress

Soft rock is seen at the site, at a depth of 3 m below ground level. Though no geotechnical studies were conducted after the collapse, collateral evidence, in and around the collapse site, suggests no appreciable change in ground levels manifested through settlements. Masonry or RC frame buildings in the vicinity showed no cracks due to settlements. In addition, portions of the stone masonry storey that are intact after collapse of the structure above it, suggests no evidence of any foundation distress.

### 3.3.4. Interventions on the Madras terrace floor

Oral rendition by locals reveal that in the 1960s, the Madras terrace floors supported on timber joists were found to be in a dilapidated state. A repair intervention was undertaken to replace deteriorated timber joists. The floor slabs were apparently cut open to facilitate removal of dismantled joists through the tower. New timber joists were never placed, pointing to a possible destabilisation of the floor diaphragm-wall system. Exposure of a weakened masonry system to the elements (moisture) could have accelerated the deterioration. In 1991, interventions led to replacing the Madras terrace slabs with RC slabs, when excessive deterioration was noticed in them. This delicate operation requires supporting the existing floor and casting of RC, before the former is removed completely. Details of the modus operandi are not known, but this could have contributed to the instability of the structure, if carried out without respecting its equilibrium. The floor diaphragm essentially ties the orthogonal walls together. Voids in the masonry should have been treated adequately after removal of timber joists and thick Madras terrace floors. Workmanship of executed repair is a critical factor.
3.3.5. Possible explanation for the collapse
The collapse of the Vijayagopuram could have been a phenomenon of accumulated damage from different sources, namely destabilising effect due to replacement of timber floors, rainwater seepage and subsequent weathering of masonry. Further, there is general ingress of water through the openings provided all over the tower. The collapse may have been triggered by the final degradation of the masonry, locally caused by the heavy rains prior to collapse. The crack facilitated seepage of rainwater into masonry walls over the years, accelerating washout of lime mortar. Collapse seems to have occurred under vertical load alone, once the material deteriorated adequately in few critical areas. Undertaking interventions on such structures without understanding the engineering implications of the interventions, namely importance of the floor diaphragm in the equilibrium of the structure, and the unscientific replacement of materials are important lessons from the collapse.

4. ANALYTICAL STUDIES ON A HISTORICAL GOPURAM

4.1. Prototype structure for analytical study
A prototype structure, the Rajagopuram of Sri Kamakshi Amman Temple in Kancheepuram, Tamil Nadu (see Fig. 7a) was selected for assessment and development of strengthening strategies. Distress mapping through visual survey was done for the gopuram. The survey revealed that while the granite three-leaf masonry and brick masonry walls showed no signs of structural distress or material deterioration, the timber joists and rafters supporting the Madras terrace slab were severely damaged (see Fig. 7b-c). This is a classical damage state described in § 2.2 and Fig. 3, which over time leads to excessive deflection of the brick-lime concrete floor. As discussed in the case of the collapse (§ 3), the role played by the floor diaphragm in tying the walls together and reducing lateral deflection of the masonry walls in the tower could be crucial. Structural modelling and analysis was carried out of a 3D elastic model solid model of the gopuram to study the effect of the floor diaphragm (see Fig. 7d).

4.2. Structural modelling and analysis
Solid tetrahedral elements were used to model granite, brick masonry walls and floor slabs on a PROE platform and analysed under gravity and lateral loads in an ANSYS workbench. Three models were developed to study the influence of the floor diaphragm on the structural behavior of the gopuram:
   a) Case 1: The gopuram modelled with the Madras terrace floor slab;
   b) Case 2: The gopuram modelled without the Madras terrace floor slab, to mimic a situation where such slabs have been removed due to excessive deterioration.
   c) Case 3: The gopuram modelled with an RC slab (i.e. a system with greater in-plane stiffness).

In case 1, the Madras terrace slab with timber joists and rafters was modelled as a brick-lime concrete floor of equivalent thickness ($t_{eq}$) after estimating the elastic stiffness, $K$, of the combined system (see Eq. (1), (2)). Slabs were modelled with fixed end conditions, due to sufficient bearing area within masonry walls. The granite three-leaf masonry was modelled as a single-leaf wall due to lack of information on the actual cross sectional configuration, including material properties of the core.

Fig. 7 (a) Rajagopuram of the Kanchi Kamakshi Amman Temple; (b-c) Deterioration of timber joists/rafters supporting the Madras terrace floor; (d) 3D solid model of the gopuram

1955
\[ K = \frac{1}{L^3/12E_m I + L/A_s G} \]  

\[ t_{eq} = \frac{[(\text{Volume}_{\text{brick-lime\ concrete}}) + m \times (\text{Volume}_{\text{timber}})]/A_s}{E_m/E_{\text{timber}}} \]  

\( L \) is the length of the slab normal to the direction of lateral force, \( E_m \) is the Young’s modulus of brick-lime concrete masonry, \( I \) is the section’s moment of inertia, \( G \) is the shear modulus, \( m \) is the modular ratio \( (E_m/E_{\text{timber}}) \).

**Fig. 8** Normal stresses (in Pa) at the base of the structure (a); entire structure under gravity loads (b) for case 2

Comparison of axial stresses at the base of the structure shows that there is no significant deviation in the compressive stresses across the cross section (1.17-0.76 MPa, see Fig. 8a) among the three cases studied. However, the tensile stresses in the brick masonry walls (~0.5 MPa) in the absence of the Madras terrace slab are not negligible. In addition, lateral deformations in the masonry walls for the same case increase by more than 50%, in comparison to the cases with slabs. With due consideration to the limitations of linear elastic analysis, it may be inferred that the Madras terrace floor system offers a certain amount of lateral restraint to the masonry walls of the tower. In the absence of such lateral restraint, masonry walls may be expected to undergo larger lateral deflections, and progressively over time, this can contribute to the weakening of masonry with initiation of tensile cracks, and in turn, increased deflections, finally leading to P-Δ effects, loss of stability and collapse.

### 4.3. A possible repair strategy

Post-collapse investigations (§ 3) and preliminary analytical studies (§ 4.2) point to the role played by the rather flexible floor diaphragm system in the equilibrium of tall, hollow masonry towers as the gopura. Deterioration of timber joists and the brick-lime concrete layer is very common. In view of challenges in the maintenance of timber in warm, humid climates, with structural safety and conservation as the main goal, it is suggested that in case of excess deterioration of timber elements, they be replaced with structural steel hollow box sections, adequately designed and matching the dimensions of the original timber sections. Granite blocks embedded within the masonry walls can serve as bearing blocks for the steel box sections to avoid stress concentration in the masonry.

### 5. CONCLUDING REMARKS

The current paper focuses on the structural safety of ancient masonry towers in South Indian temples. Experience from post-collapse investigations of an ancient gopura, visual surveys of existing gopuras to develop an abacus of damage and structural evaluation of one distressed structure, highlight the role of floor diaphragms in ensuring stability. Scarce maintenance is one of the prime reasons for deterioration of the Madras terrace slabs, including the structural timber elements.

The floor diaphragm enables tying of masonry walls together, and thereby reduces lateral deflection of the masonry walls. Though the removal of a weakened Madras terrace floor implies reduction of self weight of the structure, such a measure could result in increased lateral deflections of masonry walls due to the absence of the lateral restraint offered by them. The state of stress in the masonry walls, caused by increased lateral deflections, may consistently be increased additional lateral loads (wind or...
earthquake) and material deterioration. That is to say, the tensile stresses may reach a value for which the formation of cracks may be expected, and consequently a further increase in deflections. Undertaking repair interventions on historical structures, without understanding the engineering implications of the interventions, can have dire consequences. Repair solutions have to be evolved with due consideration to the existing equilibrium and load paths in the structure, its historical value, removability of interventions, but primarily structural safety.

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