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Heat Flux Analysis due to Lightning Strike on Tubular Columns in TV and FM Towers

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ABSTRACT

Lightning is a natural phenomenon when hits on a body causes multiple damages such as melting and burning at the point of contact, mechanical damage due to sound wave propagation and destruction due to magnetic flux. Lightning drains the electrical current up to 200 kA and the electro-thermodynamic reaction of the material may cause degradation, stratification, and surface breakdown. Most of the field observations of TV and FM towers' collisions due to lightning strikes show that the main tubular columns have been severely ruptured in the vicinity of the foundation. The high temperature generated during the flow of electricity produces heat through the conductive structure of the main body of the tower, as well as the expansion of gas inside the pipe which ultimately results in the explosion of the pipe and rupturing the towers. In this paper, a part of a tubular column of the tower is chosen and analyzed in ABAQUS software under the effect of lightning induced heat flux. The results show that the very high heat flux generated at the tubular column of the tower could be the main reason for the fracture.

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1. Introduction

Lightning is a natural phenomenon that can depend on relative factors such as position, altitude, mountain, humidity, cloud height, and weather type such as tropical, Mediterranean, polar, or desert. Damage caused by lightning strikes on structures has led people every day to reduce the damage caused by lightning; to model this natural phenomenon and to calculate the probability of its collision with equipment and facilities, all possible scenarios and situations should be taken into account. Whatever the structure is constructed at a taller height, the greater the likelihood of a lightning strike. Television and telecommunication towers are among the structures that are often built in mountainous areas, and because of this, and since most of these sites are operated without an operator, protecting them against lightning is very important.

A lightning strike of between ten and 100 million volts and a current of 10,000 to 200,000 Amps can generate around 100 billion watts of energy, which is not found in all its nature. According to National Aeronautics and Space Administration (NASA), the evacuation of clouds usually occurs in less than a few hundred to several thousand seconds [1].

Abdelal and Murphy [1] developed a physics procedure to predict the thermal damage of composite material when struck by lightning. The procedure used the finite element method with non-linear material models for presenting the extreme thermal material behavior of the composite material (carbon/epoxy) and an embedded copper mesh protection system. Results were compared against published experimental data, showing the potential accuracy and computational cost of virtual lightning strike tests and the requirement for temperature dependent material modeling. Munoz et al. [2] proposed a model based on the finite element method that includes the sources of damage observed in a lightning strike, such as thermal damage caused by Joule overheating and electromagnetic/acoustic pressures induced by the arc around the attachment points. The results of the model were compared with lightning strike experiments carried out in a carbon woven composite. Wang [3] developed a numerical model with finite element analysis for predicting the lightning-strike-induced electric fields along wind turbine blades. The model was applied to the non-conductive Sandia 100-meter All-glass Baseline Wind Turbine Blade and the predicted electric fields were compared to the dielectric breakdown strength of the blades to assess the possibility of the breakdown and associated damage. Also, a corresponding computational procedure was developed and implemented to predict the lightning-strike-induced thermal ablation damage in a laminated glass-fiber-reinforced polymer-matrix (GFRP) and carbon-fiber-reinforced polymer-matrix (CFRP) composite wind blade. The predicted thermal ablation damage in the CFRP composite wind blade was validated by comparisons with existing experimental results. Kamiyama et al. [4] examined lightning strike damage to cross-ply carbon fiber reinforced epoxy and composite laminates to clarify the effects of the resin properties on lightning strike damage to CFRP laminates. Results showed that the composite laminates sustained remarkably minor damage such as carbon fiber breakage, changes in color of matrix resin, and delamination on the front surface compared to epoxy. In addition, the results indicated that the electrical conductivity and onset temperature of thermal decomposition, the char yield, the inter-laminar fracture toughness and other material properties strongly affect lightning strike damage to CFRP laminates. Guo et al. [5] investigated the effect of expanded foils with anisotropic electrical conductivity on the lightning strike protection (LSP) of carbon fiber reinforced polymer (CFRP) composites. The results demonstrated the excellent performance of the expanded foils in suppressing the heavy lightning strikes. Importantly, the damage morphology of post-lightning specimens indicated that the electrical conductivity of expanded foils was anisotropic, which was confirmed by numerical simulation.

Foster et al. [6] performed a simulation study using an established modeling approach for composite damage prediction due to pressure loading. The results for the first time quantified the significance of pressure loading, demonstrating that although a pressure load can cause damage consistent with that measured experimentally, it has a negligible contribution to the overall scale of damage. Sun et al. [7] experimentally investigated damage characteristics of CFRP laminates subjected to multiple lightning current strike. The experimental results indicated that the CFRP laminates suffered serious lightning damage, including fracture of the carbon fibers and layer delamination. Dong et al. [8] analyzed damage of CFRP composites under combined lightning current components D and C. It was observed that the component D controlled the in-plane damage area, while the sequential injection of component C aggravated the in-plane damage extent and tended to induce in-depth damage. Vogler et al. [9] examined a numerical investigation into key factors controlling excavation of hard rock via electro-pulse stimulation under realistic operating conditions. As well as, in this study the effect of grain size on rock breakage was investigated by comparing fine and coarse grained rocks. The results demonstrated that all investigated factors are crucial to the efficiency of rock fragmentation by electro-pulsing. Lee et al. [10] performed a new finite element (FE) methodology to predict highly nonlinear, transient thermal-electrical-mechanical responses of carbon/epoxy laminates subjected to simulated lightning currents. To this end, a series of fully coupled thermal-electrical-structural analyses was employed to characterize effects of radially and asymmetrically expanding lightning arc channels on coupled thermal, electrical, and mechanical damage in AS4/3506 carbon/epoxy laminates subjected to relatively low (40 kA) peak lightning currents. It was observed that the predicted electrical, thermal, and mechanical responses were strongly influenced by the arc channel shape, expansion, surface current magnitudes, and mechanical pressures applied inside the arc channels. The FE models showed that the predicted thermal damage in an expanding elliptical arc channel most closely matched with observed physical lightning damage.

To the large extent which authors have researched, despite the great importance of this issue, there are no independent and coherent researches on lightning damage at the base of television racks. Therefore, a study on the structure, as the second part of this study, results in a better understanding of the damage caused by lightning at the base of television towers. In the third part, the factors that contribute to the fracture of the bases, as well as the methods of conservation are discussed. In the fourth section, a base element in ABAQUS software is modeled by thermoelectric loads, and the results and suggestions for further studies are presented in the fifth section.

2. Structure

Wind turbines, including structures in the world such as television and communications towers at risk of lightning strikes. As shown in Figure 1, wind turbine blades suffer the most from poor maintenance and various lightning strikes [11]; hence, studies on how damage to the blades and how to reduce or zeroing the injuries has been done.

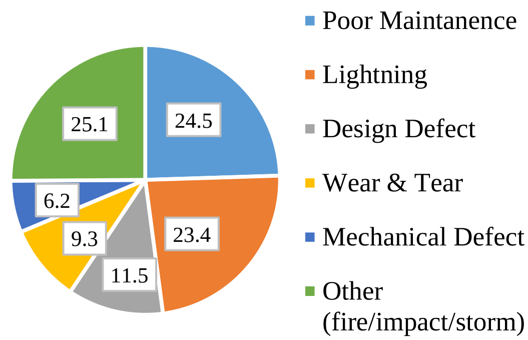

Fig. 1. Most frequently damages reported for wind turbines [11].

Studies on lightning damage in composite wind turbine blades show that the direct effect of lightning strikes on matrix polymer composites often involves the velocity of increasing temperature, melting or burning at extreme lightning strikes and mechanical damage caused by lightning, including magnetic forces, and the sound wave is the acoustic shock. Basically, the damage occurred due to the lightning strike is multiple.

Composite materials are designed to achieve optimal performance and enhance the level of mechanical bearing through a combination of at least two main components. Generally, matrices are epoxy, polyester, etc., and enhancers such as carbon fibers, aramid fibers, Nano-carbon tubes, and so on.

The matrix part acts as the base for composite, with the envelope and support of the amplifiers to maintain the relative position of the amplifier while transmitting the loads. Carbon fiber reinforced polymer composites (CFRP) and glass fiber reinforced polymer composites (GFRP) are used in the wind turbine blade industry. Composites reinforced with carbon fibers, are conductive, so during the collision of the lightning, in addition to the extreme thermal flux, joule heat is also formed through the conducting structure. Composite materials used in wind turbine blades are typically made of glass fiber reinforced matrix polymer composites. The benefits of widespread use of GFRP composites for turbine blades include a good ratio of high strength to weight, economical economy, and flexibility in design, durability, and permanence, non-conductivity, and corrosion resistance. CFRP composites are much more potent and lightweight than GFRP. However, in many cases, CFRP composites are much more expensive than GFRP composites, which prevent them from being used extensively in the industry [12].

The other similarity of wind turbines and television towers is that both structures are being constructed in places that are more exposed to lightning strikes than the rest of the regions. Huge mountainous areas, or large plains, are places that often have the most massive amounts of lightning. The next factor creates the same conditions for wind turbines and towers in front of the lightning, which their high numbers are used at the surface. According to the US department of energy, wind turbines are widely used in the US wind power industry [11]; in Iran, TV and FM towers are much used to power the urban and rural areas.

Another issue is the high height of both structures, which puts them easily at the risk of a lightning strike. The relationship between the height of the wind turbine tower and the number of lightning strike collisions, which is coincided with the estimate of the number of lightning strikes per year, is shown in Figure 2, in which the horizontal axis is stormy days of thundery and vertical axis estimates the number of lightning strikes per year. The use of higher altitude towers can have a significant effect on the use of more areas than signal, but on the other hand, with the increase in altitude, increase the risk of collision of the lightning.

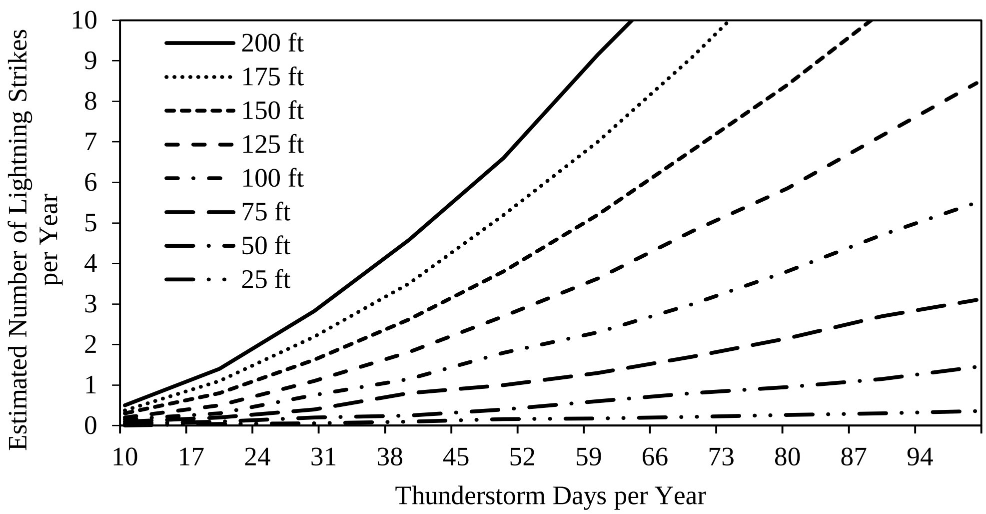

Fig. 2. Lightning strikes vs. wind turbine tower height [11].

3. Factors of fracture of the bases

The physics of the thunderbolt must be known to identify the factors of fracture of the tower. Lightning evacuation is basically the failure of air insulation (about 3 million volt/meters), which is created by a large electric field between the cloud and the earth or between two clouds. The magnetic field created between the cloud and the earth or between two clouds heats the adjacent air molecules and directs them to the volumetric expansion of the air causing sound waves (Thunderbolt). Finally, the thunderbolt canal is plasma, and the surrounding air temperature can be warmed up to 50,000 degrees Fahrenheit, which is approximately 5 times the surface temperature of the sun. The plasma lightning channel can discharge an electrical current above 200 kA [12].

The most important specific characters of lightning include:

A) The voltage of the lightning usually reaches 10 to 20 million volts and sometimes reaches up to 100 million volts.

B) Lightning current that is about 10,000 Amps and sometimes reaches up to 200,000 Amps.

C) The power of lightning, which, according to the power formula P = V×I, lightning typically has about 100 billion watts of energy.

The direct effects of lightning on materials are often thermal and mechanical; the rise of temperature and melting or burning at the point of contact is the thermal effects of the lightning strike, because when the lightning strikes hit the structure, in addition to the injection of intense thermal flux, the jolly heat also establishment by conductive structure of the object that can also causes the material to change from one state to another, such as filament sublimation.

In addition to thermal damage, lightning strikes also cause mechanical damage. According to Figure 3, heat accumulation due to the flow of lightning through a composite structure, decomposes the polymer matrix and liberates the gases from decomposition. After the explosion, these gases are enclosed under the layers or between two layers and the layering occurs. If the tension due to the internal pressure of the gases from decomposition exceeds the resistance of the tear of the fibers, fiberglass failure occurs [12].

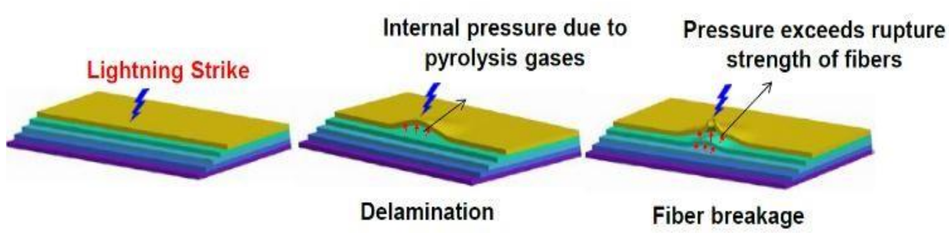

Fig. 3. Lightning-induced delamination and fiber breakage in polymer-matrix composite structures [7].

Figure 4 shows the damages due to the lightning strike from the moment of hit and the electro thermo-mechanical coupling in the composite structures.

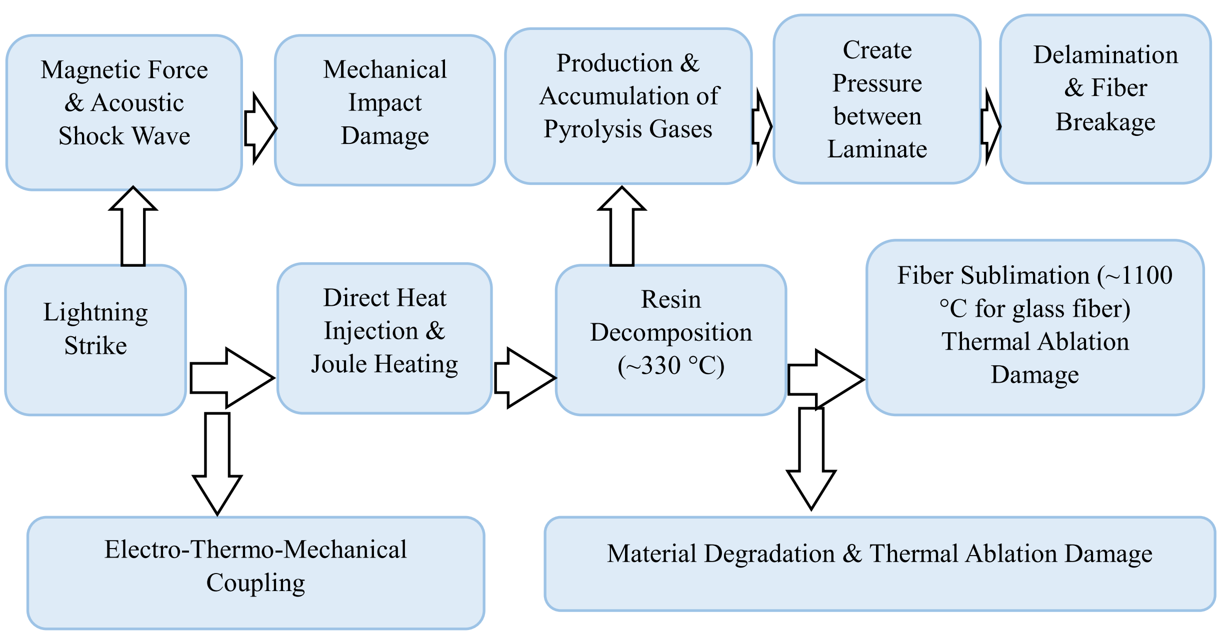

Fig. 4. Electro thermo-mechanical coupling in composite structures.

According to the objective observations one of the reasons that may be involved in the fracture of the base is the intense air expansion at the moment of the lightning discharge and the explosion of the tube pipe as a gas container, as it is likely that the stress caused by the dynamic load resulting from the expansion of the air It alone can break the pipe wall. Figure 5 shows the tear along the longitudinal axis of the base.

Fig. 5. Tear of the base of TV & FM tower due to lightning strike.

Also, the high temperature created at the instant of electric flow through the wall and the jowl heat that was produced through the conductive structure of the base body of the tower are also factors that played a decisive role in surface erosion and severe corrosion of the pipe. However, magnetic flux alone cannot be a factor in the tear of the pipe and only accelerates the corrosion over time.

4. Protection methods

The destructive effects of lightning are due to direct lightning strikes on the structure, or the induction voltages of its electromagnetic fields. To protect the structure against lightning, the following must be observed:

- Avoid direct impact of lightning strike on structure
- Conduct the lightning strike to the ground safely
- Disperse and neutralize the lightning strike on the ground

In the Wind turbine blades used mesh by copper wire. This network directs the thundering stream to the edges of the blade and prevents them from causing direct damage to them. In the television and FM towers to prevent a direct lightning strike on the tower, a rod is used at the top of the tower; a lightning strike collides with a lightning strike through an intermediate conductor, a cross-sectional copper-stranded cable, guided to the ground through the copper plate and moisture are dispersed. There are various standards for lightning protection systems, some of which are listed in Table 1 [12].

Table 1
Lightning protection standards [12].

Standard	Description
IEC	International Electro Technical Commission
IEC-62305	International Lightning Protection (published in 4 sections) 2010
IEC-62561	Features and specifications of components used in lightning protection systems (Published in 8 sections)
ISIRI-6213-1	Standard for protection against lightning in Iran based on NFC and IEC standards.
IEEE	The Institute of Electrical and Electronics Engineers An international professional and nonprofit organization dedicated to helping to advance technology in general and in areas related to electrical engineering and computer as well as related fields in particular.
IEEE-998	Lightning direct strike protection guide
IEC 61643-11	Low Voltage Protection Devices - Lightning Protection Devices Attached to Low Voltage Systems - Requirements and Test Methods
NFC 17 102	Lightning protection system by active thunderbolts (electronic)

The probability of a lightning strike contact on a building or structure depends on the size of the structure and the intensity of lightning. For this reason, various parameters such as the number of direct lightning strikes in the building (Nd), the lightning flash density, or the average annual lightning intensity in the area where the building is located (Ng) and the total area of the building equivalent. The total area of the building (Ae) is the earth's surface, where the probability of a direct lightning strike per year equals the probability of a direct lightning strike into the building, and is equivalent to a surface with collisions of lines with a 30-degree slope in all directions of the building Passing above the building and the surface of the earth. The number of acceptable annual lightning strikes (NC) is calculated from different formulas according to the stated standards. After applying the coefficients C1: relative position of the structure, C2: type of structural materials, C3: building contents, C4: building occupation and C5: The coefficient of the effects of lightning collisions on the building, eventually the corresponding level of protection of the corresponding table is obtained.

5. Modeling of the tower element

In this section, the element of the base is discussed under the thermal load of lightning strikes. In ABAQUS software [13], the steps of modeling and solving an issue, called a module, are performed respectively.

5.1. Part module

The three-dimensional model of the tower base that is a piece of hollow cylindrical was designed in this module.

5.2. Property module

In this module, the various properties of the base of the tower are recorded. The qualifications of piece used in this analysis are:

K: Conductivity or thermal conductivity and its unit w/k.m, where w watt, k is the unit of temperature in kelvin and m is the unit length in meters. This coefficient for steel is 80.4 w/k.m.

C: Specific heat coefficient or heat transfer coefficient and its unit is j/gr.k or j/kg.k, where j is the unit of energy and kg unit of weight. This amount is 444 j/kg.k for the desired piece.

E: The elasticity modulus of steel is 210×109 Gpa.

ν: The Poisson factor is considered to be 0.20-0.30.

ρ: The steel density is 7850 kg/m3.

5.3. Assembly module

The assembly stage has passed because of the fact that the desired section is composed of one part and does not need to be assembled.

5.4. Step module

In this module, entering the step manager section, there are four steps to analysis:

1) The first step is the initial boundary conditions of the two basic principles.

2) The second step is the thermoelectric load caused by the lightning strike; it should be noted that the heat generated at the base of the duct decreases greatly in a few hundredth second. Here the load is defined as thermal or thermoelectric, and unstable. The requested time is set to 0.01 S.

3) The third step is heat transfer, and then the air is cooled.

4) The fourth load is due to the expansion of the air on the body of the element. This step is defined dynamically.

5.5. Interaction module

This module relates to the data entry for the contact between the components.

5.6. Load module

Load, force, and reciprocal conditions are defined in the load module. In this section, static and dynamic loads are brought to the base of the tower, and the boundary conditions of the two ends of the base are considered as half-closed; The thermoelectric load caused by the lightning strike and the dynamic load caused by the expansion of air molecules to the base were applied. For the load conditions in the load module, the PINNED option has been selected because the boundary conditions of the two ends of the base are semi-closed.

In the loading module, in the first step, the load is considered as a coupled thermal-electric for the software and defining distributing loads uniformly extensive. The load swing field is selected instantaneously.

5.7. Mesh module

Meshes for elements are considered as media axis that this form of mesh in cylindrical parts creates better symmetry.

5.8. Job module

When the analysis enters this part, it means that all the data is entered correctly.in this part, the model name, the number of model elements, the type of analysis, and the status of the data entry are shown.

5.9. Visualization module

In this section, all outlet outcomes include thermal flux contours, temperature, magnetic flux, stress, strain, and so on. Using the output results, we can analyze the effect of lightning-induced thermoelectric loads on the base of the tower.

6. Thermal flux analysis

By applying a lightning strike to the desired element with a flow of 100,000 Amp, which produces temperatures close to 50,000 degrees Fahrenheit or 27,000 degrees Celsius, after the required data is entered into the software, in the visualization module, Cantor The figure given in Figure 6 is visualized. This cantor shows the conditions of the base element at the moment of the collision of the high power rod mentioned.

In this section, the thermal flux quantity of the head reaches of the base more than 3.026×103 or more than 3000 j per hundredth of a second, causing high thermal stress in the tower. This causes serious damage to the structure. But on the other hand, this high heat flux has occurred in a fraction of a second, and a few moments after the collision, the energy of the shaft is reduced to a lower flux.

The lowest tension, in the body of the base element at the furthest point of the collision is 2.522×102, or 252 j per hundredth of a second; this means that, due to the passing of the lightning strike, in the farthest part of the element from the encounter, the tension is very small.

Figure 7 shows the heat transfer per unit area in a fraction of hundredths of a second reaches its peak, and then with a loss of 100 percent, in a moment it is zeroed, and the heat transfer cycle begins again and continues; a remarkable point is that at the first moment, One millionth of the first second, the heat transfer in a cycle is twice as high as in the next cycles that this is due to the low electric charge and potential energy in a millionth of a second First.

Surface degradation and corrosion observed in some structures are due to the same continuous currents that progress over time and eventually cause cracking. In the AM antenna, if the antenna is routed directly to the antenna, then the antenna system will not be able to send radio waves, and the RF waves are practically ground; therefore, an open grill system should be used so that only a lightning strike can be transmitted to Earth. This is also true in antenna harness cables (Figure 8). For this reason, at the end of this thunderbolt system, two spheres arrays have been built with a special and robust alloy to support the operation of lightning transmission without affecting the antenna's function. (Figure 9); in these spheres, it is clearly that when the lightning strikes, due to the arc intense electrical arc between the two metals, over time, many corrosion occurs, and as more surface is destroyed, corrosion also happens faster.

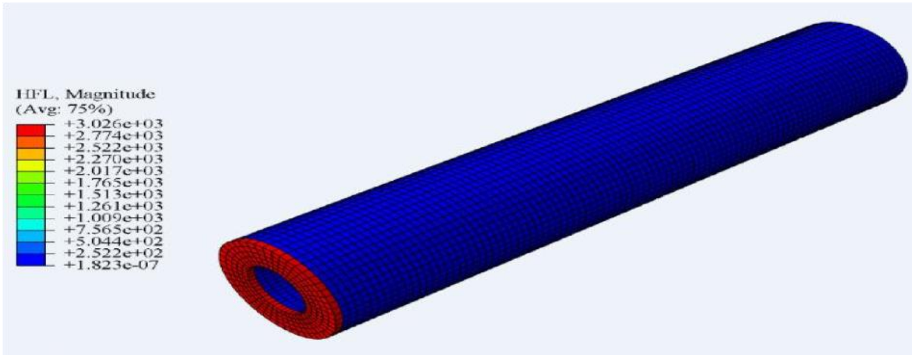

Fig. 6. Effect of thermal flux due powerful lightning.

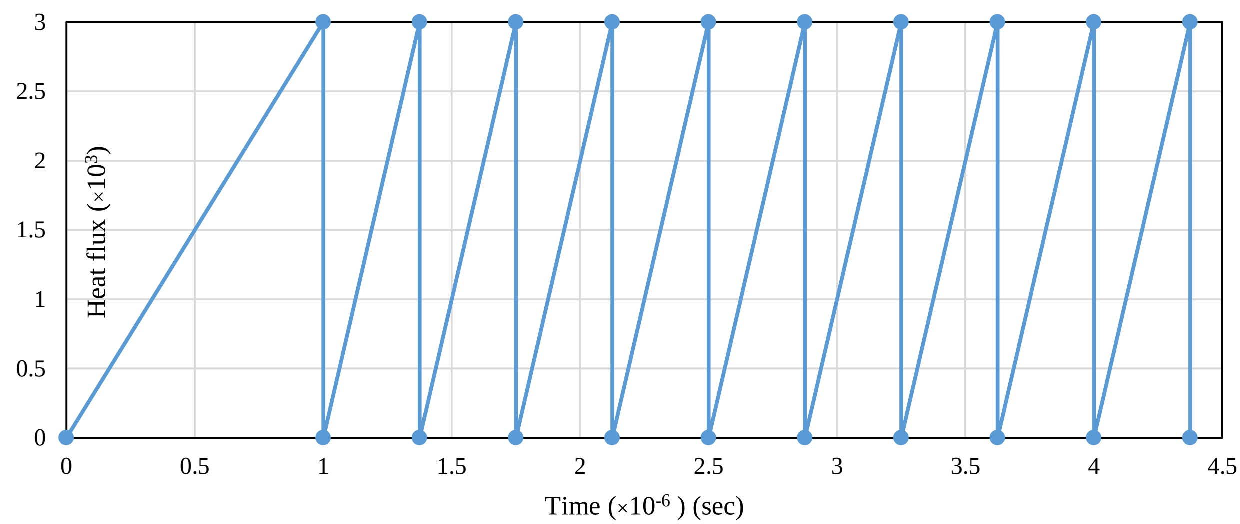

Fig. 7. Change of thermal flux vs. time.

Fig. 8. Leading rope of AM radio aerial.

Fig. 9. Superficial demolition due to lightning strikes.

The rupture of the base body occurs in all cases from the inside outwards. This is a case of bursting hypothesis due to various lightning factors such as dynamic pressure due to gas expansion, strong electric current flow from the base body, high heat of electrical flux and magnetic flux in the base body. Sometimes, there are two or more factors that can cause these injuries.

7. Conclusion

By striking the lightning rod on the tower, both existing instrumentation devices, such as TV transmitters and FM, and the tower itself, are damaged. The thermal destruction and degradation caused by the flow of lightning strike from the body of the tower, the thermal flux resulting from the passage of electric current from the conductor, from the symptoms of these injuries. One of the damages observed in the television towers is the fracture of the base of the tower in the direction of the longitudinal axis of the member. Considering the applicability and comprehensiveness of ABAQUS software in analyzing specific cases, the software was used for modeling.

According to the analysis of the results, it has been determined that very high thermal flux alone can cause fracture of the base of the tower; In addition, various heat damage over time causes a severe loss of structural stability.

Other effects such as thermal stress and electrical potential are not capable of causing damage to the tower alone, but they can cause damage alongside other factors.

8. Suggestion

1. Assess the impact of the use of composite materials on the body of the tower of the television towers.

2. The effect of wind force on the fracture of the base of the tower.

3. Check the relationship between the angle of the tower's deflection during installation and the base breaker in the same direction.

4. The effect of increasing the thickness of the pipeline, evaluating the strength of the base against the lightning.

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