Modelling, Measurement and Control B
Vol. 87, No. 2, June, 2018, pp. 97-100
Journal homepage: http://iieta.org/Journals/MMC/MMC_B

Analysis of thermal effect on carbon fibre reinforced polymer cable

IfeOlorun Olofin*, Ronggui Liu

Department of Civil Engineering, Faculty of Civil Engineering and Solid Mechanics, Jiangsu University, No 301 Xuefu Road, Zhenjiang 212013, China

Corresponding Author Email: epher2002@yahoo.com

https://doi.org/10.18280/mmc_b.870206

Received: 6 June 2018
Accepted: 27 June 2018

Keywords:
cable system, carbon reinforced polymer cable, steel cable, thermal effect

ABSTRACT

Realizing that an important factor such as thermal load must be considered during analysis and design for a cable system, this paper presents the behavior of elastic cable based on differential thermal theorem namely catenary-based approach. To this end, the traditional known material – steel - and carbon fibre reinforced polymer were subjected to varying temperature values through simulation and the behaviour pattern were compared. Results obtained showed that the influence of temperature on steel cable is more evident with higher values than carbon fibre reinforced polymer. This makes carbon fibre reinforced polymer cable an ideal substitute when it comes to application in regions with high temperature.

1. INTRODUCTION

The design and application of cable structures with carbon fibre reinforced polymer cable are being investigated presently [1] because the researchers' seek materials with light weight, high tensile strength and less prone to temperature change to be utilized in construction. Materials existing outside room temperature are prone to thermal loads which arise from different sources either hot or cold. Thermal load is the foundational aspect for calculating thermal stress which affects the serviceability of any structure, particularly a cable structure.

With the increasing usage of carbon fibre reinforced polymer cables, little research works on thermal effect based on theoretical model, numerical analysis and field measurement can be accessed. It is a well-known fact that the co-efficient of linear expansion of carbon fibre reinforced polymer is lower than steel. Hence the need to explore such outstanding property is important especially when considering large span cable structures in extreme weather conditions.

In this paper, the influence of thermal effect on the mechanical properties of carbon fibre reinforced polymer cable is compared with its counterpart, the traditional steel. Several factors such as suppressing force, stress generated and elongation of the structural member were considered to show the effectiveness and consistence of carbon fibre reinforced polymer cables where temperature related cases are considered in cable-structures.

2. LITERATURE REVIEW

Recently, Liu et al. [2] stated that negative thermal load is the controlling factor for member stress while positive thermal load is the controlling factor for nodal displacement. In addition, solar irradiation has a significant effect on the temperature distribution and thermal behavior of large span spatial structures. Similarly, Zhao et al. [3] stated that components connected to supports were sensitive to thermal loads and the internal force can be released by deformation. Chen et al. [4] investigated the effect of temperature changes on steel members in a suspen dome and concluded it is significant and should not be overlooked. Researchers have addressed the thermal effect on suspended and inclined cables [5-7]. Temperature change can cause expansion and contraction in a cable components, causing negative effects on tension forces. The deformation can induce the dynamic characteristics of the structure which has significant influence on the stability of the structure [5]. The effect of temperature cable can be crucial when long term mechanical performance and life fatigue of stay cables are considered, especially in case of application based on cables made of carbon fibre composites [6]. The influence of prestress losses because of temperature changes should be considered for steel cables in practical designs [8]. Similarly, Chen et al., [9] examined the effect of cable material characteristic on a suspen dome and concluded that at high temperature the effect of the expansion co-efficient of the hoop and radical cable in a suspen dome was larger on the maximum displacement, bringing about a precise linear expansion co-efficient for cables. From reviewed articles, it can be observed that the material used for the cable structure is steel and some problems were encountered in respect to thermal effect. Considering such factor, it is salient and vital to discover a potent material that can replace steel in such conditions.

2.1 Thermal stress configuration

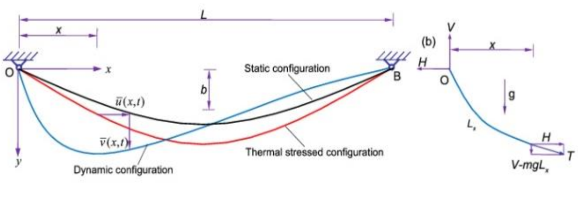

Figure 1. Configuration of a cable system [5]

A cable system is prone to three configurations namely static, dynamic and thermal as illustrated in Fig. 1. When a cable is assumed to be a flexible member, catenary theory gives an elastic behavior description and also takes account of inelastic thermal effects.

The temperature due to environmental condition changes the static equilibrium configuration equation under the influence of temperature which is given as [5]:

$$\frac{\partial}{\partial s}\left[(T+T)^{1}\left(\frac{\partial x}{\partial s}+\frac{\partial u}{\partial s}\right)\right]=0 \tag{1}$$

$$\frac{\partial}{\partial s}\left[(T+T)^{1}\left(\frac{\partial y}{\partial s}+\frac{\partial v}{\partial s}\right)\right]=-mg \tag{2}$$

where *u* and *v* are cable displacement due to temperature effect and T^1 is the tension force. Considering the linear elasticity of the material and kinematic formation, the additional tension is given as:

$$h^3+\left(2+\beta+\frac{\lambda^2}{24}\right)h^2+\left(1+2\beta+\frac{\lambda^2}{12}\right)h+\beta=0 \tag{3}$$

Where $h=\frac{H^1}{H}, \lambda^2=\left(\frac{mgL}{H}\right)^2\frac{EA}{HL_e}, \beta=\alpha\Delta t L_t\frac{EA}{HL_e}$ (4)

$$L_e=L\left[1+\frac{1}{8}\left(\frac{mgL}{H}\right)^2\right], L_t=L\left[1+\frac{1}{12}\left(\frac{mgL}{H}\right)^2\right] \tag{5}$$

If cables are assumed to be perfectly flexible members, catenary theory gives an exact description of its elastic behavior and that would allow inelastic thermal effect to be considered.

2.2 Mechanical Influence on Loaded Cable Element

The mechanical equation based on load effect on cables within a structure is

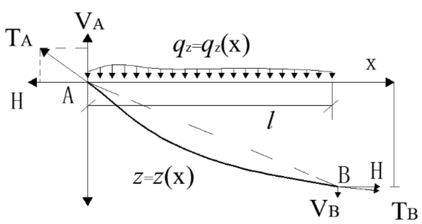

Figure 2. Cable member [9]

The differential equation is given by[9]

$$H\frac{\partial^2 z}{\partial x^2}+q_z=0 \tag{6}$$

$$q_z=q\times\sqrt{1+\left(\frac{\delta z(x)}{\delta x}\right)^2}=q_0\times\frac{\sqrt{1+\left(\frac{\delta z(x)}{\delta x}\right)^2}}{1+\frac{T}{EA_o}} \tag{7}$$

$$H=\frac{\delta^2 z(x)}{\delta x^2}+\frac{R_s}{R_e}q_0=0 \tag{8}$$

$$R_s=\sqrt{1+\left(\frac{\delta z(x)}{\delta x}\right)^2} \tag{9}$$

$$R_e=1+\frac{T}{EA_o}=1+\varepsilon_T \tag{10}$$

where E= elastic modulus of the cable, A=cross-sectional area, q_0= self-weight, T=Cable tension, q= concentration of stress.

2.3 Effect of thermal loads

When thermal loads are imposed on live loads, the actual configuration varies as well as the cable stress which can be induced with respect to the temperature. Thermal loads act upon structures for periods much longer than live loads. Minute temperature variation always cause deformation in material properties such as expansion, contraction and bending, but this often disappears when the initial temperature is recovered.

When thermal effect are considered, Hooke's law becomes [10]:

$\sigma=E(\varepsilon-\Delta T)$ or the inverse $\varepsilon=\frac{\sigma}{E}+\alpha\Delta T$ (11)

When temperature varies along a cable, the cable tends to generate stresses. The structure changes, varying its configuration without changing the acting load.

The cable equilibrium configuration in respect to length variation due to temperature is given as:

$$\Delta l/l_0=\alpha\Delta T \tag{12}$$

2.4 Endurance time

For energy balance in terms of thermal endurance, [11] suggested the following:

$$mc\frac{\partial T}{\partial t}=hA(T_\infty-T) \tag{13}$$

Temperature in the cable grows exponentially as $\frac{(T-T_0)}{T_\infty-T_0}=1-\exp\left(\frac{-t}{t_c}\right)$, with a characteristic time given as

$$t_c=\frac{mc}{hA}=\left(\rho L\pi D^2/4\right)c/\left(h\pi DL\right) \tag{14}$$

3. NUMERICAL EXAMPLES

In order to illustrated the effectiveness of carbon fibre reinforced polymer cables with temperature influence. A cable clamped at one side and free at the other side is considered. If the material is constrained to move, the internal generated stress accommodates imposed boundary conditions. A boundary condition is considered as:

$$T(x,t)\big|_{x=0,L} = T(t) \quad (15)$$

where x denotes the spatial coordinate in one dimension, x=0 and L denote space co-ordinate at the boundaries and T(*t*) is time-dependent temperature. A cable of length 400 m with a diameter of 10mm, which varies in temperature from ±10ºC to ±40ºC, is considered for the numerical analysis. Tab. 1 illustrates the mechanical properties considered for the analysis.

Table 1. Mechanical properties of the cables

Material	Steel Cable	Carbon fibre reinforced polymer cable
Cables self weight(kN/m^3)	78.6	16.0
Young Modulus (GPa)	1.8	1.6
Co-efficient of expansion(ºC^{-1})	1.2 x 10^{-5}	6.8 x 10^{-7}
Allowable material stress(MPa)	720	920
Thermal capacity (J(kg.K))	490	920

As illustrated in Tab. 1, steel has larger co-efficient of expansion than carbon fibre reinforced polymer. This means that when both materials are subjected to the same temperature variations, steel cables undergo large changes in volume than carbon fibre reinforced polymer cables.

4. RESULTS AND DISCUSSIONS

Thermal analyses are carried out to determine the mechanical behavior pattern of a carbon fibre reinforced polymer cable and comparison made with that of steel. Several results obtained are discussed which include suppressing force, deformation, stress and endurance time generated in each cable.

4.1 Supressing force due to temperature change

Considering the cable is fixed as both sides are restrained and undergoing a rise in temperature. Since both sides of the cable are prevented from movement, stresses develop in the cable and force it to buckle as illustrated in Fig. 3. The force is required to push back the cable into its original length known as the suppressing force.

Figure 3. Buckling of restrained cable due to temperature increase

Based on the suppressing force of carbon fibre reinforced polymer as compared in Fig. 4, carbon fibre reinforced polymer has a higher tendency of force to suppress temperature change which signifies temperature influence in the interactive force in the cable.

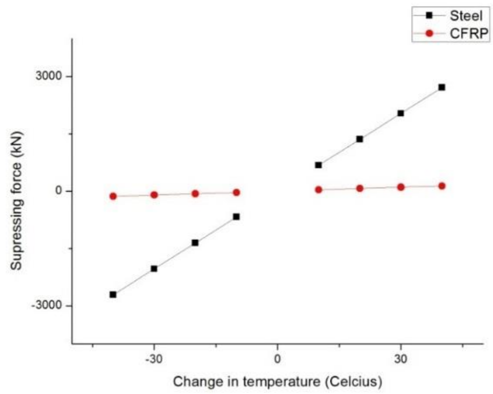

Figure 4. Comparison of temperature dependence based on suppressing force

For steel spatial structures undergoing extreme large temperature variation this is an important factor to consider because the developed forces are not negligible.

4.2 Displacement due to temperature change

The overall displacement is given as [11]:

$$u = \varepsilon L \quad \text{or} \quad \epsilon = \frac{\sigma}{E} + \alpha \Delta T \quad (16)$$

According to ASTM A514 standard, QT-100 steel has an excellent low temperature property but can't be used below 46ºC. From Fig. 5, it is observed that carbon fibre reinforced polymer cable suffers a deformation of 0.01m at a temperature change of 40ºC as to steel which is 0.192m which explains that at low temperature steel properties are affected.

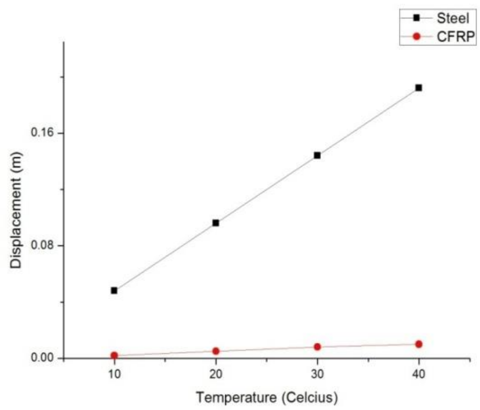

Figure 5. Comparison of temperature dependence on displacement

Due to the difference in co-efficient of linear expansion between steel and carbon fibre reinforced polymer cable, the obtained deformation varies which generate stress in the cable.

4.3 Stress due to temperature change

When a certain temperature is reached, the elastic thermal stress is influenced by variation of plastic deformation. Larger stress values were experienced for steel cables when compared with carbon fibre reinforced polymer as illustrated in Fig. 6.

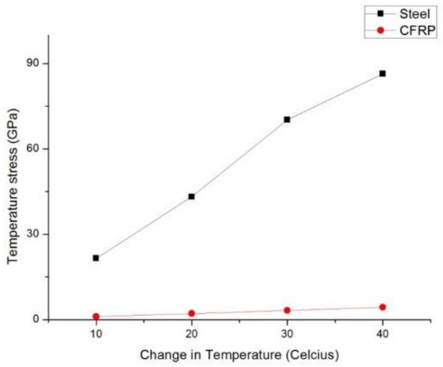

Figure 6. Comparison of temperature dependency on stress

As temperature increases the stress behavior of steel changes which gradually reduces its stiffness and strength, whereas for carbon fibre reinforced polymer the effect of thermal stress on the cable is negligible.

4.4 Influence on endurance time

Materials subjected to constant load over a period of time can suddenly fail. Assuming the heat convection of air is 20W/(m2.K), it would take 184sec for temperature to generate in carbon fibre reinforced polymer cable but about 481sec for steel cable. The results show that the endurance time of carbon fibre reinforced polymer is lower than steel as compared. However, carbon fibre reinforced polymer cable is generally not affect by environmental conditions.

5. CONCLUSIONS

In this paper a carbon fibre reinforced polymer cable is analyzed based on thermal effect and compared with the thermal behaviour steel cable to investigate the influence of temperature variation on the mechanical behaviour of both cables. Several analyses have been discussed, highlighting the influence of temperature on cables used in cable structures. It can be drawn out that

1. The mechanical properties of carbon fibre reinforced polymer cable do not drastically decrease with increase in environmental temperature as steel cable.
2. The displacement value due to temperature change for carbon fibre reinforced polymer cable is lower than that of steel
3. The stress relationship for carbon fibre reinforced polymer cable was low as compared with steel.

For realistic temperature variation, significant effect in the cables has been experienced numerically. The temperature effect on steel is much more evident with higher values as compared with carbon fibre reinforced polymer. Hence, carbon fibre reinforced polymer cable tends to have more favorable properties when it comes to temperature variation. Carbon fibre reinforced polymer cable offers a greater thermal efficiency than steel cable. Thus, this lightweight material could significantly reduce the overall cost associated with thermal control in cable structures.

ACKNOWLEDGMENT

The authors acknowledge the support of the National Science Foundation of China (Grant no: 51608234; 51478209) and Province Science of Jiangsu BK20160534.

REFERENCES

[1] Olofin I, Liu R. (2016). Numerical modal analysis of a suspen dome with carbon fibber reinforced polymer tensegrity system. Modelling, Measurement and Control, Series A 89: 13-24.
[2] Liu H, Liao XW, Chen ZH, Zhang Q. (2015). Thermal behavior of spatial structures under solar irradiation. In Applied Thermal Engineering 87: 328-335.
[3] Zhao ZW, Liu HB, Chen ZH. (2017). Thermal behavior of large-span reticulated domes covered by ETFE membrane roofs under solar radiation. Thin-Walled Structures 115: 1-11.
[4] Chen D, Wang HJ, Qian HL, Li XY, Fan F, Shen SZ. (2017). Experimental and numerical investigation of temperature effects on steel members due to solar radiation. Applied Thermal Engineering 127: 696-704.
[5] Zhao YB. (2014). Temperature effects on tension forces and frequencies of suspended cables. Proceedings of the 9th International Conference on Structural Dynamics, EURODYN 2014 Porto, Portugal.
[6] Varro G, Monlassar S. (2012). Mechanical modeling of stays under thermal loads. mechanics, models and methods in civil engineering- lecture notes in applied and computational mechanics 61: 481-498.
[7] Noisternig JF. (2000). Carbon fibre composites as stay cables for bridges. Applied Composite Material 7: 139-150.
[8] Chen ZH, Liu ZS, Sun GJ. (2011). Thermal behavior of steel cables in prestressed steel structures. Journal of Materials in Civil Engineering 23.
[9] Shen S, Xu X, Zao C. (2006). Design of suspension structure, Beijing, China. Architecture Industry Publishing House.
[10] Chen ZH, Sun GJ, Liu ZS. (2010). The effect of cable material characteristics on suspen dome. Advanced Material Research 156-157: 1251-1255
[11] Isidoro M. (1995). Thermal effects on materials. UPM.