Chapter

The Effect of Temperature on the Mechanical Performance of Steel and Carbon Fiber Reinforced Polymer (CFRP) Tensegrity System

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Abstract

This paper compares the behavioral pattern of steel and carbon fiber reinforced polymer tensegrity system in a suspen-dome that has a span of 4-m span and a 0.4-m, using the finite element method software – namely ANSYS – to undertake the analysis at various temperature regimes. These comparisons were undertaken in order to validate the performance of carbon fiber reinforced polymer cables. Under cold and hot temperatures, the elastic modulus usually reduces as a result of changes in molecular structure. Previous analysis has shown that carbon fiber reinforced polymer cables are able to resist cold and hot temperatures more than steel cables do as the integrity of steel system begins to deform at high temperatures. However, with their low thermal expansion and esthetic properties, carbon fiber reinforced polymer cables can provide structural stability for a tensegrity system in a suspen dome in regions with high temperature conditions.

Keywords: suspen dome, steel tensegrity system, carbon fiber reinforced tensegrity system, temperature effect

1. Introduction

A suspen dome is a long-span roof structure made up of two systems, a reticulated single layer and a tensegrity system created by Kawaguchi and his team. The tensegrity system is made up of three components, namely: the radical cables, struts and hoop cables as illustrated in **Figure 1**. To ensure structural stability, the cables are subjected to tension and the struts to compression. The rigidity of the dome is as a result of the self-stress equilibrium between the cables and the struts.

It is observed in the literature reviewed that a structure with steel material has some setbacks that, hopefully, the use of a new material can overcome, especially since the need for long-span structures is currently trendy. This paper describes the elastic plastic state in respect of temperature changes of carbon fiber reinforced polymer cable as a tensegrity system in a suspen dome in comparison with that of steel cables.

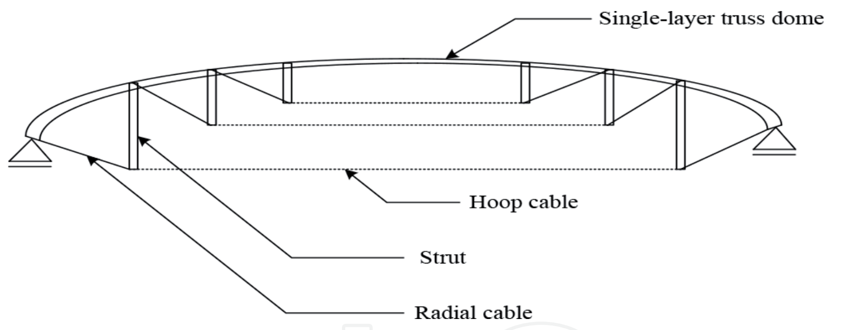

Figure 1.
Suspen-dome (structural system).

2. Literature review

Civil Engineers are seeking new types of materials to create slender structures with outstanding strength in their structural designs for long-span structures. Carbon fiber reinforced polymers are currently being used in various engineering fields based on their high stiffness, high strength and low density. Researchers have investigated that carbon fiber reinforced polymer cables can be used to strengthen steel members both with numerical and experimental methods [1, 2]. However, based on literature review, it is clear that researchers have not provided guidelines for its implementation in space structures such as suspen dome. Early researches focused on static and dynamic effect of fire, and joint treatment [3–13] of suspen dome structures with steel materials for numerical and experimental methods. Of course, steel materials can effectively enhance the strength of structures, but a larger amount of strengthening materials would be required to improve serviceability of such structures.

Research on the environmental durability of carbon fiber reinforced polymer compared to that of steel bond is limited, particularly in civil engineering and infrastructure disciplines [1]. The relatively high modulus of carbon fiber reinforced polymer materials can enhance their serviceability and ultimate better load-bearing capacity than those of steel structures [1]. Also, since the effect of temperature rise is included in structural models which describe the structural behavior, stability of elements and material properties, the incremental reduction in steel strength with increase in temperature, a well-known phenomenon, creates the room for replacement with more resistant materials such as carbon fiber reinforced polymer. This is especially so because structures exposed to sunshine react to temperature changes. Thus, temperature exposure is one important scenario to consider when selecting construction materials. As long as the rising temperature remains below the debonding temperature threshold, the reinforcing material will retain its function.

Al-Salloum et al. [3] investigated the load-bearing capacity of carbon fiber reinforced polymer reinforced specimen exposed at 100°C, using a cylinder ϕ100 × 200 mm strengthen with a single layer of carbon fiber reinforced polymer, and the results showed that, at the specified temperature, the load-bearing capacity of the carbon fiber reinforced polymer reduces slightly. Notwithstanding this, with the continued development and application of carbon fiber reinforced polymer cables, researchers are becoming more confident in its use for bridge engineering. The brittle nature of carbon fiber reinforced polymer cables could be seen as a disadvantage for its application for a long span structure such as the tensegrity system of a suspen-dome; however, further researches in other aspects, such as temperature changes, are required to determine its effectiveness and advantage over steel cables. Steel is brittle with temperature ranging between −72 and −40°C and its ductile-brittle transition ranges from −40 to 0°C. Carbon fiber reinforced polymer

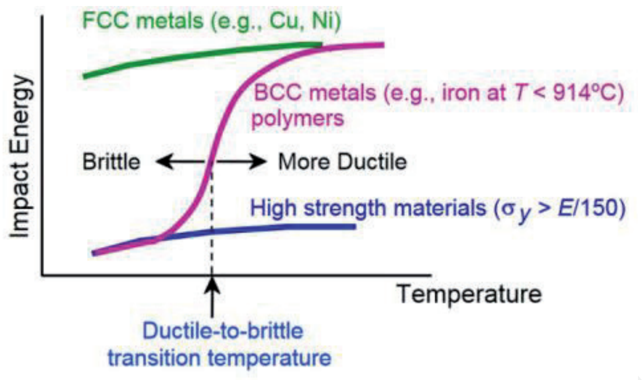

Figure 2.
Ductile-to-brittle relation.

is of high strength and brittle so it does not display a ductile to brittle transition. Steel exhibits a ductile to brittle transition and can only be applied at temperatures above the ductile-brittle (**Figure 2**) transition threshold to avoid failure without warning. Carbon fiber reinforced polymers rarely have a ductile-brittle transition threshold; hence it can be used at any temperature while steel can be used only at temperatures above 0°C.

According to Zhang et al. [14], temperature effect has a great influence on the mechanical properties of a suspen dome roof. Also, the results of Chen et al. [10] further indicated that different thermal expansion coefficients of materials will significantly affect the mechanical properties of cables that form a part of a suspen dome roof structure. Since the temperature expansion coefficient of carbon fiber is about 1/18 of that of steel cables, the influence of temperature effect of carbon fiber reinforced polymer obviously requires further investigation to determine if its temperature effect will have satisfactory impact on a suspen dome structure.

2.1 Theoretical formula on pre-stress losses based on temperature effect

Evaluation process of pre-stress loss affected by temperature is given as:

$$\Delta L = \alpha L\, o\, (t - t_o) \tag{1}$$

$$\varepsilon = \Delta L / L = \alpha (t - t_o) \tag{2}$$

$$\varepsilon_x = \varepsilon_{xx} + \varepsilon_{xy} = \alpha_L (t - t_o) + \nu_{\min} \alpha_T (t - t_o) = (\alpha_L + \nu_{\min} \alpha_T)(t - t_o) \tag{3}$$

$$\varepsilon_{xy} = \nu_{yx} \varepsilon_y \tag{4}$$

$$\sigma_x = \varepsilon_x E \tag{5}$$

$$\Delta N = A \sigma_x \tag{6}$$

where: ΔL – deformation length of cable, L – the initial length of the cable, α_L – Longitudinal linear expansion coefficient, α_T – transverse linear expansion coefficient, ε_x – the total strain in the x-direction, ε_{xx} – the strain component in the x-direction due to deformation in the x-direction, ε_{xy} – the strain component in the x-direction due to deformation in the y-direction, $\nu_{\min}$ – times Poisson's ratio, ν_{yx} – Poisson's ratio in the y-direction of the material, ε_y – the total strain of the cable in the y-direction, E – effective elastic modulus of cable, A – cross-sectional area of the cables.

3. Description of proposed model

The model in the study is shown in **Figure 3a** and **b**. It has a span and rise of 4 and 0.4 m, respectively (making a rise-to-span ratio of 0.1 that satisfies the span to rise ratio recommend by Kitipornchai et al. [4]).

Basic assumption

- The tensegrity members are pin-jointed.
- The external loads are applied at nodes.
- The self-weight is transferred to nodes as point loads.
- Cables are elastic

The single-layer (upper section of the suspen-dome structure) consists primarily of hollow beams which are 20 mm in diameter and 1.2 mm in thickness. A large cross-section gives a high stiffness which contributes to the overall stability of the shells. In this study, the uniformly distributed load is converted to nodal loads at all nodes on top of the suspen dome. For example, a uniformly distributed load 3 kN/m^2 is converted to nodal load of magnitude 20 kN. A distributed load of 20 kg was assumed to be the dead load applied on the roof, including the loads on the cables. The initial force was designed to increase as external loads increase to avoid slacking when the structure is in service. If the loads are increased beyond a certain limit, the structure will collapse suddenly under any little disturbing force. Hence, any designer of a new structure should be interested in knowing the load factor value which would cause the structure to collapse. Subramanian [5] stated that the detailed information about the behavior of the structure at or near the critical load is insignificant for practical purposes. As a result of this statement, different loading conditions were not considered in the investigation. For numerical reasons the temperature loads were taken to be −30 and 30°C (cold and hot levels). Any valve of ΔT can be applied because the assumption of linearity is considered.

A typical numbering of nodes and elements illustrated in **Figure 4** due to the symmetrical nature of the structure where E*i* represents element and *i* number range from 1 to 5 and N*i* represents node, *i* a number ranging from 1 to 5, respectively.

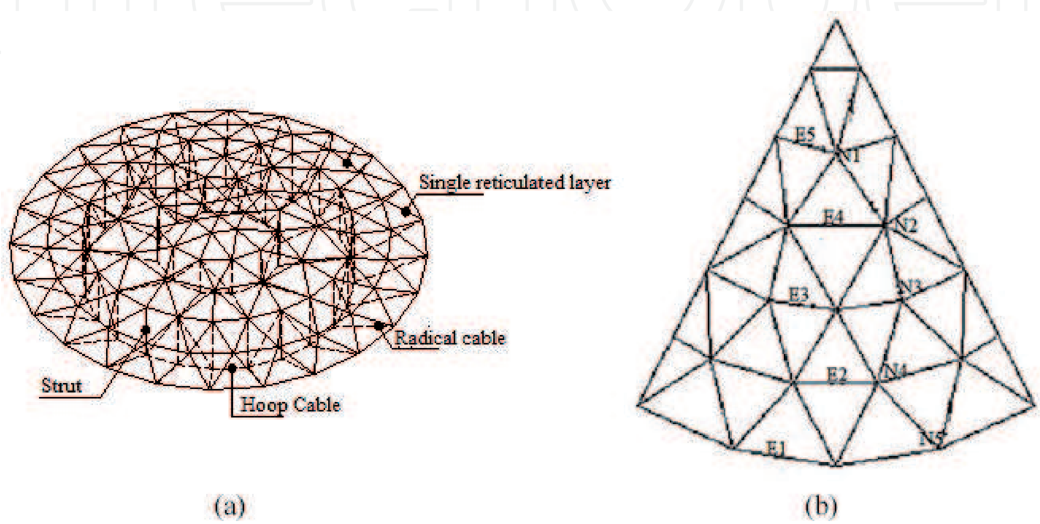

Figure 3.
Details of the model. (a) A sketch of the geometry of the suspen dome. (b) Numbering of nodes and element.

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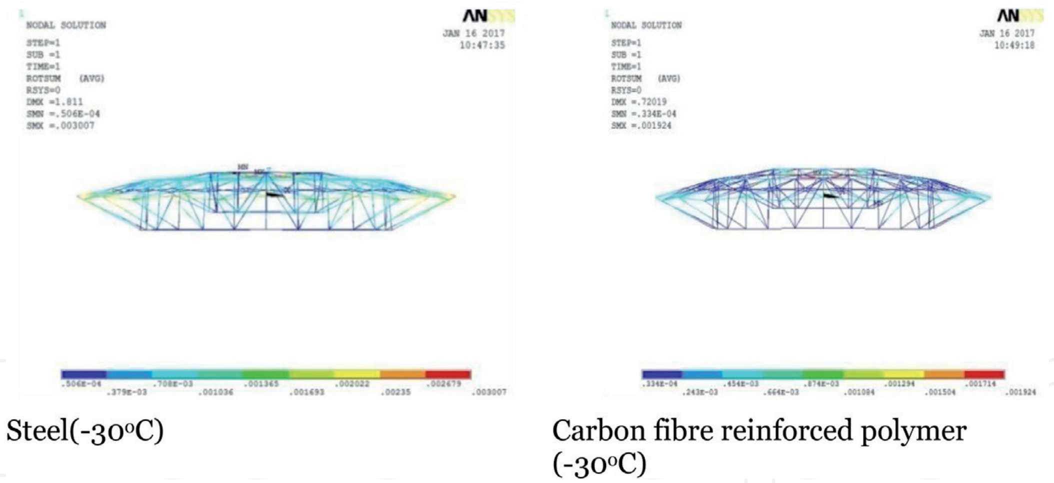

Figure 4.
Comparison of steel and CFRP tensegrity at −30°C.

	Steel cables	Carbon fiber reinforced polymer cables	Steel section
Modulus of elasticity(N/mm^2)	1.8×10^5	1.6×10^5	2.05×10^5
Poisson's ratio	0.3	0.3	0.3
Thermal expansion (K^{-1})	1.2×10^{-5}	0.68×10^{-7}	1.2×10^{-5}
Tensile strength (MPa)	835	2550	

Table 1.
Properties of the materials.

3.1 Description of the properties of materials

In this section the values of the parameters of the materials and those of the materials used for each element of the system are described. The properties of the materials for the cables and single reticulated layer dome are illustrated in **Table 1**.

4. Results and discussions

The use of tensegrity system provides an interesting solution to the stability of a suspen dome. This has prompted the proposal of using carbon fiber reinforced polymer cables. The results are based on analogy and can satisfactorily anticipate the behavior of the structure.

4.1 Effect on structural member based on numerical study

For steel structure at both cold and hot temperature, shown in **Figures 4** and **5**, the member bars of the upper single layer reticulated shell at mid rib stress increase due to the pulling force of radical cables, strut and hoops cables. It must be noted that when the cables are loose at the temperature load, the suspen dome cannot maintain its structural form and a collapse takes place due to some cables being slack and the strut being in tension.

At the outermost ring, the displacement is smaller due to the constraint boundary condition which minimizes stress in its member and the further the nodes are away to the mid rib the larger the displacement. The inner cables are of relatively large deformation. Pre-stressed cable has an impact on the behavior of a suspen

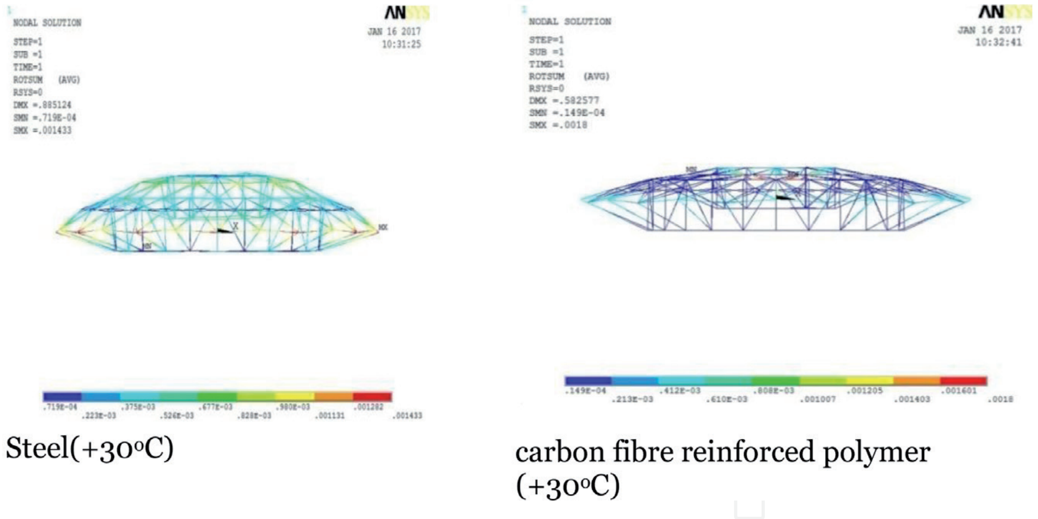

Figure 5.
Comparison of steel and carbon fiber reinforced polymer tensegrity at +30°.

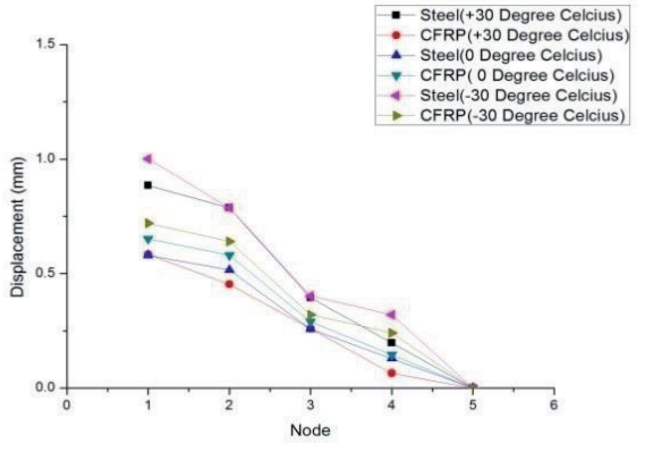

Figure 6.
Displacement against nodes.

dome structure, however with the increase in temperature of steel cable, the stiffness and load bearing capacity reduced drastically.

For the carbon fiber reinforced polymer tensegrity system at both cold and hot temperature, the cables tend to be in tension resisting the pushing force from the single layer reticulated shell to avoid slack in cables and tension in struts, as shown in **Figures 4** and **5**. Deformation of the structure in both cases is due to stress, a tensile or compressive stress that is a result of the thermal expansion.

For steel cables, the stress-strain effect increases tremendously with increase in temperature value which causes the structure to expand thereby reducing its serviceability. However, the difference in displacement effect for carbon fiber reinforced polymer cable was minute as shown in **Figure 6** which implies that a steel material used as the single reticulated layer expands and deforms with cold and hot temperature changes whereas carbon fiber reinforced polymer cables are constrained to avoid deformation.

4.2 Effect on single reticulated layer

The stresses of the members are not zero as shown in **Figure 7** which indicated the structure has not reached its bearing capacity threshold under the given load. The results also demonstrate that at hot and cold temperatures, carbon fiber

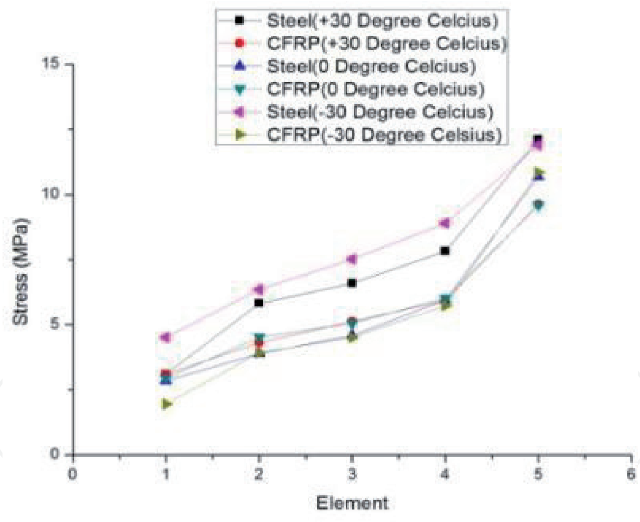

Figure 7.
Axial load vs. element number curve.

Cable	Steel	Carbon fiber reinforced polymer
Hoop cable	333.15	310.57
Radical cable	352.10	308.06

Table 2.
Internal force in tension members at +30°C (N).

Cable	Steel	Carbon fiber reinforced polymer
Hoop cable	365.45	304.57
Radical cable	353.42	301.06

Table 3.
Internal force in tension members at −30°C (N).

reinforced polymer tensegrity system maintains the same minimal stresses in members compared to steel tensegrity system.

4.3 Effect on pre-stress losses on the cable members

Tables 2 and **3** illustrate maximum internal forces generated in the outer hoop and radical cable of the structural system due to temperature effect. The internal forces for both the hoop and radical carbon fiber reinforced polymer cable are minimal compared with steel.

Hence, an overall stability with reference to temperature is guaranteed for a suspen dome with carbon fiber reinforced polymer tensegrity system.

5. Feasibility consideration

The numerical results of this study show that the proposed application of carbon fiber reinforced polymer cables for a tensegrity system in a suspen dome is more effective compared to steel tensegrity with respect to temperature effect. The results also show that a composite material has less adverse effect on the stress in the structural members in terms of temperature changes. Fureai dome has been constructed using the suspen dome system in Nagaro prefecture, where there is heavy snow fall. It is proposed to measure the changes in cable tension force due to the snow fall and temperature changes [5]. With the results obtained, it is suitable for situations where the temperature factor is considered. Thus the traditional suspen dome roof structure of steel cables can be replaced with carbon fiber reinforced polymer cables because they can achieve better design results than those of steel.

6. Conclusion

This study has shown that carbon fiber reinforced polymer cables have displayed desirable traits which can be exploited in the design of a tensegrity system. The deformation attribute in terms of temperature variation is small for the carbon fiber reinforced polymer tensegrity system hence changes in geometry can be neglected compared to steel with high displacement values under different temperature conditions.

Although there has been no relatively practical application of the concept, the results obtained in this study indicate that carbon fiber reinforced polymer cables can be recommended for use because of for its desirable effects. The objective of this study, using a small suspen dome model to investigate the influence of temperature changes on the stability of a suspen dome, has been achieved satisfactorily. Thus, this paper demonstrates that the proposed carbon fiber reinforced polymer system can be effectively used to enhance the serviceability and stability of a suspen dome.

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Conflict of interest

The authors declare no conflict of interest.

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