Defining lightning-safe structures for all socio-economic communities

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Four levels of lightning-safe structures are defined based on the protection expected from various lightning injury mechanisms under thunderstorm conditions. This work, therefore, provides clarification for the long-standing issue of determining the most suitable recommendation for lightning safety in various socio-economic layers of society, especially in underprivileged communities. These globally uniform and consistent guidelines will help standard development committees, lightning safety seekers and donors of protection systems, state policy developers on disaster management, the insurance sector and industries that provide lightning protection, in determining the most appropriate lightning safety measures for a given target, based on the safety requirements, societal behaviour and affordability.

Significance:

- Lightning safety module developers could confidently adopt the definition of safe structures provided here in their guidelines.
- The ambiguity on both indigenous and commercial lightning safe structures (purpose made) is cleared.
- Standards could specify the essential features of a structure that can be considered lightning safe.

Introduction

During the last century, the lightning-related death count reported in developed countries such as the USA shows a significant decrease.[1-5] Experts have cited this decrease as being due to the lightning safety awareness programmes, improvements in the national education system and urbanisation.[6]

On the other hand, the statistics of the last two decades reported in many developing countries show a significantly high number of deaths per unit number of population (usually given in deaths per million or 10 million people), with South and South East Asia[7-10], Africa[11-13], and Latin America[14-16] leading in the number of casualties. Unfortunately, there are no statistics of fatalities available in most of these countries to compare whether there is a variation in the number of casualties over a long period. Several studies have attributed this relatively high number of lightning-related deaths and injuries in developing countries compared to those in the developed world to high lightning ground flash density (most of the developing countries are in the tropics whereas developed countries are in temperate regions), high population density, low literacy rate, labour-intensive outdoor employment, and lack of medical and healthcare facilities, etc.[17,18]

If there has been an increase in the number of casualties over the last two decades, then one of the major reasons will be the wide expansion of communication and media accessibility to even the most remote societies and isolated settlements over the world.[19-22] Furthermore, the rapid population growth, which leads to more outdoor work and unsafe sheltering, migration of communities from high vegetation to low-grown landscapes, and even the increase in thunderstorm activities could not be overlooked without proper research or survey.

Many of the above studies and further investigation in Africa[23,24] on the pattern of lightning-related incidents reveal the following observations:

1. In developed countries, a majority of incidents are related to outdoor activities or seeking shelter in temporary structures such as camping tents, bus stops, and golf carts.
2. In under-developed countries, especially in the less-privileged communities, a significant number of incidents have taken place while the victims were taking shelter in permanent structures such as homes, churches and other religious structures, schools, and agricultural stores.
3. In the case of (2), the number of deaths and injuries in each case is most often between 2 and 20.
4. In underprivileged communities, the location of the incident reveals that, even if the victim is aware of the danger of lightning, they could not move to a lightning-safe shelter within a reasonable distance from the location of the incident.

These observations raise the question of where a safe place would be for a person to seek shelter if a thunderstorm were at close range? Then follows the inevitable question: what types of structures are considered to be lightning safe? The answers to these questions are of significant importance to the committees that develop standards, national disaster mitigation policies, and the insurance sector.

Holle and Zimmermann et al.[25,26] have provided information on suitable locations to seek shelter in thunderstorm conditions. Zimmermann et al.[26] state that large, enclosed structures, such as those with plumbing and electrical wiring, may be safer than small or open structures to seek shelter in a thunderstorm. This information is valuable for the general public to minimise hazards from lightning, but these authors do not provide specific reasons for their recommendations or specify all the necessary conditions for a structure to be considered lightning safe.

Therefore, to date, no standards, guidelines or research publications have provided a well-specified and consistent definition to be used to classify a structure as lightning safe or not, and, for those structures classified as lightning safe, from what type of lightning effects. The aim of this study was to resolve this long-standing requirement in lightning safety science.

Lightning-related injury mechanisms

Lightning affects living beings through various modes, which are termed lightning injury mechanisms. Here, we use the term 'living being' for a human being or other animal (plants are excluded), which may be subjected to lightning-related injuries.

Lightning may affect living beings through several primary and secondary injury mechanisms.[27-31] As is the case in many lightning-related risks and effects, the 'primary' and 'secondary' effects are not well defined in the literature. Thus we provide the following definitions for these mechanisms.

Primary injury mechanism

A primary injury mechanism is one in which a mode of lightning affects a living being due to the lightning current itself or a primary effect of the lightning current.

As per this definition, primary injuries include an injury due to the passage of current in the body due to direct injection or a potential difference across body parts caused by the lightning current; generation and propagation of shock waves due to the heating of air due to the lightning current; and emission of intense light/UV radiation due to the passage of lightning current in the air. Thus, the following seven cases could be categorised under primary injury mechanisms.

1. Direct strikes: direct injection of current into the body
2. Side flash: current entering the body through an arc from a lightning-struck object
3. Step potential: current flow due to the potential difference between two parts in contact with different ground points
4. Touch potential: current flow due to the potential difference between two parts in contact, typically with a point in the current passage and ground
5. Upward streamer: unsuccessful upward streamers from the body of the victim in the vicinity of a stepped leader
6. Barotrauma: skin and eardrum damage due to the shock wave
7. Intense light: vision impairment (temporary and long-term effects) due to the emission of high-intensity light, either in visible or UV spectra

These injury mechanisms apply to all living beings, both humans and other animals.[32] Note that if the lightning energy transfers to a service line, such as electrical or communication networks, either by resistive or inductive coupling (capacitive coupling would hardly pose a threat to life), it may affect an occupant inside a structure through arcing (which may be categorised as a side flash). If that energy transfers to the earth wiring system, both step potential and touch potential injuries are possible.

Secondary injury mechanism

A secondary injury mechanism is one in which a mode of lightning affects a living being through a secondary physical process between the current flow and the injury point.

The following cases are a list of possible secondary injury mechanisms:

1. Heat, emission of toxic gases, shooting of firebrands etc. due to a fire erupted by lightning
2. Flying wood splinters due to the explosion of trees and similar objects due to lightning
3. Falling of heavy objects detached from structures struck by lightning (e.g. detached masonry or concrete)
4. Falling from heights due to structural instability or psychological shock caused by lightning
5. Collapsing energised power lines or exploding transformers
6. Psychological trauma due to intensive pain or witnessing carnage caused by lightning in the vicinity

These secondary injury mechanisms are mostly environment-dependent. Thus, those who seek protection against lightning should be aware of the risks of potentially dangerous objects in the vicinity.

Lightning safe structures

Existing lightning safety measures and the need for defining safe structures

Over the last century, the concept of seeking shelter in a safe structure under overcast conditions has been commonly used in lightning safety guidelines, policies, and research documents.[6] However, there is thus far no proper definition for a safe structure against lightning. In many developed countries, homes and most other commercial/industrial buildings are considered sturdily built structures that could protect an occupant from lightning-related injuries. The popular slogan in the USA among lightning safety promoters, 'when thunder roars go indoors', may have been formulated in consideration of these sturdy structures being lightning safe.[6,33]

On the other hand, many studies from South Asia[17,34], Africa[11,35] and South America[15,36] reveal that the situation on these continents and subcontinents is different from that of developed countries. The majority of rural communities and under-developed communities even in urban areas in such regions live in thatched-roofed and clay-walled shelters, wooden structures covered with thatch or iron roofing sheets, or in polythene or fabric-covered metal/wooden structures. Most of these shelters, which the communities call their 'homes', are far below even the quality of tents at camping sites in developed countries. The condition of sheltering structures in the workplace environments of these communities is not very different from that of their homes.

For these underprivileged communities, it may not be advisable to seek shelter in such unsafe structures under overcast conditions. In fact, a significantly large number of lightning-related casualties reported in Africa[13] and South Asia[34] are associated with such structures. In most of these cases of indoor accidents, there were multiple deaths in a single incident[37], whereas in the majority of outdoor incidents, the number of victims was either one or very few[38].

The lightning-unsafe nature of long-occupied structures (homes or workplaces) of a vast majority of communities in densely populated South Asia is a significant challenge in curbing lightning accidents in the region. Note that several lightning safety modules have been launched in the region over the last two decades by several expert groups.[39,40] Although methodical assessment of the success of these programmes has not been carried out so far, the high number of frequently reported lightning accidents may be an indication of the inability of the programmes to achieve their objectives.

The behavioural pattern of the public in underprivileged societies, under thunderstorm conditions, has been studied previously.[8,23,40] In many such communities, a majority of the workforce earns their income on a daily wage basis. In many cases, the wage given at the end of the day is performance-based (output of the assignment). Thus, in the event of an approaching thunderstorm, the outdoor workforce will be very reluctant to stop their work and retreat to a safe shelter which may be at a considerable distance. Such a work interruption would cost them a few hours of their daily wage, which could have a significant impact on their lifestyle. The pattern of lightning deaths observed in countries such as Bangladesh[39], India[10,41], Sri Lanka[42], Uganda[23], and Zambia[13] shows that the majority of outdoor accidents have taken place on agricultural fields, lakes and lakeshores, construction fields, and mining sites. It is evident that, in most cases, the victims have remained at vulnerable locations despite their awareness of the risk, due to a reluctance to stop working. The majority of lightning safety modules that have been developed for these underprivileged communities have not been successful[40], as the module developers have failed to take these human behavioural patterns into account. The prime reason for such an oversight may be the direct adoption of safety modules from developed countries. These modules have proven to be highly successful over the last century in many developed countries[1], where the labour laws dictate that safety measures should not have adverse impacts on employee wages.

In the above context, in underprivileged communities, it is imperative that the authorities of the country (local or central governments), non-governmental donor organisations or employers provide lightning safe structures at group or individual scales at workplaces. Because of the financial limitations of these countries, safety providers will give due attention to maximising the gains of their investment. This demands consistent standardisation of the level of safety provided by the protection measures. Even in wealthy communities and commercial sectors, cost-optimisation is a well-practised concept, thus, to invest in lightning protection measures on any scale, the investor will require a cost–benefit analysis.

As the cost of a lightning protection system (LPS)[43] for a given housing structure may be several times higher than the annual income of most people in many developing countries, it is highly unlikely that individuals will adopt standard protection measures, even if the lightning risk level is high. This high cost has prompted entrepreneurs in several South Asian and southern African countries to invent low-cost lightning protection measures in the last few years (author's personal experience). However, in the absence of any benchmarking or guidelines for these protective measures, a majority of safe structures or safety measures introduced to the public in these countries carry a high risk of failure, inviting lethal injuries and property damage to the protection seekers.

Another concern regarding safe shelters has come into the spotlight as purpose-made safe shelters have become a research interest in the last few years[44] – namely that these purpose-made safe structures require standard criteria to be qualified as lightning-safe structures. Thus, a consistent definition for levels of safety of such structures is a need at present. Figure 1 shows a safe shelter that has been tested in the high voltage laboratory at the University of the Witwatersrand in South Africa.

Photo courtesy of Mr Tim Mukansi and Mr Mathew Woodhead

Figure 1: Personal purpose-made lightning safety structure under impulse current testing in South Africa.

The scientific frontiers, especially standards committees, need a platform, based on accepted scientific norms, to develop quantitatively specific guidelines for safe structures. Therefore, it is a requirement at present to develop a set of definitions for various types of lightning-safe structures, that are either in practice or at the research phase. The formulation of design, material and implementation specifications, considering both safety and affordability of the public, will be the next phase of this study which usually needs a collective contribution from a group of experts (technical committees of standards institutes).

Proposed definitions for lightning-safe structures

Safe structures are defined at four levels based on injury mechanisms. The definitions allow designers to determine the required level of protection depending on the practicality of constructing/accessing the structure and human behaviour in thunderstorm conditions, especially in underprivileged communities (Table 1). The level of safety increases from Level IV (least safe) to Level I (the safest).

Table 1: Definition of lightning-safe structures

Safe structure level (SSL)	Definition of the structure
SSL IV	A structure that protects the occupants only from a direct strike, side flash, step potential, touch potential and upward leader.
SSL III	A structure that protects the occupants from all primary injury mechanisms but not from the effects through service lines.
SSL II	A structure that protects the occupants from all primary and secondary injury mechanisms but not from the effects through service lines.
SSL I	A structure described as at SSL III with a coordinated surge protection system and reasonably good electrical earthing system.

Safe structure levels (SSL) IV and III are suitable for protection seekers or protection system donors that have a restricted budget but still need at least basic protection. Many structures may be considered SSL IV or III, as they are or with a few low-cost modifications, once proper guidance is given to the occupants regarding appropriate occupancy. Structures at SSL IV are ideal for group protection of bound communities (fisheries, farming, mining, informal settlements, construction industry, etc.). It may be productive to incorporate safe structures with periodic awareness programmes for potential users. At workplaces, as there is the possibility of periodic workforce replacement, such programmes should be repeated and made compulsory (they could, for example, be incorporated with regular fire drills).

SSL II and SSL I are typical of sturdy buildings found in many developed countries and middle/upper-middle-class societies in developing countries. However, in most countries in the world, installation of surge protection devices is not compulsory, thus, a majority of domestic structures do not have internal lightning protection. Therefore, SSL II structures may be much larger in number than SSL I structures. It is not uncommon that a significant number of indoor lightning accidents involve victims who were using plugged-in electrical appliances at the time at which they were affected, according to news reports.[45-47] Thus, apart from safeguarding equipment and service systems, surge protection plays a vital role in human safety as well. Industrial and commercial buildings, hospitals, IT academies, etc. should be upgraded to SSL I, especially those in regions of high lightning ground flash density.

The following structures are categorised according to each level:

SSL IV:

1. A building with roof and floor made of concrete, having no covering walls but large in internal space, with or without external LPS. The internal space is large enough to avoid occupants being subjected to side flashes or step potentials if there is no LPS installed. The International Electrotechnical Commission[48]

specifies at least 1 m (preferably 3 m) separation from possible lightning current paths (in this case, possibly concrete pillars) and also among occupants. The size of the internal space should be sufficient for such spaced occupancy.

2. A building with a metal roof that is firmly connected (both mechanically and electrically) to metal struts, having no covering walls but large enough in internal space to allow the abovementioned spaced occupancy, with metal struts properly grounded (typically, factory buildings).
3. A structure with any type of roof, having no covering walls, but with properly designed external LPS, preferably with a ring conductor.[43]
4. A purpose-made safety structure with no covering to absorb the shockwave or to prevent intense light. Note that at present many of these purpose-made safe structures are in design or testing phases, thus, there are no standards for their quality assurance.

SSL III:

1. All structures specified under SSL IV but with a covering material or reasonably good shielding to absorb the shockwave and prevent intense light. Note that building structures described under (1) and (2) in the above category (SSL IV) would be considered SSL II if they had sturdy walls (made of brick or concrete) or were covered with electrically continuous and mechanically stable metal facades/sheets.[43]
2. Thatched roofed houses (fully covered) with properly designed LPS. Note that thatched roof houses without LPS do not fall under any SSL.
3. If the occupants wear earplugs, eyewear that cuts off intense light and UV, and clothes that are capable of absorbing the shockwave, then a structure at SSL IV can be treated as at SSL III.

Note that if SSL IV or SSL III structures are provided with a coordinated surge protection system they could be denoted as at SSL IV* or SSL III* but not as SSL II or SSL I.

SSL II:

1. A fully covered large sturdy structure made of concrete and/or brick walls, with no possibility of internal materials collapsing, being displaced or catching fire in the event of a lightning strike (either due to the lightning current itself or a secondary effect due to lightning such as a falling tree), with or without external LPS. Examples are cinema halls, shopping complexes, large hotels, and large hospitals.
2. A small/medium-sized, reasonably covered structure with properly designed external LPS and situated at a location far from being affected by secondary mechanisms such as falling trees. Brick-walled and tile/metal-roofed domestic buildings can be considered to be in this category.
3. A metal cargo container turned into a housing structure with proper ventilation. Note that if such a housing structure has no external service line (electricity or water) penetrating it, the structure can be treated as at SSL I.

SSL I:

1. All structures that fulfil the criteria for SSL II, and that have a coordinated surge protection system and power earthing system according to the relevant electrical standards. The installation of coordinated surge protection devices has been specified comprehensively elsewhere[49]. Further discussions on the subject can be found in Gomes[32] and Gomes and Gomes[50].
2. All structures that fulfil the criteria for SSL II and that have no service lines penetrating the structure from outside could also be treated as at SSL I. Hence, vehicles with a fully covered metal structure with a minimum thickness of 0.5 mm (steel) or 0.7 mm (aluminium) of the body cover[43] could be considered as at SSL I.

Note that the above classification considers only the safety of the occupants; it does not give any indication of the level of safety of anyone outside the structure. A person or animal may be at risk of being subjected to both primary and secondary injury mechanisms. The severity of the injuries may depend on various parameters such as closeness to the structure, earthing system of the structure, soil resistivity, personal height and environmental factors.

For concrete or brick-walled structures with an external LPS (SSL II and above), the design itself takes measures to prevent side flashes to occupants inside. However, if there are metal railings or metal window/door frames etc., that are connected to the LPS and are within human reach, it is advisable to keep a distance from such. A minimum separation of 30 cm can be treated as a rule of thumb in this case.

In the event of lightning striking into a structure at SSL IV or SSL III, there is always a possibility of either touch potential (if the occupant is in contact with a current path) or side flash (if the gap between the current passage and the occupant is too small). Thus it is advisable to keep a certain minimum distance away from such external current paths. The voltage drop along a metallic conductor, which is part of the LPS, could be calculated using Ohm's law generalised for impedance (capacitance neglected):

$$V(l) = iRl + Ll\,\frac{di}{dt}, \qquad \text{Equation 1}$$

where *V(l)* is the voltage at length *l* of the current path concerning the ground (in kV), *l* is the length of the current path from the ground plane (in m), *R* is the resistance along the current path per unit length (in Ω/m), *L* is the inductance along the current path per unit length (in H/m), *i* is the current (in kA) and *di*/*dt* is the current derivative (in kA/μs)

Due to the extremely low value of resistivity in a good conductor, the first term of the above equation becomes negligible compared to the second term as the lightning current is injected into a metal. The second term increases with the increasing current derivative. Of the three types of lightning current waveforms – positive stroke, negative first stroke and negative subsequent stroke – the last has the highest current derivative.

The upper 5% value of the peak current derivative of negative subsequent strokes is nearly 100 kA/μs. The value of *L* of a standard copper tape of 50 mm cross-section (2 mm × 25 mm) is about 1 μH/m. Thus for a 1-m length:

$$V = 100 \text{ kV/m} \qquad \text{Equation 2}$$

If an occupant inside a safe structure stands on the same potential as that of the base of the current path at the head level, they will be subjected to a nearly 200 kV potential difference between their body and the current path, provided that the person is the only passage that the lightning current can take.

The 50% value of the impulse breakdown strength ($V_{50\%}$) of air is approximately 30 kV/cm; however, the actual value can vary based on the shape of the arcing points (electrodes), humidity, temperature, etc. at a given instant. The randomness of the breakdown voltage could also be taken into account. Thus, a minimum of approximately 10 cm should separate an occupant and the external lightning conductor of a safe structure.

The International Electrotechnical Commission[43] provides an empirical formula to compute this minimum separation:

$$S = k_i\,\frac{k_c}{k_m}\,l, \qquad \text{Equation 3}$$

where k_i, k_c and k_m are factors that depend on the level of protection, the number of parallel current paths and the medium between the current path and the body, respectively, and *l* is the distance from the possible arcing point along the current path and the nearest equipotential surface (most often the ground). Following the values given in the tables by the

International Electrotechnical Commission[43], at a height of 2 m for a single current path, the minimum separation becomes:

S = 8 cm (lightning protection level (LPL) III and IV)

S = 12 cm (LPL II)

S = 16 cm (LPL I)

Note that here the term LPL is different from SSL. One may refer to others[43,51] to understand the definition and application of LPL.

As most of the small structures and safe structures may be classified as Level IV or III, the 10-cm minimum separation can safely be considered as a rule of thumb for the safe distance for structures of SSL IV and III having a single current path. As the number of current paths increases (number of current-carrying conductors), the minimum separation can be calculated by dividing the 10-cm value by the number of conductors. For example, in the safe structure shown in Figure 1, which has four conductors to facilitate current flow, an occupant should be advised to keep a minimum separation of 2.5 cm between any inclined metal bar and their body. The minimum separation (or even keeping no separation) between the human body and the outer surface of the insulated current-carrying conductors is not discussed in this study as the matter is under scientific discussion in the technical committees of standards institutes (e.g. South African National Standards[52]).

Applications in society and socio-technical challenges

Lightning-safe structures play a key role in the lightning and thunderstorm safety modules adopted in the national framework of disaster mitigation in many countries with high lightning occurrence density. In the hierarchy of hazard control mechanisms, proposed by Gomes and Gomes[53], the entire pyramid collapses in the absence of the technology layer that essentially includes safe structures. One of the primary challenges in curbing lightning-related injuries, in many under-developed countries in the tropics, is the lack of adequately safe shelters for overcast conditions. Thus, even if the two upper layers, awareness and forecasting, have been fulfilled, injuries are inevitable if the public cannot seek shelter in a safe location as a thunderstorm approaches. Therefore, it is essential to adopt a certain family- or community-based SSL to safeguard human life and livestock. As per the above classification, the following types of shelters do not come under any category of lightning-safe shelters unless they are given comprehensive lightning structural protection:

1. Permanently built small dwellings:
   - indigenous shelters made of clay and bio-materials such as round huts in Africa (Zulu huts, mud huts, straw huts, rondavels etc.), fabric-covered dwellings such as gers (yurts) in Central Asia, thatched or other plant-based material roofed and clay/wooden walled houses in South and South East Asia, Africa, and South America
   - shanties (informal small dwellings made of a combination of various materials such as wood, polyethene, PVC, metal sheets, thatch, clothes) in highly populous cities in under-developed countries
   - small brick-walled houses with tile, thatch or tin roofs in a majority of lower-middle-class settlements in under-developed countries
   - medium-sized brick-walled and tin-roofed halls that are used for congregation purposes, typically found in Africa and South Asia (especially in Bangladesh)
   - thatched-roofed shelters on wooden poles used as either watch huts or resting shelters in rural agricultural lands
   - bus stands, small open sports pavilions, telephone booths, rain shelters in adventure tracks and forest trails etc.
   - treehouses and chalets on the water in the hotel industry
   - wooden housing for livestock and wooden stables
2. Temporary or makeshift dwellings:
   - resting shelters for outdoor workers in various sectors such as construction, fisheries, metal quarry, sand, mineral and metal mining, agro-processing (outdoor)
   - prayer cubical at outdoor work sites or roadside for travellers, especially in Islamic countries
   - shelters of city hawkers
   - camping tents, beach huts, cabanas

The above unsafe structures could be upgraded to SSL IV or SSL III by providing lightning protection measures at least at LPL IV.[43] In the process of designing and implementing the LPS, it is important to take possible fire hazards into account due to the arcing between the current path of the lightning and hidden metal parts that sandwich inflammable material such as thatch and grass, softwood, layers of rubber and polythene, cotton clothes and hardboard planks. In many small dwellings in underprivileged communities, it is common to use metal bars, nails, wires etc. from inside the structure to enhance the mechanical stability of the wall materials. These metal components could act as either loosely grounded or floating electrodes that could trigger arcs from the current path via the wall material, causing a fire. Gas cylinders resting on the walls could also be dangerous for the same reason. Figure 2 shows the air termination and down conductor that rests on a thatch roof in a human living structure in Uganda. Towards the upper part, the down conductor has a length of about 5 m from the ground level, which makes the minimum separation about 20 cm to avoid possible arcing. However, it has been observed that inside the roofing structure, radial metal wires are positioned about 10 cm from the down conductor to stabilise the wooden frame. In the event of a lightning strike to the air termination, there is a high possibility of arcing between the down conductor and the nearest wire igniting the inflammable thatch layer on the arc path. Thus, it is of prime concern to develop a firm standard on the positioning of a LPS, before upgrading such structures with inflammable out layers to a certain SSL.

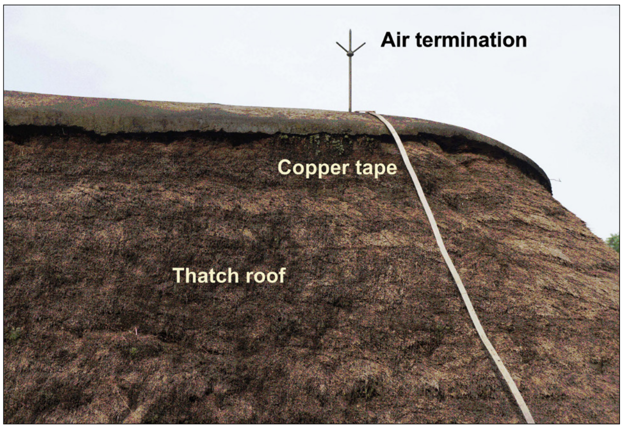

Figure 2: Thatch roof structure showing the down conductor of a lightning protection system resting on the roof.

The heat generation at the point of attachment of the LPS may raise the temperature of the material momentarily to several thousand degrees Celsius. This is a matter of concern for the LPS designed for small dwellings. Most housing structures in underprivileged communities in developing countries use inflammable materials such as wooden planks and used tires to prevent the roofing material from being blown away by the wind. These materials are often repositioned naturally in regions of heavy rainfall and wind gusts, and thus the chances of these inflammable materials positioned on top of the LPS or very close to the LPS should not be overlooked.

In countries where fully thatch-covered structures are widely used in both underprivileged communities and the entertainment industry (Southern Africa, South East Asia and Pacific islands), the question arises as to how to upgrade such structures to SSL III through provision of a single-pole LPS computed to have the cone of protection, by protection angle method or even rolling sphere method as per the International Electrotechnical Commission[43]. Typically, the edge of the roof of such structures (the most probable arcing point) is around 2–3 m from the ground level (Figure 3). As these structures come under LPL IV, the minimum separation between the air termination and the edge of the roof, according to Equation 3 will be 8–12 cm. This standard recommended minimum separation should be revisited for several reasons:

1. The tall mast may undergo considerable amplitude of swing due to the rain and wind during thunderstorms. Thus the actual separation may be reduced significantly.
2. Most often, these thatched roofs are mechanically supported by chicken mesh, metal wires, aluminium planks etc. These metal parts could act as floating electrodes under high electric fields, thus the breakdown voltage may be drastically reduced.
3. Mini arcs can be formed at the joints of the mast (along the mast itself) due to rusting and loosening of fasteners. This can trigger fires if loosely hanging straws are in the vicinity of the arc path.

Figure 3: Thatch roof housing structures with single-mast lightning protection system.

For the above reasons, the recommendation of the minimum separation between the single mast and the roof edge of the thatched structure should be reanalysed by the Technical Committee 81 of the International Electrotechnical Commission[43]. In South Africa, many LPS providers keep a 1-m distance between the mast and the roof edge as a rule of thumb for minimum separation in protecting thatched structures. It is emphasised that a more formal and rational method of computing the minimum separation between the LPS and the structures with the outer covering of inflammable materials should be formulated in the standards, that also takes into account the metal parts such as chicken mesh or wire radials on the roof.

The other issue regarding the single-mast LPS of thatched structures is the step potential hazard. Typically, these masts are provided with single, vertical, rod-type earthing systems. In the event of a high-amplitude lightning current entering such a mast, a sizable potential gradient may develop at the ground surface, both inside and outside the structure, despite the mast having low earth resistance (at DC or low frequency) – a potentially lethal situation for occupants. The surrounding of the mast at ground level and the floor of these structures (usually of underprivileged communities) is usually clay (as in Figure 4a), which exposes both occupants of the structures and those living beings in the surroundings to lethal step potential hazards. The classification of such thatched shelters as SSL III must take this important aspect of a single-mast LPS into account.

Hence, a ring conductor (Type B earthing conductor as specified by the International Electrotechnical Commission[43]) around the structure should be compulsory for the safety of living beings occupying the shelter. Having a layer of insulation material around the earthing point, at least for a radius of up to about 2 m, could help prevent step potential to living beings in the proximity (Figure 4b). However, the insulation material and its dimensions need to be specified in the standards developed.

The development of compulsory guidelines to standardise purpose-made lightning-safe structures[44] is also a need at present. There is high demand for purpose-made lightning-safe structures in the entertainment industry, sports such as golf, hiking, mining industry, security services (e.g. for guard posts), etc. These structures come in the form of a tripod, pyramidal skeletal, metal cage, cubical structures, etc. For the safety of multiple living beings, conversion of abandoned cargo containers to suit human occupation is also proposed and/or practised in several countries at present.

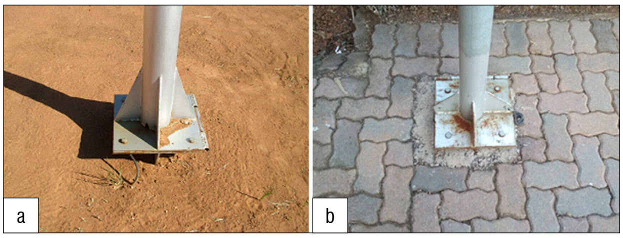

Figure 4: (a) The base of an air termination mast with single deep driven rod. The rod surface is bare earth. (b) A similar case with surrounding of the base covered with a layer of cement bricks, that may act as an insulation layer. Note that the area of surface coverage may not be sufficient.

The standards that include these purpose-made safe structures should cover both the structure and its use. Aspects of the structure itself include material dimensions, occupancy space dimensions, joints, entrance, etc., while usage includes time of entrance (in the presence of an approaching thunderstorm), occupying positions, actions to be taken while occupying inside, etc. Note that, almost all portable lightning protection schemes proposed so far do not have a proper earthing system, thus step potential safety is ensured only through equipotentialisation of the interior bottom plane of the structure. Thus, a sufficiently long advance time (before the thunderstorm approaches) should be specified to enter the safe structure. During the thunderstorm, no one should approach or stand near the structure, to avoid step potential hazards.

Another non-lightning-related risk that may be taken into account in using purpose-made lightning-safe structures is flashfloods that can accompany thunderstorms in some tropical landscapes. Thus, the safe structure user should pay attention to avoiding floodplains or possible water-accumulating localities before erecting the structure. The applicability of the safe structure could be improved by taking into account other possible secondary effects as well.

Animal deaths due to lightning are also not uncommon as per recent news reports from various countries.[54-56] In the case of lightning accidents involving wild animals, a death count of over a few hundred is not unheard of (e.g. the deaths of over 300 reindeer on a hillside of the Hardangervidda mountain plateau, Norway in 2016[54]). Such outdoor casualties are unavoidable with any viable methodology; however, the loss of indoor livestock could be safeguarded by upgrading animal shelters to SSL IV as a minimum. Due to their large horizontal body span, many livestock (such as cattle, horses, donkeys), may easily be subjected to touch potential and step potential hazards.[57,58] Thus, when unsafe animal shelters are upgraded to SSL IV or SSL III, special care should be taken to prevent animals from being in contact with current paths. Precautions should also be taken to minimise possible step potential hazards. Implementing a barrier between the current path and the maximum reach of the animal from the inside, and implementing a ring earth conductor, can significantly reduce the hazard level. A structure with such an arrangement could be identified as a sub-category; for example, as SSL IV (A) or SSL III (A), where 'A' signifies 'animal'.

One of the beneficiaries of this safe structure categorisation is the insurance sector. At present, most often, insurance policies are issued for buildings based on the existing LPS of the structure. However, it is difficult to quantify the risk for informal structures without having definitive terms to specify the level of safety, thus insurance policies are developed on crudely estimated risk factors. With the above-defined SSLs, these estimations could be done more methodically and consistently. Once the definitions are adopted by standards, the risk calculation will have legal acceptance as well.

Once the SSL concept is established, the cost reduction of design, material and implementation of LPSs could conveniently be done without compromising safety. For example, consider that there is a need to reduce the dimensions of materials of an SSL IV shelter, as an essential cost reduction step. The defined SSL will guide the designer to reduce the volume of materials to an extent that the structure will still safeguard occupants from the first five injury mechanisms, irrespective of the modifications. Thus, the designer could compute the reduction of dimensions as far as the structure could ensure the optimised attachment, safe passage of current to the ground level and neutralisation of charge in soil, without giving rise to dangerous thermal, electrical or mechanical effects. The definition of safe structures will also enable designers to determine parameters such as durability, aesthetic appearance, and convenience, which have no direct impact on the level of safety, and can be compromised to reduce costs.

Conclusions

Lightning safety modules at both community and individual levels depend heavily on easily accessible lightning-safe structures. The absence of such structures has shown that safety education and thunderstorm forecasting are futile in underprivileged communities as decades of safety programmes have not produced a significant reduction in lightning accidents (e.g. in South Asia). Thus, it is of prime importance to implement lightning protection measures in structures housing individuals or provide lightning-safe structures at the community level (to be occupied under thunderstorm conditions) in these societies. Another requirement is to provide lightning protection measures for existing temporary structures or to make purpose-made LSSs available to people using camping, outdoor sports and entertainment facilities, regardless of whether the region of concern is developed or not. The same concerns apply to outdoor workers in industries such as construction, agriculture, fisheries and mining.

One of the hurdles in determining a suitable lightning-safe structure for a given application is the lack of definition for such structures. As the structures should be recommended based on not only the safety criteria but various other socio-economic aspects as well, it is not useful to have a single set of specifications for all such structures. Thus, the recommendation from this study is for four levels of safe structures that can be applied to a wide spectrum of buildings.

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Competing interests

I have no competing interests to declare.

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