International Symposium on Lightning Protection (XV SIPDA), São Paulo, Brazil, 30th September – 4th October 2019.

Lightning Caused Multiple Deaths: Lethality of Taking Shelter in Unprotected Buildings

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***Abstract*— Lightning affects human beings and animals through several mechanisms of which direct strikes are referred as the most lethal. However, our investigations show that a clear majority of multiple lightning deaths by a single ground flash have been occurred while the victims were inside structures, where injury due to direct strikes is impossible. This study analyses the electric field distribution of a lightning struck unprotected building, during the return stroke current phase. The outcomes depict that the field enhancement at the head level of the occupants at various locations inside the structure is large enough to attract arcing either from the roof or the walls. The field enhancement strongly depends on the type of lightning current and the materials of the roofing and walls. For the simulation of lightning current waveforms and distribution of electrical fields and potentials, MatLab and ANSYS Maxwell software have been used. Consequently, the paper emphasizes the need for implementing low-cost protection schemes in under-privileged societies in regions of high lightning density to minimize the casualties.**

***Keywords*— lightning, injuries, under-privileged, low-cost protection, human safety**

I. Introduction

Lightning is known to be a silent killer of nature, despite the huge bang it produces, due to the fact that it kills sporadically all over the world. Most of the methodical studies on lightning injury and death have been done in developed countries such as USA [1-6], UK [7-9], Australia [10-12], and France [13, 14]. A common feature of lightning casualties in these countries is the low number of deaths per strike. Most often a lightning causes single death and few injuries in these countries and rarely the number of deaths may reach two. The number of victims that do not succumb to their injuries also may not be that high. Most often the casualties have been reported while the victims are involved with outdoor activities. In the recent times there are hardly any indoor lightning accidents reported in USA. There are many reasons for such observations in developed countries of which few are listed below.

a. Gradual enhancement of lightning safety awareness for the last century and the continuous updating of knowledge from the recent past due to wide usage of multimedia [15, 16].

b. Availability in abundance of sturdy structures in every part of a given country, so that people can seek safe shelter under thunderstorm conditions [16, 17].

c. Ready accessibility to thunderstorm detection and warning systems [18].

d. Moderate or low occurrence density of lightning in many temperate regions [19, 20].

These observations, together with the affordability of the public and industrial/commercial sectors for standard lightning protection systems belittled the need of low-cost lightning protection systems for the last many decades. Even the international standard committees (IEC, NFPA, AUS/NZ etc.) refined the recommendations on lightning protection systems making them more stringent and costlier to be implemented.

In contrary to the observations in developed countries, a number of papers published during the last ten years show that the situation in under-privileged societies in the developing world is much worse [21]. This surge of papers, which came into the limelight mostly due to lightning awareness programs launched in Asia and Africa during the last and current decades, revealed that there are grave issues to be addressed in many parts of the world which were concealed from the scientific world for all these years. Many of these under-developed countries are characterized by non-frequent, still non-rare events of multiple deaths due to lightning. The first multiple lightning casualties were reported a way back in 1870's as Dr. Georg Schweinfurth described the death of six women by a single lightning strike in Uganda, in his book "Im Herzen Von Africa" which was translated into English in 1874 [22, 23], in his note re-confirms that such incidents are not that rare in the eastern parts of Africa.

Many incidents in developing countries reported in the literature show an interesting feature. In a majority of cases where there are multiple casualties by a single strike, the accident has taken place while the victims were taking shelter inside roofed structures [24-28].

Such observation is very much in contrast to the common belief that lightning accidents are more probable outdoors, a fact that is verified by the records in developed countries [21]. Therefore, it is a need at present to make a comprehensive study on this matter and develop recommendations to minimize such mishaps in the future. In the above backdrop, this study has been done to show that such indoor lightning risk is realistic as per the lightning reports so far and analyze the mechanisms that may affect occupants of an indoor structure in the event of a lightning strike.

II. Cases of Multiple Deaths

To justify our claims regarding the high number of lightning related indoor multiple deaths in developing countries, several cases have been searched and documented. Information on these lightning accidents were collected from printed, electronic and audio-visual media, distant communication with experts and journalists in relevant countries and face-to-face communication with subjected individuals. The authentication of data have been verified by cross-referencing through different sources of information. A majority of the documented events are from the African continent.

- In March 2018, Seventh Day Adventure church with iron roof and brick walls in Nyaruguru district in the Southern Province of Rwanda have been hit by lightning reportedly killing 16 people (14 on the spot) and injuring similar number. Over 140 people were housed in the church by the time the lightning struck the building.

- In West Darfur 23 trainee soldiers were killed and 90 were injured on the 2nd of August 2011 when their shelter is struck by lightning. Interestingly, the Radio Dabanga, which reported this news on the 3rd of August 2011, in their printed media, states that the soldiers were housed in a metal roofed structure by the time the accident took place. No further information could be obtained in this regard.

- In January 2014, within a period of one week two lightning incidents that took place in Burundi killed 11 people and injured 60 others. In one incident a lightning struck a school building killing seven students and injuring 51 others in Nyanza-Lac, a city located about 150km south of the capital Bujumbura. In a week prior to this incident, a lightning strike to a small church building in a village in the Eastern Burundi caused four deaths and nine injuries. Unconfirmed reports implies that the structures in all cases have iron roofs.

- On 28th of December 2013, 8 people in a congregation, inside a Seventh Day Adventure church in Malawi, were killed as a lightning struck the building. In addition, over 40 devotees were injured as the incident took place in the capital city Bujumbura, while the victims were attending the afternoon prayers. The structure was made of iron roof on brick walls.

- On 08th August 2012, 13 people were killed and 20 were wounded as lightning struck a makeshift mosque in a small village, named Saraswathi, in North-East Bangladesh (About 200 km from the Capital Dhaka). As per the CNN news report, published on the 11th of August 2012, the structure was an iron-roofed wooden hut which has been temporarily used for evening prayers as it was the holy month of the Muslim community. A sizable number has been gathered for the religious event by the time the structure was hit by lightning.

- In June 2011, lightning has struck a junior school in Runyanya Primary School in the Masindi area in western Uganda, killing 18 children and their teacher. Later reports (unconfirmed) state that the teacher has not succumb to his injuries. There were 52 students injured in the event. The building was made of iron roof on brick walls. Figure 1 (Photograph with the courtesy of Mr. Hudson Apunyo) shows the affected school one year after the incident.

- Eight construction workers were killed and six were injured in Mpumalanga, South Africa on the 20th of November 2013, when lightning struck the tent that they were sleeping at night. The tent, which is a temporary structure which had a tin-roof and wooden supports.

Even in cases of large number of injuries (no or low number of deaths) by a single strike are mostly related to sheltering inside structures with some sort of a roof cover. Two well documented such cases are given below.

On the 11th of November 1994 lightning struck a camp tent during the small hours injuring 28 people; 26 children and two adults. The incident took place in a rural area in the Northern Province of South Africa. The incident has been analyzed in detail and documented in [29].

On 05th August 1987 a lightning killed 6 people and injured another 6 in a coastal city (Ikumi-kaigan) in Japan [30]. As per the documented details, the victims were about 50 m away from the sea shore. All 12 people in the group have been affected by the strike. The researchers that reported the incident suspects that all the victims were struck by multiple terminations of the same lightning flash.

Figure 1. The building that has been lightning affected at Runyanya Primary School in Uganda, one year after the incident. The structure is made of brick with cement or clay plaster and the roof is made of iron sheets. (Photograph with the courtesy of Mr. Hudson Apunyo)

III. METHODOLOGY

Computations were done by simulating lightning current waveforms for negative subsequent stroke, negative first stroke and positive stroke by MatLab software and the potential and field distribution in a simple housing structure under lightning strike, by ANSYS MAxwell software.

As a majority of the structures where the above incidents have been taken place are iron roofed (iron sheets of around 0.5 mm thickness that could commonly be found in many African and South Asian countries), we considered a house with iron sheet roof (sometimes referred as corrugated metal roof) on brick/clay or wooden walls. The housing structure with the dimensions considered for the computation is shown in Figure 2(a). Figure 2(b) shows the model that is used in the ANSYS Maxwell software. The electrical properties of the materials of the structure are given in Table I. The resistivity of clay/brick may be a lower end value of the parameter. The thickness of the roofing material and wall materials are given as below. All these figures are representative values of materials and structures found in Africa and South Asia.

Iron roof sheets: 0.5 mm

Clay-brick walls: 10 cm

Wooden planks: 2.5 cm

The lightning current waveforms applied were simulated by the Heidler function and corresponding temporal factors specified in [31] and amplitude factors given in [32]. As it is for the human safety analysis, we used upper 5% amplitude values for all three current waveforms; negative subsequent stroke, negative first stroke and positive stroke (Table II). The front duration and stroke duration has been taken as lower 5% and upper 5% values respectively to reflect the worst case scenarios (Table II). The lightning strike point was considered to be the edge of the top ridge (in this case considered as the front of the house) as that is the most probable place of strike in such structural arrangement [33].

The Heidler function of current waveforms used in this study is given in the equation below.

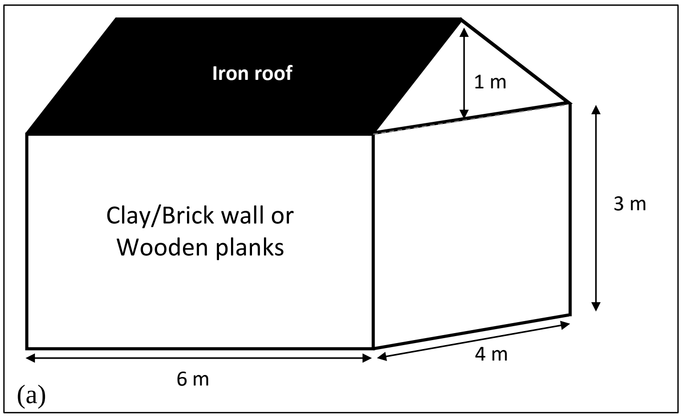
$$i(t) = \sum_{k=1}^{m} \frac{I_{0k}}{\eta_k} e^{-t/\tau_{2k}} \frac{(t/\tau_{1k})^{\eta_k}}{1 + (t/\tau_{1k})^{\eta_k}}$$

where

$$\eta_k = e^{-\tau_{1k}/\tau_{2k} \left(\eta_k \left(\tau_{1k}/\tau_{2k}\right)\right)^{1/\eta_k}}$$

Table I. The electrical properties of the materials of the housing structure used in the simulation

Property	Iron	Dry Wood	Clay
Relative permittivity (ε_r)	10^{10} (infinity)	4.0	5.5
Relative Permeability (μ_r)	5000	1	1
Resistivity (ρ)	10^{-8} Ωm	10^{9} Ωm	500 Ωm



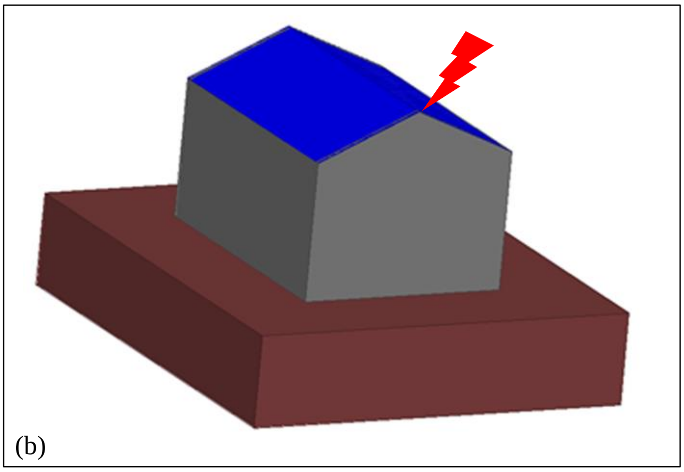


Figure 2. (a) Housing structure with external dimensions (b) The structure that has been implanted in the ANYSYS Maxwell. The lightning sign indicated the point of injection of the impulse current.

Table II. The parameters of the simulated current waveforms

Current waveform	Amplitude (kA)	Front duration (μs)	Stroke duration (μs)
Negative subsequent	28.6	0.22	140
Negative first	90	1.8	200
Positive	250	3.5	2000

We selected four random locations inside the structure, L1-L4, to place the human body (Figure 3). At each location the peak potential gradient have been calculated up to 2 m in the absence of any object inside. The 2 m height is selected as it could be considered as an average height of a human being.

The human body has been considered as a cylindrical structure with hemispherical top as it is shown in Figure 3. As the pre-return stroke streamer current is quite small, the influence of streamers to the human body resistance is negligible (such as ionization, splitting or rupturing of tissues etc.). Hence we considered a total body resistance of about 1000 Ω that will be corresponding to an average body resistivity of about 25 Ωm [34-36]). As almost 80% of the human body consists of water we considered the permittivity of human body as that of water, 78 [37]. This value is quite in agreement with the relative permittivity of most of the body tissues [38]. The relative permeability of the body was taken as 1. The second set of calculations have been done in the presence of the human body to find the field enhancement at the human head. The charge distribution on the roof is also computed to find the possible arc emanating points at the roof.

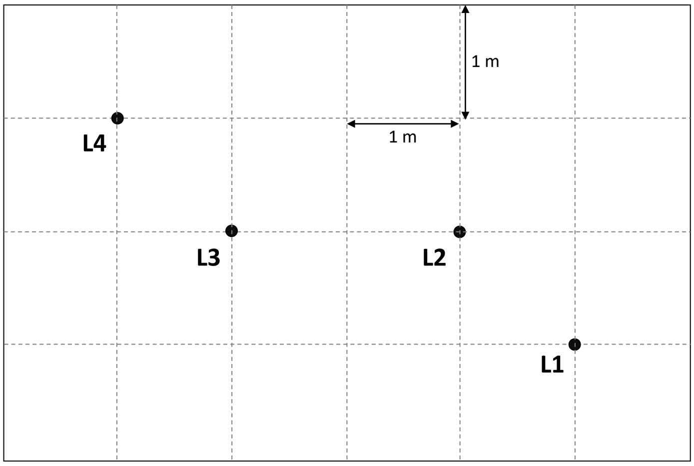


Figure 3. Positioning of the human body model at four places in the housing structure of dimensions 6m × 4 m.

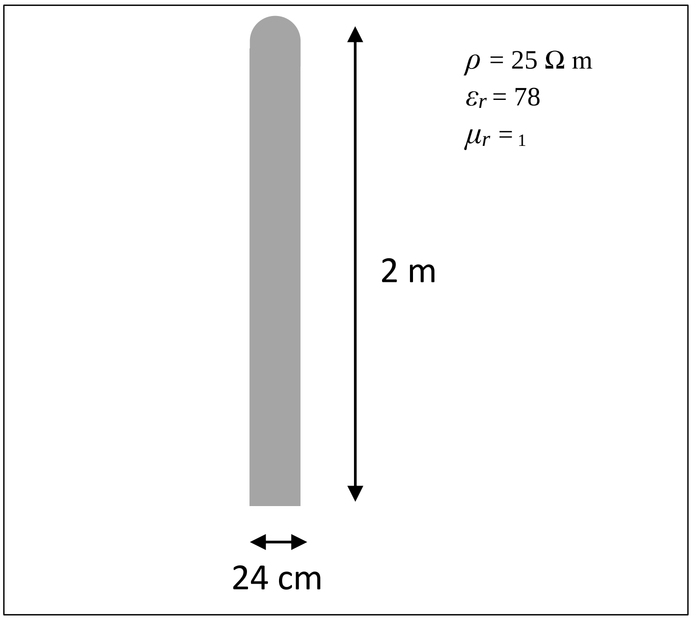


Figure 4. Human body model used in the simulation

IV. Results and Discussion

Table III shows the maximum electric field (magnitude) at a 2 m height along a vertical line from ground level (zero potential reference) at points L1 to L4 in the absence of any objects inside the housing structure. For a plane-plane gap in air, the breakdown voltage is in the order of 3 MV/m. Hence, as per the values given in the Table-4, for a clay house the chances of having an arcing between any parts of the roof to an extremely high resistive object (good insulator) is almost impossible as the peak electric fields are about or more than 2 magnitudes below the breakdown threshold of air. However, in the event of lightning strike to a structure with dry wooden walls (wooden planks) such arcing is possible in negative first stroke and positive stroke of lightning waveforms. It is marginal in the case of negative subsequent stroke. The most probable arcing point is L1 out of the four locations. It may obviously be due to the proximity to the wall/roof edge and the lightning strike point. The slight increment in the field as one moves from L3 to L4 reveals that standing closer to a wall/roof edge is more effective in attracting a side flash than standing closer to the strike point.

Table IV depicts the electric field values just above the head of the human models (at 2 m height) when they are placed at the four locations L1 – L4. Now it can be seen that in all six cases the potential is above the breakdown threshold of air thus chances of side flashing to all human beings are now higher.

Figures 5 depicts the charge distribution on the housing structure with clay walls for positive stroke. Similar charge distributions could be seen in the cases of negative first stroke and negative subsequent stroke as well. The charge distribution patterns emphasize that there is a high risk of getting multiple side flashes to the human beings of objects that are placed close to the lower roof edges. This is a fact to be investigated by collecting reliable data on the positions of victims of multiple fatality incidents that have been reported so far.

The deposition and retention time of charge concentration on the roof due to a lightning strike is sufficiently large, especially in the case of positive lightning, to facilitate multiple arcing in to many human beings that occupy inside the house. The situation becomes worse as the wall material becomes larger in resistivity. Thus, it is highly recommended that structures with steel roofing on materials such as wood, clay, bricks etc. should seriously be treated with respect to lightning safety to prevent further accidents that may cause multiple victims. If a properly designed lightning protection system is prohibitively unaffordable to a mass community, at least the metal roof should be well grounded at multiple points.

The presence of human beings inside an unprotected structure that described in this study may greatly enhance the side flashing probability, especially for lightning currents with lower amplitudes and longer rise times. Lower roof edge heights (especially the lower edge of the roof) and greater human heights (height of the posture), increases the possibility of arcing from roof to the body. Although it was not investigated in this study, there is also a possibility of sequential secondary side flashes when a tall body is surrounded by shorter bodies (due to the standing height or other types of postures). In such cases, even a single side flash from the roof may affect several people, even causing lethal injuries. The correlation between the charge distribution and the temporal variation of the body current through the arc, as the number of side flashes increases, is now under investigation. The output of this study, combined with medically sound human body model could predict the possible number of side flashes and injuries once the current parameters and housing structure details are provided.

Table III. Electric field (V/m) distribution at 2m height at L1-L4 in the absence of human body model

Wall material	Current waveform	L1	L2	L3	L4
Clay	Negative subsequent	6.70×10^{3}	6.30×10^{3}	6.40×10^{3}	6.50×10^{3}
	Negative first	2.35×10^{4}	2.05×10^{4}	2.10×10^{4}	2.20×10^{4}
	Positive	6.05×10^{4}	5.70×10^{4}	5.75×10^{4}	5.85×10^{4}
Dry wood	Negative subsequent	2.90×10^{5}	2.65×10^{5}	2.67×10^{5}	2.75×10^{5}
	Negative first	1.26×10^{7}	1.15×10^{7}	1.16×10^{7}	1.21×10^{7}
	Positive	1.14×10^{8}	1.05×10^{8}	1.06×10^{8}	1.09×10^{8}

Table IV. Electric field (V/m) distribution at 2m height at L1-L4 in the presence of human body model

Wall material	Current waveform	L1	L2	L3	L4
Clay	Negative subsequent	3.70×10^{6}	3.35×10^{6}	3.58×10^{6}	3.60×10^{6}
	Negative first	1.15×10^{7}	1.00×10^{7}	1.02×10^{7}	1.10×10^{7}
	Positive	2.25×10^{7}	2.10×10^{7}	2.15×10^{7}	2.20×10^{7}
Dry wood	Negative subsequent	7.83×10^{7}	7.45×10^{7}	7.49×10^{7}	7.64×10^{7}
	Negative first	1.79×10^{9}	1.30×10^{9}	1.40×10^{9}	1.48×10^{9}
	Positive	3.00×10^{10}	2.80×10^{10}	2.85×10^{10}	2.95×10^{10}

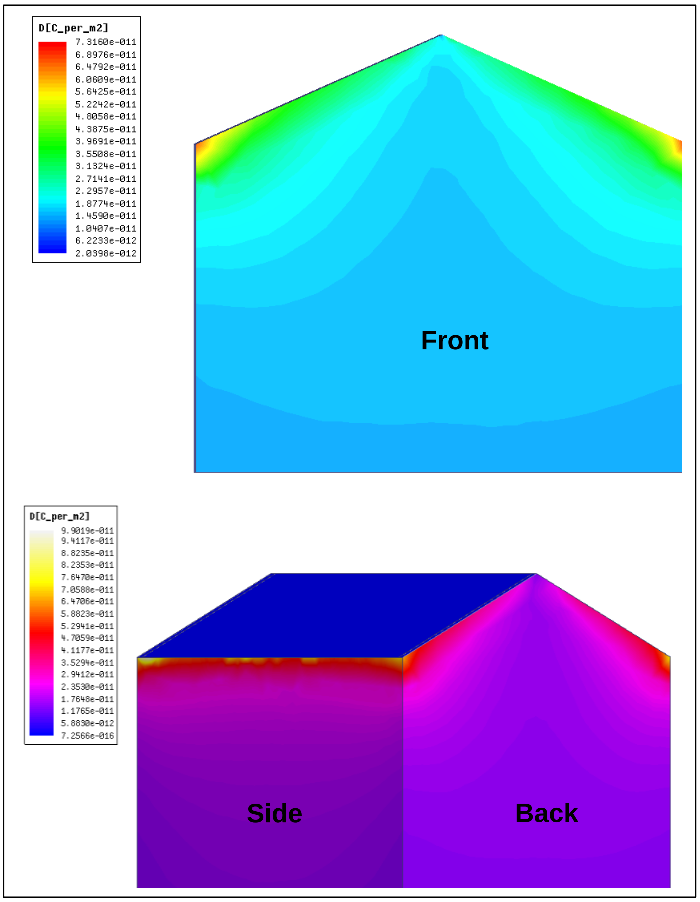


Figure 5. Charge distribution in the housing structure of clay walls for a positive stroke

This study can be extended to find the possibility of multiple death among livestock and zoo animals as well. In the cases of four legged animals the most speculated mechanism of injuries is step potential [39], however the possibility of multiple side flashing from the roof could not be totally eliminated. The smaller height of the shelters where such animals are herded increases the probability of side flashes. In Africa, a majority of rain shelters for animals are made of low-level metal roofs erected on wooden poles. As per this study, such structures highly promote the initiation of multiple upward streamers from the animals, causing multiple deaths.

V. CONCLUSSIONS

The simulation presented in this study shows that the multiple deaths due to a single lightning strike that have been reported in many incidents in Africa and South Asia in the recent past is very possible when the people seek shelter in iron roofed housing structures that have brick, clay or wooden walls. The probability of side flashing inside the structure increases drastically as human bodies with standing posture are present. The resistivity of the wall material also play a significant role in the enhancement of electric field at the roof level. Positive lightning generates the highest electric fields due to the large peak current. They may also generate larger number of side flashes due to the high charge content injected into the roof.

In the case of multiple bodies, there is a high possibility of side flashes from the lower edges of the roof to the human bodies. The proximity of the body to the lower edges of the roof is more significant in intercepting a side flash than the proximity of the body to the point of strike. Further studies are needed to predict the highest number of side flashes possible from the roof structure to multiple human bodies, once the current parameters and housing structure details are given.

Acknowledgment

Authors would like to thank The ESKOM Power Plant Institute (EPPEI)-HVAC; School of Electrical and Information Engineering, University of the Witwatersrand, South Africa, Institute of Power Engineering (IPE), Universiti Tenaga Nasional (UNITEN), and Electrical Department, Islamic Azad University, Iran for the excellent facilities, including software accessibility provided for this project.

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