"Indian Temples – a Structural Engineering Marvel"

A Brief engineering report on Indian temples

General :

India is a land of saints and spirituality, nature, art and culture; not only so in past the land was rich in economy also. Hence, it was attacked by many foreign armies in history. Almost for 6 centuries or more, *Moghal* army, European army have dominated the pre independence period in this land. The constant attacks, unstable political conditions and growing illiteracy, poverty, associated problems never allowed the common citizen to grow as an artist for the nation. But this was not the state six hundred years back. The land was rich in terms of not only its culture but also for the construction. Probably India was the land of 'Engineering' artists. Here, the old temples and forts have resisted the vagaries of the weather for centuries and they are the evidences of this statement. These temples have sustained floods, earthquakes, heavy winds with a very stable response; not only so a few temples have sustained the bombing by foreign armies in past and recently blasts, terrorist attacks etc. exhibiting stubborn design principles. In those days – architecture, planning, budgeting, designing, manufacturing and construction everything used to go hand in hand; the holistic or the 'Complete' thinking about the structure was a key principle behind the success and long life behind these structures. Thousand years back, when these temples were built, there were no established Design principles, testing methods, software, calculators, and spreadsheets etc. were available. Still the end results exhibited by these temples are fabulous (engineering performance in terms of forces, deflection, cracking etc). Thus these '*Vastus*' are really 'Structural Engineering Marvels'.

Fig.1 – Typical 'Shikar' of a South Indian Temple showing lowering of Centre of gravity, for better seismic response.

In the present paper, author has made an attempt to rejuvenate the memories of these 'Engineering marvels', and briefly discussed various components / corners of the construction, in light of known engineering principles, as on today. Hopefully the paper will help the state-of-the-art engineering to excel ahead by studying the past.

Introduction :

In India if we enter in a structure, where we can sense a great fragrance of flowers, *Dhoopa*; where we see pleasing architecture glowing a mild light of oil lamps (*Deepa*); where we hear a soothing music and *Vedic* chants (hymns and Mantra) which completely deep our sole in serenity, then we may rest assured that we are standing in an Indian Temple, because Indian temples is a place of 'peace'!!

India has many temples which are as old as 1000yrs or even more. As we know, mainly these temples were the places for spiritual practices / pilgrimage; but apart from that many temples were also used for education, accommodation and political movements, and as for practicing archery and gym (body building, yoga etc.) too. Most of the temples were built by the kings / emperors / '*Raja*' and '*Maharajs*' or even rich people like merchants and jewellers. Ancient temples were classified as per their era, viz. *Shiv-Kalin* temples, '*Pandav-Kalin* temples, '*Peshva Kalin'* temples etc. (word '*Kalin'* indicates the respective Era / time).

Fig.2 – Typical carving of Lord Ganesh – in Basalt,, at Ellora cave, Maharashtra

Mostly the temples were built in stone, with limited use of timber and metal (mainly for carving and architectural details). Strong stones viz. sandstone, basalt, marble was given a first choice. Often the Idol of a deity was preferred to be carved in a glazing-black coloured river stone from Nepal (stone obtained from River *Gandaaki*). But the local availability of the stone often used to decide the selection of material for construction of structural components. In certain cases the temples are found to be carved out of a single large rock formation (viz. caves and *Stupas*). The temples can be broadly classifies as North-Indian, south-Indian temples and central Indian temples, based on the style adopted. The availability of river water near construction sites, expert workers, elephants or bulls to doze the construction material has also made significant impact on the structure. The carving done in hard stone with fine grain size like marble, basalt and pink sandstone has shown better performance than the carving done in stone with large grain size or porosity, cracks, empty pockets etc. e.g. amygdaloidal basalt, Deccan-trap etc. (Refer, Fig.2 to Fig.5).

Fig.3 – Carved corbel at Adlaj Step well, Ahmadabad

Fig.4 – Elegant flower carving in Sandstone, at Adlaj Step well, Ahmadabad

Fig.5 – Scripts carved in stone walls

Mostly the religion of the king who built the temple, used to govern the 'Form' or the 'Style' of the temple.

Planning of theses Temples :

The planning of Indian temples used to start with selection of a correct site. The site usually

was selected so that the temples get intermingled with the surrounding atmosphere. Often planning of Indian temples used to be very exhaustive and critical issue; often the planning use to be done by a senior, visionary artist available with the king, keeping in mind almost all the possible issues apart from the technical ones – like the nature (environment), people around the temple, their culture, traditions, resource availability, funding from the kingdom, reach from the town (accessibility), security / safety from foe. No compromise was allowed, at planning and execution stage of the temple. The set principles / rules were never broken; as after doing so the person was supposed get heavy penalty or even imprisonment. The deity (or the god) for which temple is constructed used to be the focal point of entire construction, hence used be placed in secured, inner most chamber of the temple (popularly called as '*Gabhara*' or '*Garbha Griha*'). Next to the main deity, other deities also used to be considered for the planning.

The entrance of these temples often used to be, point of attraction. The temples used to be surrounded by mammoth size walls from all the four directions, each having one opening / entrance to the temple (popularly called as *Maha-Dwar*). Touching these walls, from inside, often small rooms used to be constructed, as shelter from people working and visiting the temple and even as storage space for goods, food grain required over the year. An access to the top of these rooms (terrace) was also a common practice. This access was found to be created using stone steps.

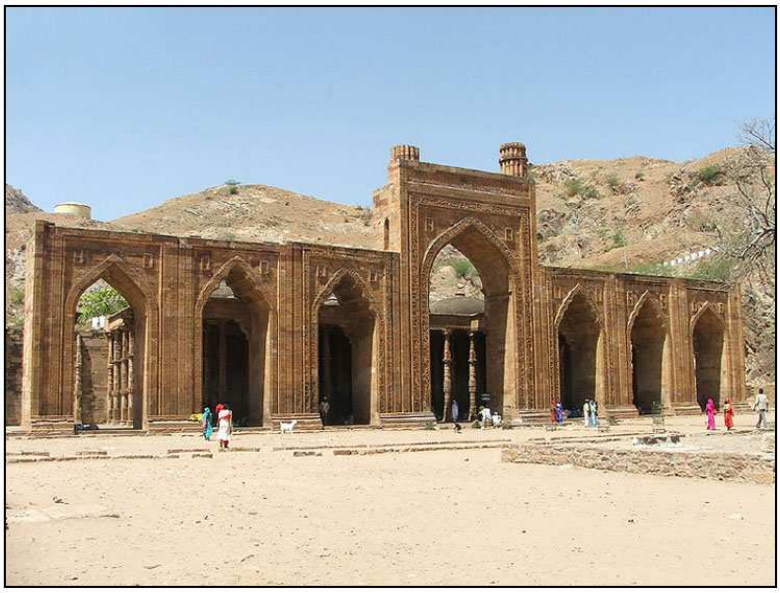

Fig.7 – Walls around an old mosque

Fig.6 – Typical Main Entrance

Fig.8 – Renovated Temple of lord Ganesh at Ganpati pule in lap of

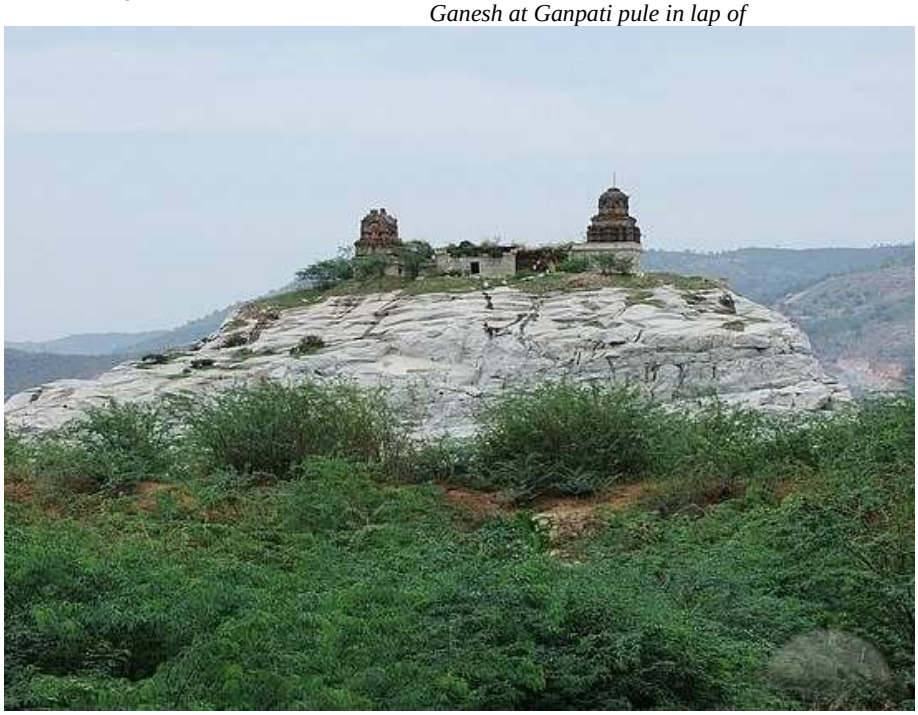

Fig.9 – Typical Temple located on the top of the mountain / hillock

Now a days we find these shops are occupied by shop owners / trustees of these temples and even illegal encroachments at certain places..

Each of the temple built by Maratha emperor (*Peshvas*) consumed about 5 lakh to 15 lakh rupees (almost three hundred years back) and about five to ten years time to construct each temple, with about hundred to hundred and fifty skill masons, working for day and night. The temples located in southern India, were mostly on flat ground (baring a few exceptions) and were constructed rapidly, unlike the old temples located on hills in top-northern India. We must note here that in those days software for 'slope stability analysis', 'soil stabilization techniques', 'deep foundation methods' etc. were not available the 'Planner' used to select sites with stable rock / soil mainly and only. To work inside the caves at higher altitudes, the visionary planners had devised a technique of 'using a reflecting metal surface (like mirror, reflecting a beam of light with sunlight) placed on the opposite hill slope. Old temples of *Kashi Visveshwara, Mathura, Kalaraam (Nasik), 12-Jyotirlinga, Devi-Temples (Kolhapur), Minakshi Temple, Surya Madir* etc. are some of the classical examples of Indian temples.

Structure :

The main construction used to be placed on a stable soil, on the massive foundation block. Often, the plinth level used to be of 6 feet height or even more than that. The foundations used to be dug deep below the existing ground level. To avoid seepage of water to the foundation, and even to facilitate the visitors to move around / encircle the temple, stone paving used to be provided on the periphery of the main temple. The paving used to keep the growth of large trees and shrubs away from the main temple, and thus helped to protect the

Fig.10 – Nicely decorated, yet heavy plinth of a typical Indian temple

Fig.11 – Stone paving in the temple area

footing. Because of the pavement it was possible to maintain the cleanliness of the temple also. During the festivals and processions, the stone pavement used to be helpful to act like a floor slab for people to dance, sleep, dine etc.

Fig.12 – Load bearing Pillars of the temple

On the massive foundation-plinth block the workers used to place strong pillars to withstand the entire vertical loads of the roof, except the central dome, just above the deity. The central dome used to be supported using solid stone walls on the periphery of the dome. Often these pillars (columns) used to be derived out from a single piece of stone, usually away from the site and then transported and placed at the desired destination. In rare cases it is observed that the columns are made up of two or more pieces glued together using organic resins or some times with molten lead. The

verticality of the columns was a critical issue, as in olden days there were no heavy load lifting devices / hydraulic cranes in existence. The job used to be done by a team of skilled masons along with helpers in a few weeks time, using a simple plumb bob suspended on all four sides from the top of the columns / capital. Considering the present situation and scientific growth the job done by our ancestors is very much satisfying.

The artists used to use circular / rounded pebbles (looking like potatoes) from the river bed to transport the heavy objects on the slopes (in absence of elephants or bulls or horses). The pebbles used to serve as ball bearings to roll-on the object. In a few case circular wooden logs were also used. Rarely even poor men / villagers were used in place of animals.

Fig. 13 – A typical view inside Indian temple (from Udaipur) with door of Central Chamber and the outer

Fig. 14 – Column with circular corbel (something like what is done in a flat slab roof)

Fig. 15 – showing stone roof projections on the edges of the temple

Fig.16 – Crud Arch form found in an incomplete temple

Mostly the columns used to have the brackets or corbels to place the beams on them (ref. Fig.3 and Fig.14), these corbels were sized such that the bearing stress was never a problem. The beams were of small length considering the limited flexural capacity (tensile strength) of the stone. Often the beams were found to have a gentle camber or replaced with the stone arch as shown in the Fig.16. The key stone can be prominently seen in this picture.

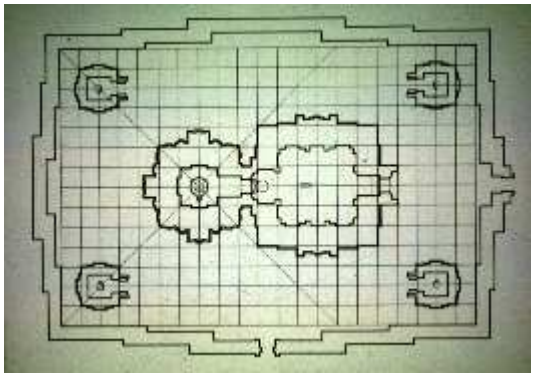

Fig.17a – Typical floor plan of an Indian Temple

In olden Indian temples constructed using seasoned wood (especially in northern most India and *Konkan* region), could have longer beam spans as timber has lesser weight and better performance in flexure as compared to stone. On the main beam seating on the corbel, secondary beams / slab panels used to be placed in stone or timber (as per the requirement), to form the roof enclosure. Lightweight stones like *slate* or *shell* were preferred more. The stone roof used to have even cantilever projection at the outer boundaries of the temple, the flexural moment at the end of the cantilever used to be resisted by burring the support under heavy dome / walls on the top of the roofs (ref. Fig. 15).

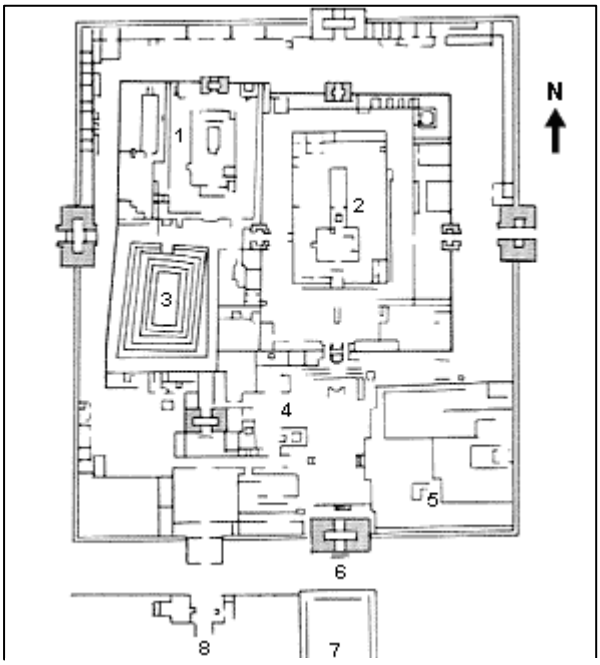

Fig. 17b – Typical Plan of One more Temple

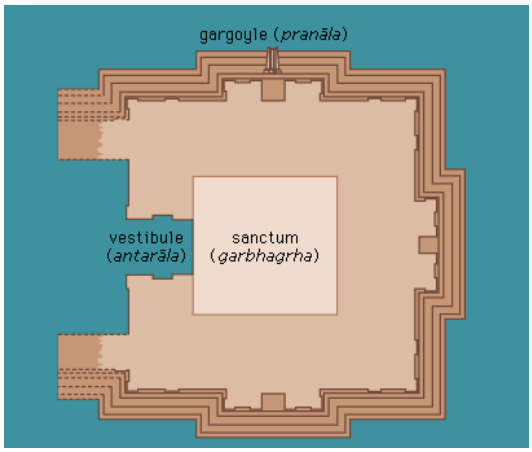

Fig.17c – Typical plan of Inner Chamber of an Indian Temple

In temple there used to be a numbers of so called non-engineered components (like parapets, architectural works, facia, drains etc). When subjected to adverse loads the performance of even these components was (though not excellent but) satisfactory, unlike the response we see in today's structures. Typical features around the temple like '*deep-mala*', 'water-lakes', 'flower garden', 'large size kitchens' etc are commonly seen in Indian temples.

In the olden days, the plan of temple used to be always symmetric (ref Fig.17), which we have realised very lately (described in IS:4326 and IS:1893 about plan irregularity and torsion effect on the structure). The strong walls of the innermost chamber from the deity and the outer chamber supported on the heavy columns can be seen clearly from this plan. During earthquake the solid stone walls of the inner chamber used act somewhat like a '*shear wall*' and helped to perform better. Those who have worked rigorously in earthquake prone areas may endorse this observation. Out of twelve main temples of lord Shiva (popularly known as *Baara-Jyotirlinga*), most of the *Jyotirligas* were founded on land which is an active seismic zone. These temples are more than thousand years old or so, still have very less impact of past earthquakes.

In olden days there was no concept of rigid 'beam-column Joints', 'Pusher-over analysis' 'plastic analysis' etc.; to sustain large loads the artists had to adopt a large numbers of columns. In many temples as there were large numbers of columns, it was difficult to have a column free space (and the sight was restricted, largely). Invention of high strength concrete and steel, prestressing technology etc. has resolved this problem to a great extent in the recent temples.

The temples which were constructed in dry / arid or dessert type land, water storage was of great importance. In such temples, tapping of perennial resources like large natural / artificial ponds / reservoirs / streams used to be very important task. Crack free bedrock for retaining

the water was also an important parameter which the planner had to keep in mind. Temples located in Maharashtra, Madhya-Pradesh, Karnataka it was not a major problem to source water but temples in Rajasthan of even in Hilly areas were built considering the problem of water retention in mind. Clay strata (in the form of aquifers / acquiclud) to store water was even used by the visionary artists.

Fig. 18 – Well-painted Stupa – which shows lowered down C.G.

Fig.19- Typical stepped water ponds

Even large size wells used to be a part of temples, especially temples on coastal region like *Konkan, Kerala, Orissa* where the ground water level used to be shallow and the supply of water from perennial underground streams was expected the well were dug there.

Construction of '*Shikhar*' or '*Minar*' or a '*Ghummat*' or a Dome above the central chamber (just above the main deity) was considered to be a most challenging task. A special team of skill masons used to work on this part of the construction. It

used to consume lot of time and money to build these typical structures. As the Shikhar of Dome used to be the highest part in the temple, and could be viewed from long distance the artist used display there all skills to make it perfect. The alignment, the joinery, the carving, the colour scheme used of the shikhar used to be done meticulously (ref. Fig-18, Fig-20). The part spherical dome is commonly found in Islamic temples. But this construction used to be very difficult, in absence of modern techniques.

A few *Minars* / *Shikhars* / Domes are found to be of about 200 feet or more height. It is a matter of investigation that how the masons would have erected the pieces so perfectly at this height and matched them! Study of many stone domes shows that the joinery was done using lime, resins or similar matter. But the key stone was kept very tight yet attractive. If we

Fig. 20 – Heavily carved stone temple from sothern India

analyse the shape, thickness of material as compared to the strength of material used, probably the masons have dome much better job. In those days the understanding about membrane forces, bending action in domes etc. was not know as we know in today's time. Then how the size of various units was fixed is not clearly know to modern science.

Fig.21 – Typical Buddhist Temple in Timber

Unlike stone temples, construction roof was not a complicated mater in temples built in timber. Only the stability yin heavy wind (in absence of self weight) was an issue of concern for timber roofs. The carving and the paining work done in timber structures is better than those in stone structures.

Maintainance:

From the structural construction it may be clear that the olden temples required very nominal maintenance. In most of the stone structures, the seepage of water and growth of vegetation,

algae was a commonly faced problem. In modern time the contractors just solve this problem using acidic solutions. But in olden days it was not a feasible solution. Hence in many olden temples we find damages due to vegetation growth also. The timber structures were damaged due to fires by the foreign army.

Fig. 22 - A typical Dome constructed in stone

Apart from the protection of structure from environment, protection from attacks of the Foreign army was a major issue which Indian temples have faced. The planning used to take care of the possibility of attack, still the attack done by use of launchers '*Toaph*' used to be an issue of worry. In certain temples were metals or molten lead was used at joinery, could sustain the bomb attacks to a great comfort. But other temples just got flat in such attacks.

Fig. 23 – Large size tree truck, barcnches, which have damaged the structure of the temple

Fig.24 – A largely damaged Stone temple in earthquake

In history many temples are found to be party constructed. Or even a few are constructed by unskilled labours. Most of such temples came down to earth during seismic activity also. The kingdom used to appoint a special team of workers to maintain the temples, law and order at these places. This could be the reason behind the sound health of these temples.

Forensic Investigation :

Till now we know that most of the olden temples have performed great in many ways (when we compare to the state of engineering developments in those days); but very less magnitude of research is found to be done on the 'Engineering Marvels' to really quantify there 'mass', 'stiffness', 'damping'. Numerical investigations to compute / predict the response to dynamic loads (viz. wind and earthquake), environmental loads, using sophisticated methods is not found to be done on a large magnitude. Core testing of the damaged parts, where the binding material is exposed is hardly done, by any one.

Estimation of Time period of these massive structures is another grey area. We do not mean that nothing has happened in terms of scientific studies till now; but whatever has studies have happened are very nominal. Computer simulations / mathematical studies etc. are rarely noticed. At some place experts from reputed Institutes are trying to improve the seismic behaviour of the temples using Base Isolation techniques (retrofitting). At a few places structural health monitoring devises are set to monitor and just the response. At ta few places protective coatings are prescribed by the experts. And many more attempts (which are still very limited) are on. . . coming Time will decide the effectiveness of these techniques.

Very less reliable data about the response of these structures in devastating earthquakes of Uttar-Kashi, Bihar, Jabalpur, Kutch-Bhuj, Latur etc. is available.

Conclusion :

Indian Archaeological department, civil and structural engineers, common citizens, local authorities have done handsome job to Identify and preserve this 'Structural Engineering marvels'. But still they need to be studied in more depth from 'mathematical' and 'Structural Analysis' and 'Design' point of view. Because in absence of intricate mathematics how the olden masons / workers were successful to quantify the structural behaviour, is the unsolved question? Also, in absence of modern concepts like durability, ductility, performance, strength, stiffness, flexibility etc. how the material has sustained for so many years (a large numbers of structures built in modern time start showing the signs of dilapidation in first ten or twenty years only !!).

Who will unwind the mystery of these structural engineering marvels !

* * *

References :

Following references were found useful for the preparation of this article :-

1) Temples in Maharashtra – published by Government printing press, Maharashtra
2) Indian Temples – CBS publisher, New Delhi
3) *Mandire aani Pratike* – (a book in Marathi Language)
4) Data on internet about Adlaj steeped well
5) Wikipedia
6) Various other websites
7) Various reference IS codes

Author of this paper :

Engr. Vivek G. Abhyankar- C.Eng
Life member - ACI (Ind), ICI, INSDAG, IIBE, IASTR, ISSE
Structural engineer,
Mumbai

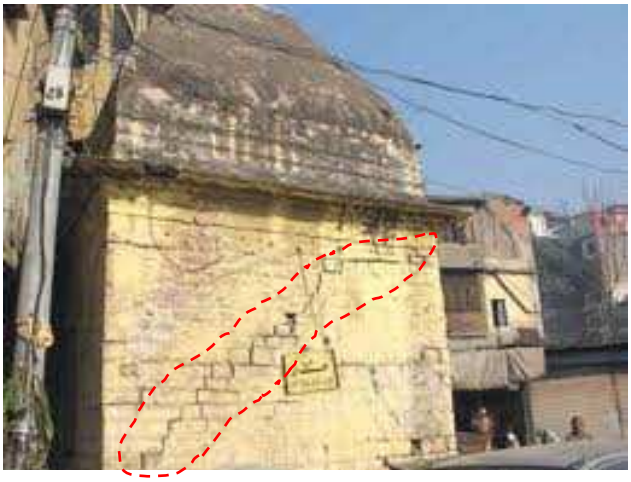

Fig.25 – Diagonal cracking in the Masonry wall of an Olden Temple

Fig.26 – A large temple went under water during flood

Fig.27 – A large temple went under water during flood

Fig.28 - Vertical Cracks through central axis (Temple outside Indian)

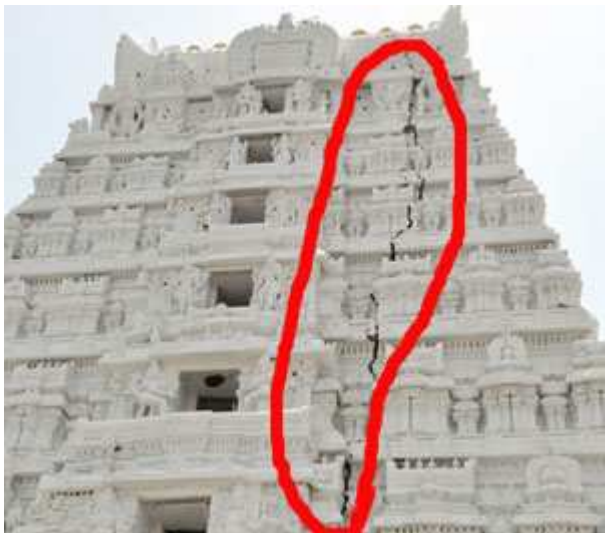

Fig.29 – Cracks in Large size Kalahasti Gopuram