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Does Temperature Effects to Propagation and Growth of Cracks in a Stay- cable of Cable-Bridge due to Lightining–Strike?

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Abstract In this paper we considered if temperature effects propagation and growth of cracks in a stay- cable of cable- bridge due to lightining strike. We dealed with the longest stay- cable of M1 pylon of Rio –Antirio bridge. We showed that after an hour the last will be cut down. Our result coincides with reality, since on 2005 a lightining stroke cut down the longest stay cable at M1 pylon of Rion- Antirion bridge. We concluded that temperature plays a great role to propagation and growth of cracks.

Keywords: *temperature, propagation and growth of cracks, longest stay- cable of Rion - Antirion bridge, lightining strike, cut down*

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1. Introduction

The purpose of this paper is to study if temperature effects propagation and growth of cracks in a stay- cable of a cable bridge due to lightining strike. For this reason we will consider the cable -bridge at Rion–Antirion in Greek.

2. The Rion-Antirion Bridge

2.1. About Lightinings

Lightining is a natural phenomenon due to a sharply discharged of a charged cloud [1,2]. The lightinings are classified into two categories: positives with charge +q and negatives with charge -q. 90% of lightinings are negatives. Values of some characteristic magnitudes for lightinings are contained in Table 1. The last deal with intensity of electric current I, electric charge q, time duration and velocity of lightinings.

2.2. Technical Informations for Rion - Antirion Bridge

The cable - bridge of Rion –Antirion is the largest at the world. Its construction completed at 2004 and units Pelloponisos with the rest continental Greek, as indicated in Figure 1. The length and width of its deck are respectively 2.252m and 27,2m.There are four pylons M1, M2, M3 and M4 on the deck of the bridge.

Figure 1. The photo Rion-Antirion bridge

Table 1. Values of the characteristic magnitudes of lightinings. Taken from [1,2]

CHARACTERISTIC MAGNITUDES	POSSITIVE LIGHTININGS 10%	NEGATIVE LIGHTININGS 90%
Electric current intensity I	$50KA \leq I \leq 300KA$	$10KA \leq I \leq 50KA$
Electric charged q	$100Cb \leq q \leq 680Cb$	$-30Cb \leq q \leq -20Cb$
Time duration t	$20msec \leq t \leq 50msec$	$10msec \leq t \leq 15msec$
Velocity v	$c = 1.2.10^6$ m/sec	$c = 1.2.10^6$ m/sec

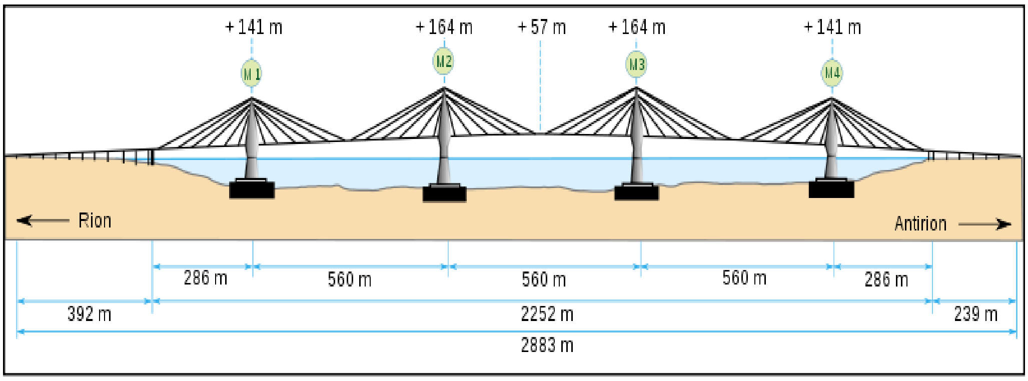

Figure 2. Schematic view of the Rion –Antirion bridge. Taken from [3]

Table 2. Values of cross - sections for polyethelene tube

Diameter of the cable :	$d_o = 25cm$
Cross-section area of the cable:	$S_o = \pi d_o^2/4 = 490.625cm^2$
Diameter of galvanism wire rope	$d_1 = 15mm = 1.5cm$
Cross - section area of galvanism rope	$S_1 = \pi d_1^2/4 = 1.76625\ cm^2$
Cross - section area of 70 galvanism wire ropes	$S = 70S_1 = 123.6375cm^2$
Cross-section area of the ring of tube HPDE	$\Delta S = S_o - S = 366.9875\ cm^2$

Table 3. Values of characteristic properties for HPDE [4]

Density	$940Kg/m^3 \leq \rho_o \leq 965\ Kg/m^3$
Temperature	$\theta = 130^oC$
Thermical contraction coefficient	$\alpha = 1.7x10^{-4}K^{-1}$
Thermoconduction coefficient	$\lambda = 0.43W.K/m$ σε 20^oC
Resistance	$R_o = 10^{14}\Omega.m$ σε 20^oC

Every pylon contains stay cables that connect the deck of the bridge to the pylons, indicated in Figure 2.

Cable is a composite material and consists of paraller galvanized wire-ropes contained in a high density polyethelene tube HPDE. The diameter and length of the longest cable at M1 pylon (Rio) are d_o=25cm and L=300m respectively [3]. This cable consists of 70 galvanized wire-ropes. Each wire –rope has a diameter d_1 =15 mm. Values of cross- sections areas: of the cable, of the galvanism wire- rope, of 70 galvanism wire ropes and of the ring tube HPDE of the longest.

HPDE and for 70 galvanized wire- ropes of longest cable of M1 pylon [3] cable of M1 pylon are contained in Table 2. Also values of characteristic properties of material HPDE are contained in Table 3.

3. The Physical Approximation of Our Problem

As we stated earlier the longest cable of M1 pylon is a composite material and consists of polyethelene tube HPDE (outer material) and steel (inner material). The steel consists of 70 galvanized wire-ropes [3], as indicated in Figure 3.

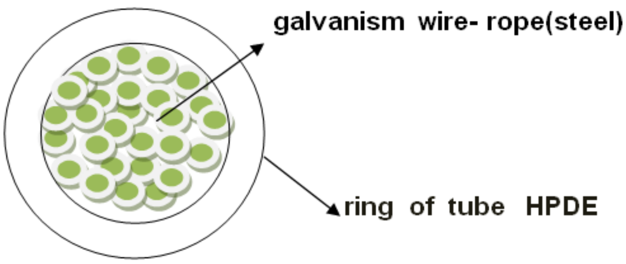

Figure 3. The cable is a composite material.

3.1. A HPDE Material Subjected to an Electric Field

Initially for t=0 the outer part of the cable had a density ρ_o, temperature $\theta_o = 20^o$ and was under a tensile stress σ_o:

$$\sigma_o = B_o / S_o \quad (1)$$

where B_o is the weight of the deck at M1 pylon and S_o is the cross - section area of the cable given in Table 2. The mass of the deck is [3]:

$$m = 555000Kg \quad (2)$$

and consequently:

$$\sigma_o = B_o / S_o = m.g / S_o = 111.10^6 \, N / m^2. \quad (3)$$

From the other hand the ultimate tensile stress for the material HPDE is [3]:

$$\sigma_t = 1770MP\alpha = 1770.10^6 P\alpha = 1770.10^6 N / m. \quad (4)$$

At t >0 a lightining strikes the longest cable of M1 pylon of Rio-Antirio bridge nearest at its top and particularly at point K (d_o, z_1) with z_1<<L, indicated in Figure 4.Then an electric field is produced and displaces the material particles. Assume that:

$$u_x = At + B \text{ and } u_z = \Gamma t + \Delta \quad (5)_{1\text{-}2}$$

where u_x and u_z are respectively the horizontal and vertical displacements, while A, B, Γ, Δ are unknown.

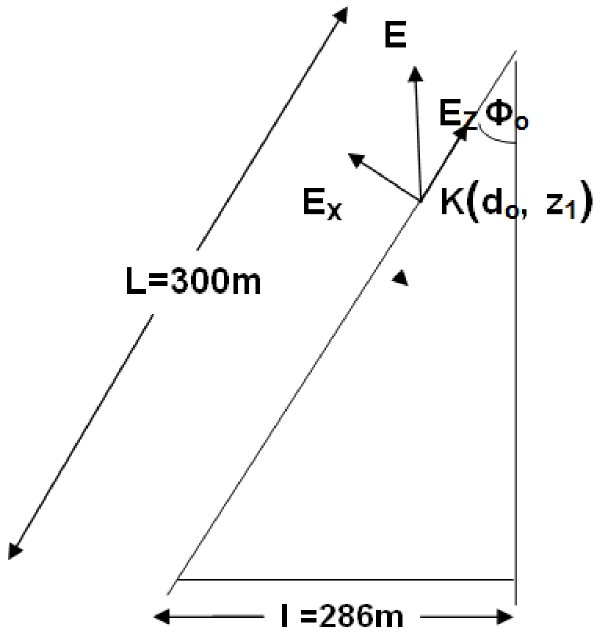

Figure 4. A lightining strikes the cable length L at the point K(d_o, z_1) and an electric field E is produced

The balance of mass for HPDE material is:

$$d\rho / dt + \rho\left(v_{x,x} + v_{z,z}\right) = 0 \quad (6)$$

where ρ and v are its density and velocity respectively. Then (6) because of $(5)_{1-2}$ concludes:

$$d\rho / dt = 0 \rightarrow \rho(t) = \rho_o. \quad (7)$$

The stress -equation for HPDE material are:

$$\rho_o \ddot{u}_x = \sigma_{xx,x} + \sigma_{xz,z} + F_x = \sigma_{xx,x} + \sigma_{xz,z} + qEsin\varphi_o$$
$$\rho_o \ddot{u}_z = \sigma_{zx,x} + \sigma_{zz,z} + F_z = \sigma_{xz,x} + \sigma_{zz,z} + qEcos\varphi_o \quad (8)_{1\text{-}2}$$

where φ_o is the ankle between cable and deck indicated in Figure 4. and q <0 is the charge of lightning. Substituting (5) into $(8)_{1-2}$ and assuming that σ_{xz}=0 it is possible to obtain:

$$\sigma_{xx,x} + qEsin\varphi_o = 0$$
$$\text{and} \sigma_{zz,z} + qEcos\varphi_o = 0. \quad (9)_{1\text{-}2}$$

The solutions of the above are:

$$\sigma_{xx} = -qEsin\varphi_o x + \Pi(\theta, t)$$
$$\sigma_{zz} = -qEcos\varphi_o z + R(\theta, t), \quad (10)_{1\text{-}2}$$

where Π(θ, t) and R(θ, t) are unknown functions of temperature and time. We assume that:

$$\Pi(\theta, t) = t + a\theta \text{ and } R(\theta, t) = t + b\theta \quad (11)_{1\text{-}2}$$

where a, b are constants.

The stresses defined in (10) satisfy the initial conditions:

$$\sigma_{xx}\left(d_o, z_1, \theta_o, 0\right) = 0$$
$$\text{and } \sigma_{zz}\left(d_o, z_1, \theta_o, 0\right) = \sigma_o. \quad (12)_{1\text{-}2}$$

The combination of (10), (11) and (12) gives:

$$a = qEsin\varphi_o d_o / \theta_o$$
$$\text{and } b = \left(qEcos\varphi_o z_1 + \sigma_o\right) / \theta_o. \quad (13)_{1\text{-}2}$$

Consequently $(10)_{1-2}$ because of (11) and (13) takes the form:

$$\sigma_{xx}(x, z, \theta, t)$$
$$= -qxEsin\varphi_o + t + qEsin\varphi_o \theta d_o / \theta_o$$
$$\text{and} \quad (14)_{1\text{-}2}$$
$$\sigma_{zz}(x, z, \theta, t)$$
$$= -qzEcos\varphi_o + t + \theta\left(qEcos\varphi_o z_1 + \sigma_o\right) / \theta_o.$$

The balance of energy at point K is:

$$\rho_o d\varepsilon(t) / dt = \sigma_{xx} v_{x,x} + \sigma_{zz} v_{z,z} + W = W \quad (15)$$

where ε and W are respectively the internal energy per unit volume and the electric power given by:

$$W = F.v = E.q.v \quad (16)$$

where F is the electric force and v is the velocity of the lightining. The balance of energy satisfies initial condition:

$$\varepsilon(0) = \varepsilon_o. \quad (17)$$

Then (15) because of (16) and (17) becomes:

$$\varepsilon(t) = E.q.vt + \varepsilon_o < \varepsilon_o \quad (18)$$

since q <0. Therefore at t > 0 the internal energy of the material HPDE at point K(x, z)=(d_o,z_1) is

$$U(t) = \int \rho_o \varepsilon(t) dV < \int \rho_o \varepsilon_o dV = U_o. \quad (19)$$

The above physically means that a propagation and growth of crack will arise [5,6].

Substituting into $(14)_2$ the following data:

$$\sigma_o = 111.10^6 \, N / m^2,$$
$$\theta_o = 20°C = 293°K. q = -20Cb, \quad (20)_{1\text{-}2\text{-}3\text{-}4\text{-}5\text{-}6\text{-}7}$$
$$E = 10000 V / m, z = z_1 = 1m, \theta = 20000°K$$

and accounting (see Figure 4) that:

$$cos\varphi_o = \left(1 - sin^2\varphi_o\right)^{1/2} = \left[1 - (l / L)^2\right]^{1/2} = 0.309 \quad (21)$$

it results that:

$$\sigma_{zz}(d_o, z_1, \theta, t) = t + 11223{,}6MP\alpha > 1770MP\alpha = \sigma_t \quad (22)$$

That is the stress exerted on the cable at point K(d_o, z_1) overcomes its ultimate tensile stress. As a result of the above the ring of tube HPDE will be split.

ii) A material steel is subjected to an electric field.

Initially at t=0 the inner part of the cable had the same temperature θ_o=20° and was under the same tensile load σ_o given by (1).

At t>0 a lightining strikes the cable. As a consquence of the above a sharply increase of the temperature Δθ of the steel arises, given by [1,2]:

$$\Delta\theta = \exp\left[(W/R).\alpha_1.\rho_1 / S^2.\check{r}.C_w - 1\right]/\alpha_1 \quad (23)$$

where W/R, ρ_1, α_1, S_1, ř and C_w are respectively for steel: the specific Om energy in units K/ Ω, the spe-cific resistance in units Ωm, the thermical coefficient in units 1/K, the cross- section area for a galvanism wire- rope in units m², the density in units Kg/m³ and the thermocapacity in units J/Kg.K.

From the other hand the specific Om energy is given by [1,2]:

$$W/R = \int J^2(t)dt \quad (24)$$

where J(t) is the intensity of electric current of lightining.

Replacing into (23) the following data:

$$\begin{aligned} &\check{r} = 8.10^3 kg/m^3 C_W = 500J/K.Kg,\\ &\rho_1 = 0.7.10^{-6}\Omega.m,\\ &\alpha_1 = 0.8.10^{-3}K^{-1} J = 30000Adt{=}20msec\\ &\text{and } S_1 = 1.76625cm \end{aligned} \quad (25)_{1\text{-}2\text{-}3\text{-}4\text{-}5\text{-}6\text{-}7}$$

taken by [1,3,8] it results that:

$$\Delta\theta = 314.5°C \quad (26)$$

which means that a sharply increase of the temperature in a galvanism wire -rope will arise and the same goes for all 70 wire- ropes and consequently for the steel.

The ultimate tensile stress of steel is [3,8,9]:

$$\sigma_{ts} = +1770MP\alpha \quad (27)$$

Also it has been shown that [10,11]:

$$-15 \le \sigma_c / \sigma_{ts} \le -8 \quad (28)$$

where σ_c is ultimate compression stress. Then from (27) and (28) it follows:

$$14160MP\alpha \le \sigma = -\sigma_c \le 26550MP\alpha. \quad (29)$$

The displacements of material particles of the steel assume to be:

$$\begin{aligned} &u_x(x,z,t) = Kt + L\\ &\text{and } u_z(x,z,t) = -M^4t^2z + N \end{aligned} \quad (30)_{1\text{-}2}$$

where K, L, M,N are unknown and satisfy the initial conditions:

$$u_x(d_s, z_1, 0) = 0 \text{ and } u_z(d_1, z_1, 0) = 0 \quad (31)_{1\text{-}2}$$

where d_s is the diameter of steel consisting of 70 galvanized wire- ropes and can easily be calculated from Table 1. Applying the above into (30), it results:

$$u_x(x, z, t) = Kt \text{ and } u_z(x, z, t) = -M^4t^2z \quad (32)_{1\text{-}2}$$

Consequently the strains are:

$$\varepsilon_{xx} = 0, \varepsilon_{xz} = 0 \text{ and } \varepsilon_{zz} = -M^4t^2z. \quad (33)_{1\text{-}2\text{-}3}$$

Substituting (33) into thermomechanical stress- strain equations:

$$\begin{aligned} &\sigma_{xx} = \varepsilon_{xx} + \nu\varepsilon_{zz} - (1+v)\alpha E\Delta\theta/1-\nu^2\\ &\sigma_{zz} = \varepsilon_{zz} + \nu\varepsilon_{xx} - (1+\nu)\alpha E\Delta\theta/\ 1-\nu^2 \end{aligned} \quad (34)_{1\text{-}2}$$

it is possible to obtain:

$$\begin{aligned} &\sigma_{xx} = -\nu M^4t^2 - \alpha(1+v)E\Delta\theta/1-\nu^2\\ &\sigma_{zz} = -M^4t^2 - \alpha(1+\nu)E\Delta\theta/1-\nu^2 \end{aligned} \quad (35)_{1\text{-}2}$$

At continuity imposing into $(35)_2$ the following data taken from **[7]**:

$$E = 200GPa, v = 0.3\ \alpha = 10.10^{-6}K \quad (36)_{1\text{-}2\text{-}3}$$

and selecting:

$$z = z_1 = 1m \text{ and } M = 6{,}4 \quad (37)_{1\text{-}2}$$

we conclude:

$$\sigma = -\sigma_{zz} = 1677{,}72t^2 + 898{,}\ 571.10^6 \text{ for } t > 0. \quad (38)$$

Finally imposing into (38):

$$t = t_1 = 4000sec \quad (39)$$

it results:

$$\sigma = -\sigma_{zz} = 27442{,}091MPa > 26550MPa. \quad (40)$$

The physical meaning of the above is that at particular time moment t_1 the galvanism wire-rope will be splitted and the same goes for all 70 wire- ropes and consequently for steel. From the above we conclude that after the lightining stroke, the ring of the polyethelene ma- terial HPDE will immediately be cut and after an hour the inner steel will also be cut.

4. Discussion and Conclusion

Our model coincides with reality. Particularly on January 27 of 2005, just six months after the opening of the bridge, a lightning stroke cut down the longest stay cable at M1 pylon. The lightning struck the top 25cm diameter cable in the southwest fan of stays over the 286m span nearest Rion. The high density polyethylene cable was set on fire, and as a result of that the cable was completely destroyed and fell on the deck [3,12,13,14,15]. From the above we result that the temperature plays significant role to propagation and growth of cracks at our case.

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