Lightning Protection of Ancient Chola Monument in South India Based on Three-Dimensional Geometric and Electro-Geometric Techniques

S. Venkatesh, Srisailam Sreedhar, S. Thirumalini, Manjula Fernando, Sarath Kumara

Abstract*:*Lightning is one of the most commonly occurring natural phenomena which causes irrecoverable damage toedifices which include monuments that uniquely showcase global heritage. Most monuments are usually built tall since these signify symbols of victory, whereby invariably becoming vulnerable to lightning. Though several researchers have implemented various Lightning Protection Systems (LPS) to a considerable level of success, substantial statistical variations in prospective stroke currents during lightning due to factors such as climate change,complexities in geographical topography etc., present considerable challenges in obtaining a common framework for protection of structures. Hence, this research focuses on carrying out analysis based on exhaustive case-studies for an ancient United Nations Educational, Scientific and Cultural Organization (UNESCO) monument in South India. The first objective of this research is in carrying out detailed comparison of shielding effectiveness based on 3D geometric and electro-geometric LPS strategies such as Protection Angle Method (PAM) and Rolling Sphere Method (RSM). The second aims at assessment of risk in accordance with IEC 62305 for estimation of level of risk and the role of varying lightning protection levels utilizing striking distance models to obtain the appropriate choice of the location of air terminal. The third focuses on conducting cross-validation studies to assess the adequacy of the proposed location of LPS using SESShield-3D by depicting the critical zones that necessitate additional protection. In addition, shielding failure analysis of the proposed LPS is also carried out. Inferences on unshielded zones for the three-dimensional (3D) layout models of the monuments have been summarized with appropriate recommendations.

Keywords*: *Protection Angle Method (PAM), Rolling Sphere Method (RSM), Lightning Protection System (LPS), Lightning Protection Zone (LPZ), Stroke current

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I. INTRODUCTION

Lightning is a dischargecaused by a cumulonimbus cloud(thunderstorm) formed by a group of cumulus clouds. These clouds start at an altitude of 1.8 kmfrom ground level and extend up to 12 km with an anvil-shaped head at the top. Whenever the cloud is heavily charged, it begins to dischargein the form of lightning either to the nearest cloud (intra-cloud) or to the grounded structure. It has been observed that there are over 1.4 billion lightning strikes every year causing enormous damages more significantly to tall buildings and structures whereby resulting inits reduced mechanical strength and in rare cases total destruction of the edifices. In order to provide protection from direct lightning stroke, several researchers [1] have performed various laboratory and simulation studies to analysethe characteristics based on empirical curve methods, geometrical and electro-geometrical strategies to offer preventive measures formitigatingdamages due to direct lightning strikes. From this perspective, various strategies and standards have been developed to provide appropriate LPS. Such standards includeIEEE 998 [2], IEC 62305 [3] and NFPA 780 [4] etc., which provide guidelines on protection aspects for structures based on its dimensions, complexity of shape, presence of adjacent structures, risk indices, failure probabilities etc.

Incidentally, historical monuments and landmark edifices are faced with challenges related to lightning protection due to the trade-off between traditional perception (which includes apprehensions raised by the religious community) to modify the grandeur of the structure and scientific acumen and motivation to develop validated techniques for installation of LPS. Though during the past few decades LPS is being installed in heritage monuments, substantial statistical variations in prospective stroke currents during lightning due to several factors such as climate change, variation in monsoon activity, complexities in geographical topography etc present considerable challenges to researchers in obtaining a common framework for protection of structures. Notwithstanding, recently there have been significant instances of direct lightning strikes damaging the structure.

Hence, it has become imperative that a thorough analysis is carried out on such heritage monuments to ascertain the prospective risk of an impending direct lightning stroke. In this study a major sculpturally exquisite UNSECO heritage monument in south India viz., 'Gangaikonda Cholapuram' temple is taken up for detailed lightning protection studies. The study involves four major objectives. Firstly, the aim is on analysing and comparing the LPZ of the temple based on two strategies namely geometric method i.e., Protection Angle Method (PAM) and electro-geometric method i.e. Rolling Sphere Method (RSM) as stipulated in IEC 62305-3. The second, focus is on assessing the role of varying lightning protection levels and striking distance due to choose of location of lightning air terminals. The third objective is on cross-validation of the effectiveness of the proposed LPS in the monument utilizing SESShield-3D®package by identifying the critical zones during probable lightning strikes. The concluding task is on estimating the shielding failure probability analysis for existing and proposed LPS.

II. METHODS OF LPS - BRIEF REVIEW OF PAM & RSM

Based on exhaustive studies carried out by researchers to estimate and analyze the characteristics and physical properties of lighting, computation and estimation of various parameters such as stroke current, energy, charge etc. have been obtained and serve as a basis for devising four lightning protection levels (LPL) as specified in IEC 62305-1. These maximum current values relate to the threat for lightning protection of the equipment. Table I gives details about the level of protection and its current.

Table- I: levels of Lightning Protection with Maximum Current [3]

Lightning Protection Level (LPL)	I	II	III	IV
Maximum peak current (kA)	200	150	100	

LPL categories aid in assessing appropriate LPS for protection of structure based on PAM and RSM. The LPS system comprises three major components namely air terminal, downward conductor and grounding electrode. Air terminal is a metal rod consisting of a sharp end with no joints which in turn is placed at the top and corners of the structure. Downward conductor is a thin metallic strip attached from the air terminal to the grounding electrode to provide a path for the current flow to avoid damage to the structure. The grounding electrode helps in dissipating the lightning current to the ground. These components are utilized effectively by different LPS to provide protection for not only the structure with an LPS implemented but also to provide an area of protection that covers small structure under the protection zone.

A. LPS based on Protection Angle Method (PAM)

PAM was developed initially by Gay Lussac in 1823. This method presumes an inverted cone with a specific angle from the tip of the lightning rod as the zone of protection from lightning. The procedure is based on a three-dimensional (3D) concept wherein the protective angle offered by the rod is assigned a cone of protection by sweeping the line at the angle of protection 360º around the rod. PAM is popularly implemented mostly for transmission lines and substations for reducing incidents of damage due to direct lightning. However, this method has been found most appropriate for structures and buildings which are not very tall. IEC 62305-3 summarizes the findings related to the protective angle based on the ratio of the relationship between horizontal distance on the ground to the height of the rod. This correlation is depicted in Table II.

Table- II: PAM for Varying Angles as per IEC 62305 [3]

Height of the Struture (m)	10	25	40	50
Protection angle (α)	45	30	20	15

B. LPS with RSM

This method is based on electro-geometrical model which assumes that the point of lightning strike is determined when a stepped leader approaches a critical distance to get attracted by the earth or a tall structure known as striking distance. In this method an imaginary sphere of radius equal to striking distance is being rolled over and around the air terminals. The area under the sphere is considered as lightning protection zone. The radius of the sphere is dependent on the class of lightning protection system as referred in the below Table III.

Table- III: RSM with Reference of IEC [3]

Lightning Protection Level	I	II	III	IV
Rolling Sphere radius (m)	20	30	45	60

III. DESCRIPTION OF HISTORICAL MONUMENTS FOR LPS – GANGAIKONDA CHOLAPURAM TEMPLE IN INDIA

Gangaikonda Cholapuram temple which is located at Jayamkondam in Ariyalur district of South India, is a major UNESCO World Heritage Monument which was built by Rajendra Chola I, a king of the Chola dynasty. The name of the city (hence also the temple), which during the Medieval Chola period also became the capital of the kingdom during 1025 AD, was coined to commemorate the king's victory over another king of the Pala dynasty located near the Ganges. The temple is considered to house the largest linga deity (Hindu god 'Shiva') in South Indian temples measuring to a mammoth 3.96 m. The surviving temple in Gangaikonda Cholapuram was completed in 1035 AD. Though the reasons for the ravaged city are not well established, historians have attributed the destruction possibly due to several wars. It is worth mentioning that from the viewpoint of structural geometry and characteristics, the Gangaikonda Cholapuram resembles the Rajarajeshwaram complex (also called the 'Big Temple') in Thanjavur. The major monument of the temple complex is the 'Srivimana' (the main tower where the deity is located), which in turn houses the 'linga', exhibits cameos at space between pilasters and the niche sculptures at the central and end bays. The Srivimana in this temple comprises nine talas (storeys) as against thirteen talas in the Big Temple. The Srivimana is shorter than the Big Temple with a height of 48.77 m. Due to the reduced height, for similar base of the structure the profile is obviously more curvilinear and not pyramidal as that of the Big Temple.

A few distinct features and differences as compared to the Big Temple include exquisitely executed sculptures on the walls of the sanctum sanctorum, presence of khumbha-panjara (decorative motif carved on the outer wall surface) between the upper and lower recesses etc. The layout of the Gaingaikonda Cholapuram temple is shown in Fig. 1.

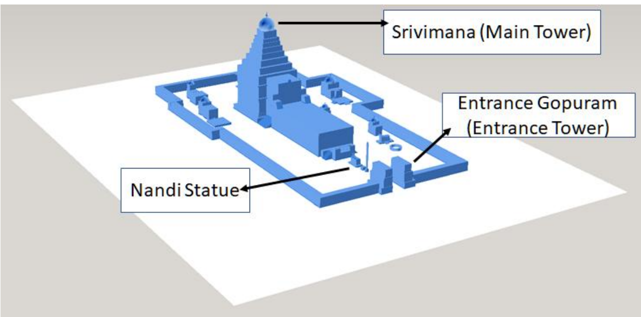

Fig. 1.Typical Layout of Gangaikonda Cholapuram Temple

A. Risk Analysis and Management for Lightning Protection System in Gangaikonda Cholapuram

The need for a carrying out lightning risk assessment becomes obvious and imperative since this procedure focuses on obtaining a credible estimate on the vulnerability of personnel and property so as to ensure an effective protective measure during lightning strike. In this connection, IEC 62305 provides a detailed and a well laid out procedure for carrying out lightning protection sufficiency analysis specifically for structures of cultural heritage so as to ensure evaluation of risk indices due to possible lightning strikes. The computation and evaluation methodology as per IEC 62305-2 [3] as a sequential process involves computing the Risk of loss of cultural heritage

$$R_3 = N_D P_B L_B \qquad (1)$$

Where N_D is the number of hazardous events due to lightning on buildings and structure and given by

$$N_D = N_G A_D C_D * 10^{-6} \qquad (2)$$

Wherein N_G is the lightning ground flash density and obtained from

$$N_G = 0.1T_D \qquad (3)$$

Where T_D is the thunderstorm days in the year;

A_D indicates the collection area for the flashes which is obtained from either A_D for isolated structures given from

$$A_D = (L * W) + 2(3 * H) * (L + W) + \pi * (3 * H)^2 \qquad (4)$$

or for complex structures with protrusions given by

$$A_D = \pi * (3 * H_p)^2 \qquad (5)$$

Where H_p is the height with protrusion

C_D represents the location factor; P_B is the probability of physical damage to a structure and L_B is the loss caused due to the physical damage which is obtained from

$$L_B = r_P * r_f * L_F * \frac{C_z}{C_t} \qquad (6)$$

Where r_P is reducing loss factor against fire; r_f denotes the reducing loss factor depending on risk of fire; L_F indicates the loss due to physical damage; $\frac{C_z}{C_t}$ is the ratio of cultural heritage in the zone to the total value of the structure.

Table IV summarizes the values of the various factors related to the computation of the lightning risk index for the heritage monument taken up in this research.

Table- IV: Risk Assessment parameters and Factors

Description for Factors involved in compting Risk Indices (IEC 62305-2)	Values Considered
Length, width and Height of the structure (Srivimana and adjoining structure)	Length – 184.06 meters; Width – 109.33 meters; Height – 51.04 meters
Tolerable risk value for the loss of cultural heritage property	10^{-4}
Thunderstorm days in a year (T_D)	55
Location factor (C_D)	1
Probability of physical damage (P_B)	1
Factor reducing loss against fire (r_p)	1
Factor reducing loss depending on risk of fire (r_f)	10^{-2}
Loss due to physical damage (L_f)	10^{-1}
Ratio of cultural heritage in the zone to the total value of the structure ($\frac{C_z}{C_t}$)	1

Based on the computation of the risk for indices it is evident from studies that the risk index of the heritage monument is $R_3 = 1.86 \times 10^{-4}$ while the tolerable value permissible as per IEC 62305-2 is of the order of 10^{-4}. It is pertinent to note that during the computation of the collection area (A_D) the area was obtained only based on the Srivimana though the super-structure in fact comprises other sub-structures of varying complicated geometries within the premises of the temple complex. Considering these factors, it is evident that R_3 will be a considerably large value thus necessitating LPS for the entire temple complex as overall layout. Incidentally, it is worth noting that a lightning rod is presently mounted atop the Srivimana.

B. Methodology for Implementation of RSM

Based on the various formulae for striking distance as discussed in the previous section, RSM procedure for the temple has been implemented in the following sequential steps:

Step 1: Selection of structure to be evaluated for lightning protection analysis

Step 2: Representation of the structure in 3D using AutoCAD and SESShield-3D

Step 2: Assessment of risk in accordance with IEC 62305 to estimate the level of risk (specifically for heritage monuments)

Step 3: Estimation of peak current (*I*) based on LPL as stipulated in standards

Step 4: Find out striking distance (r_s) in line with IEEE 998/ IEC 62305

Step 5: Based on calculation of r_s , roll an imaginary sphere over and around the structure

Step 6: Find out the critical areas, where additional protection is required and place air terminals accordingly

IV. RESULTS AND DISCUSSIONS FOR LPS

A. Results and DiscussionsBased on PAM

Detailed studies have been taken up utilizing AutoCAD® for designing the layout of Gangikonda Cholapuram temple for obtaining 3D plot of the LPZ and shielding effectiveness. Studies based on PAM clearly indicate the LPZ for the temple results in several significant regions of the Srivimana displayed as unshielded regions. Fig. 2 and Fig. 3 depicts the results during 3D analysis of the temple complex for varying protective angles as per stipulations laid out by IEC 62305-3 by considering the fixed height of the structure.

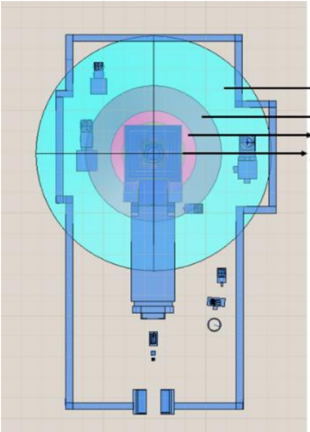

Fig. 2.Plan View Layout of Srivimana of Temple based on PAM

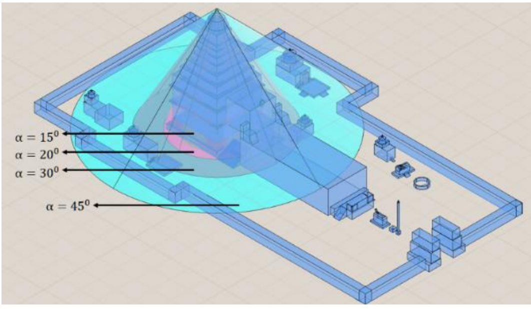

Fig. 3.3D Elevation View Layout of Srivimana in Gangaikonda Cholapuram Temple

It is evident from Fig. 2 and Fig. 3 that for the stipulated height as per IEC 62305-3, a protective angle (α) of 30˚ is not sufficient to ensure complete protection of the Srivimana, the balcony walls and structures in the first & second tier (talas). Further, the corners at these levels are under unshielded region of lightning strikes. It is also obvious from the studies that for α = 45˚ the LPZ under the shielded region substantially increases yet the entire structure of Srivimana including the adjoining structures inside the temple complex (Nandhi sculpture), entrance Tower etc., are not protected due to the placement of a single air terminal on top of the Srivimana.

B. Results and DiscussionsBased on RSM

Several researchers have performed analysis of RSM based on various striking distance formulae, of which a few significant and validated procedures have evolved into being a part of IEC 62305 for LPS shielding. Eriksson developed the collection volume model in 1987 to calculate the attractive radius for a vertical mast on a flat ground in order to improve the EGM. Later, modifications studied by Mousa and Srivastava [5] which established the relationship between the attractive radius r_a (m), lightning current I (kA) and mast height h (m) which has evolved into a specific formula for striking distance in IEEE 998 is given by

$$r_a = 8I^{0.65} \tag{7}$$

IEC 62305-3 and NFPA-780 [4] have adopted the empirical model and hence the formula for striking distance based on studies carried out by Love [6] for the initiation of upward leader by using electric field induced by the downward leader charge. This model proposed a relationship between striking distance and return stroke peak current is

$$r_s = 10I^{0.65} \tag{8}$$

Another variant of the striking distance is proposed by Cooray and Rakov [7] which is related to modifications for providing a more practical basis during modelling of a structure with a reasonably flat ground. This model gives striking distance as

$$r_s = 1.9I^{0.9} \tag{9}$$

Fig. 4 and Fig. 5 depicts the results for the shielding effectiveness based on RSM for varying classes of stroke currents as per IEEE 998 with stroke current 200 kA and 100 kA respectively. Fig. 6 represents RSM based on IEC 62305. Fig. 7 displays a plot of the RSM implementation based on the modified striking distance proposed by Cooray and Rakov [7]. These observations provide a clear insight into the appropriateness of LPZ and LPS for the heritage structure.

It is evident that for Class III and Class IV current strokes the vulnerable regions of balcony parapet and walls are unshielded and are possible regions of strikes. Only for stroke currents of magnitudes equal to and much lower than Class IV there could be a likelihood of damage to the balcony and parapet walls of the Srivimana. However, for Class I stroke current at the Srivimana, shielding of the balcony parapet walls is only meagrely under protective zone. This aspect is indicated in Fig. 4.

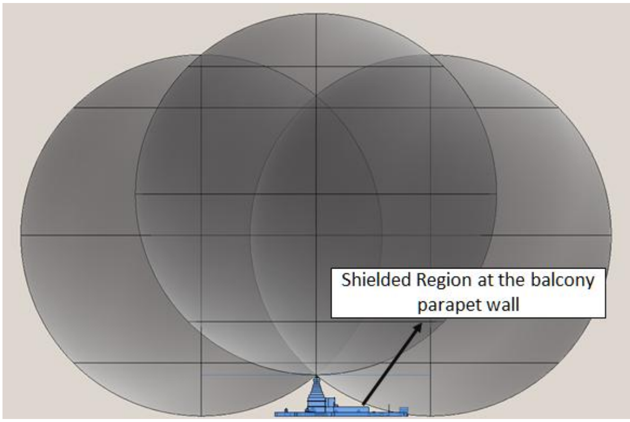

Fig. 4.3D Side view of RSM of the temple based on IEEE 998 – Class IV (200 kA)

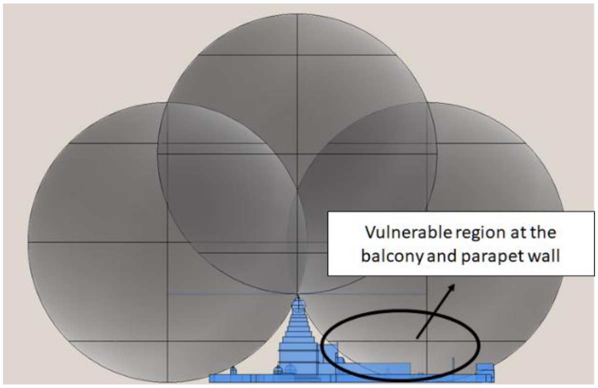

Fig. 5.3D Side view of RSM of the temple based on IEEE 998 - Class IV (100 kA)

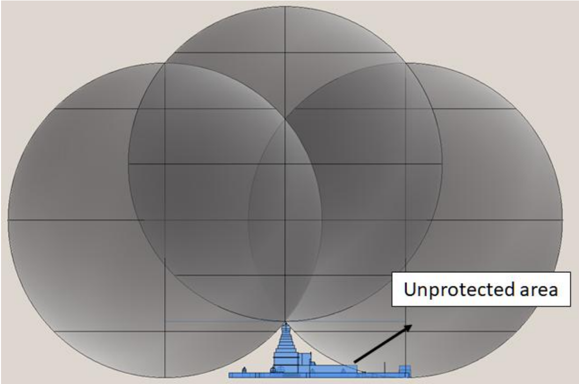

Fig. 6.3D Side view of RSM of the temple based on IEEE 998 - Class IV (100 kA)

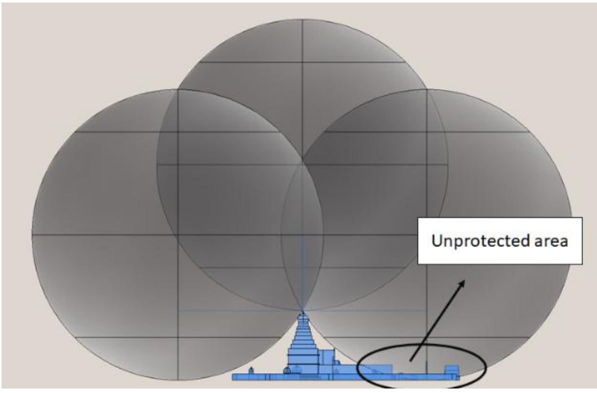

Fig. 7.3D Side view of RSM of the temple based on [7] for Class IV (100 kA)

For comparative studies and analysis, RSM based on striking distance formula as stipulated in IEC 62305-3 indicate a few significant changes in the LPZ of the monument. It is evident from studies that based on both the formulae for Class III and Class IV that there is insufficient protective zone in the balcony parapet walls. However, for Class I category it is evident that almost the entire temple complex is under the LPZ while the remnants of the entrance tower are susceptible to lightning. It is ironical that the entrance tower has been damaged during the past which has been attributed by historians due to ravages of wars or natural calamities. Table V summarizes the major observations related to unshielded regions in the monument for varying classes of stroke currents.

Table- V: Results of RSM

Class of LPL	Striking Distance (m)			Major results related to unshielded zones
	IEEE 998	IEC 62305/ NFPA 780	Cooray and Rakov	
200 kA	250.47	313.09	223.7	Entrance gopuram of the temple is unshielded
150 kA	207.7	259.69	172.67	Second tier parapet wall and corners are unshielded; Also, flagstaff and entrance gopuram are also unprotected
100 kA	159.6	199.52	119.88	Second and third tier of parapet wall are unshielded; Also, flagstaff and entrance gopuram are unprotected

C. Results and Discussions Based on Validation of PSM and RSM with SES Shield 3D®

SESShield-3D® is a powerful application software exclusively utilized to model and analyse the lightning shielding protection systems for complex structures that includes substations, industrial plants, tall edifices etc as a 3D layout provides complete lighting shielding analysis for a structure having various geometrical shapes. In addition, the package provides facility to carry out detailed analysis based on PAM, RSM based on IEC 62305 and IEEE 998 with various LPL classes, varying formulae for striking distance, failure probability analysis etc.

In order to ascertain the effectiveness of the detailed studies carried out based on AutoCAD modelling of PAM and RSM, cross-validation studies have been performed for the heritage structure. Analysis related to PAM based on SESShield, depicted in Fig. 8 and Fig. 9 justifies the observations made based on 3D analysis using AutoCAD.

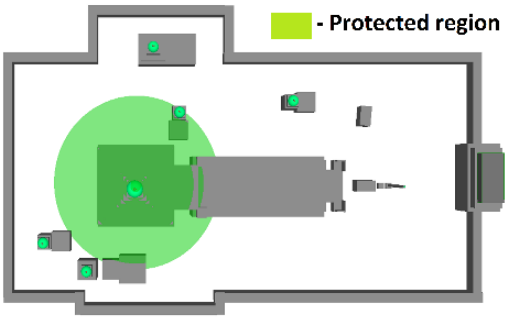

Fig. 8.Plan view layout of Srivimana in the tmeple based on PAM

Based on cross-validation studies carried out for heritage structure for varying striking distance formulae as well as for different class of LPL as indicated in IEC 62305, it is evident that the entrance tower is not protected for Class I while for those of the other classes (Class II, II and IV), the balcony and parapet walls of the Srivimana are found unshielded and does not lie under the LPZ. Fig. 10 and Fig. 11 indicate the highlighted region for the results obtained from SESShield-3D. These plots clearly concur with the studies obtained using AutoCAD for various LPL stroke currents.

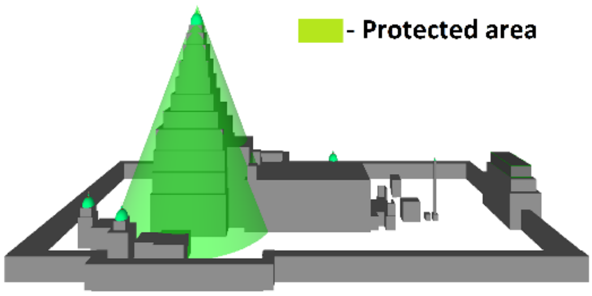

Fig. 9.3D Elevation view layout of Srivimana in the Temple based on PAM

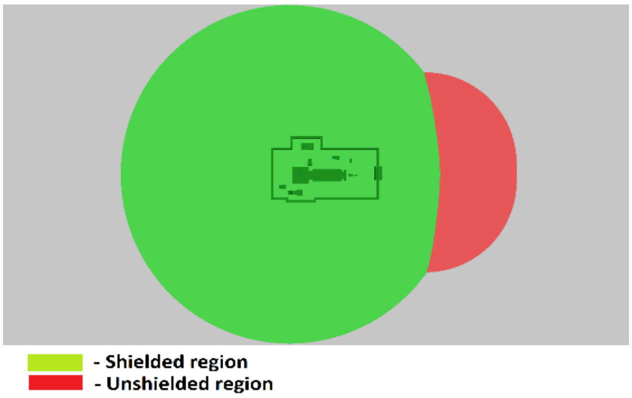

Fig. 10. Layout if Srivimana in the Temple based on RSM

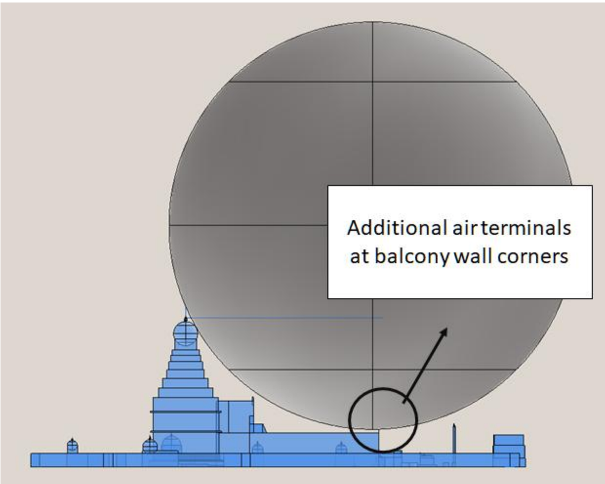

Fig. 11. Plan View Layout of Srivimana in the Temple based on RSM

D. Results and Discussions Based on Shielding Failure Analysis

This analysis is performed to estimate the effective functionality for an installed LPS on a structure. Various parameters are essential for the calculation during this analysis, such as ground flash density, keraunic level, stroke current etc. This analysis is performed to estimate the effective functionality for an installed LPS on a structure. The Ground Flash Density (GFD) is given by

$$N_g = kT^a \tag{10}$$

Where, T is the average annual Keraunic level (thunderstorm days) and 'a' is the exponent of the empirical relationship. The number of flashes in a given area is computed as

$$X_g = N_g A \tag{11}$$

Where A is the area in km2. The probability of a strike exceeding the peak current can be estimated from

$$P(I) = \frac{1}{1+(\frac{I}{I_m})^{\alpha}} \tag{12}$$

Where I is the specified crest current of the stroke in kA, I_m is the median stroke current of the distribution in kA and α is the exponent of the cumulative probability function. The Shielding Failure Rate (SFR) is estimated for the number of strokes that are not being protected and ending up in the unprotected zone of the system within a period of a year, given by

$$SFR = -\int_0^{+\infty} \frac{dP(I)}{dI} \times N_g \times A(I)dI \tag{13}$$

Where $A(I)$ is the unprotected area for a given stroke current I, $dP(I)$ is the probability of peak current in any stroke lying between I and $I + dI$.

For Gangaikonda Cholapuram temple, the SFR is estimated with the parametric values of keraunic level as 55 which gives GFD = 6.6, during thunderstorm days and the computed results are shown in Table VI

Table- VI: Results of Shielding Failure Analysis

Stroke Current Range (kA)	Unprotected Area (m²)	Probability of Stroke (%)	Expected Number of Failures(Failures/Year)
1 - 5.95	24846	2.57	4.218×10^{-2}
5.95 - 10.9	26629	8.80	1.546×10^{-2}
10.9 - 15.85	26572	14.00	2.454×10^{-2}
15.85 - 20.8	25672	15.43	2.614×10^{-2}
20.8 - 25.75	24117	13.76	2.189×10^{-2}
25.75 - 30.7	22454	10.92	1.618×10^{-2}
30.7 - 35.65	21001	8.19	1.136×10^{-2}
35.65 - 40.6	19661	6.02	7.812×10^{-3}
40.6 - 45.55	18332	4.42	5.342×10^{-3}
45.55 - 50.5	17030	3.27	3.672×10^{-3}
50.5 - 55.45	16111	2.45	2.602×10^{-3}
55.45 - 60.4	15375	1.86	1.887×10^{-3}
60.4 - 65.35	14770	1.43	1.398×10^{-3}
65.35 - 70.3	14309	1.12	1.06×10^{-3}
70.3 - 75.25	14139	0.89	8.294×10^{-4}
75.25 - 80.2	14054	0.71	6.613×10^{-4}
80.2 - 85.15	13917	0.58	5.313×10^{-4}
85.15 - 90.1	13787	0.47	4.315×10^{-4}
90.1 - 95.05	13717	0.39	3.554×10^{-4}
95.05 – 100	13624	0.33	2.947×10^{-4}

Hence, it is obtained from studies that the total expected number of failures per year is 1.467×10^{-1}or 6.8178 years between failures.

V. CONCLUSIONS

For the Gangaikonda Cholapuram temple that has been considered for the estimation of level of risk and evaluation of shielding analysis the following detailed modelling and simulation activities that have been carried out:

1. PAM has been implemented to evaluate the protection zone of the temple in addition to ascertain the vulnerable points of lightning strikes.
2. Various protection angles have been verified as stipulated in IEEE 998 / IEC 62305.
3. RSM has been implemented with the striking distance formulae as specified by IEEE 998, IEC 62305 and NFPA 780.
4. Various levels of stroke currents have been considered to analyse the effectiveness of the shielding provided by the pre-installed LPS.

Hence, based on detailed analysis of the LPS for Gangaikonda Cholapuram temple, a few important deductions which are essential for minimizing the risk related to direct lightning strike on the historical monument are summarized:

1. It is essential to consider additional air terminals at the balcony and parapet walls on the second and third tier of the Srivimana as indicated in all the methods (PAM and RSM) for almost all the LPL stroke

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current values and for different formulae of striking distance.

2. For only one air terminal placed on top of the Srivimana it is also made evident from failure assessment studies that notwithstanding the lack of complete protection for the temple infrastructure, the likelihood of lightning strike is observed to be 6 years. This necessitates additional air terminals for the unshielded regions to ensure any probable damage to the structure at the corners of the balcony and parapet walls.

3. Based on the detailed studies and analysis, as a part of this research it is recommended that two additional air terminals, each installed on the corners of the second tier (tala) balcony parapet walls would ensure more reliable LPS for the Gangaikonda Cholapuram temple precincts. This would in fact ensure protection from strikes for stroke currents of lower values (much below 100kA) also. A typical scheme of the proposed arrangement is depicted in Fig. 11.

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