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A STUDY ON THE ULTIMATE LOAD BEARING CAPACITY OF CARBON FIBRE REINFORCED POLYMER TENSEGRITY SYSTEM IN A SUSPEN DOME

IfeOlorun Olofin, Ronggui Liu

Jiangsu University, Faculty of Civil Engineering and Solid Mechanics,No 301 Xuefu Road ,Zhenjiang,China; epher2002@yahoo.com, *liurg@ujs.edu.cn*

ABSTRACT

Structural stability is one of the major factors considered for structural design. The integrity of carbon fiber reinforced polymer as a tensegrity system in a suspen dome is investigated by employing a computational model with a span of 93m. ANSYS software was employed for the investigation. The load-displacement curve of the structure was studied to understand the ultimate load bearing capacity in comparison with steel cable using Newton-Raphson and arc length methods. Parameters such as nodal displacement, stresses on the single reticulated layer and internal forces of the tension members that influence the structures integrity were considered. Results show that despite the antistrophic nature of carbon fiber reinforced polymer it possesses similar characteristics as steel cables.

KEYWORDS

Suspen dome, Tensegrity system, Carbon fibre reinforced polymer cables, Steel cables, Ultimate load bearing capacity

INTRODUCTION

Carbon fiber reinforced polymer cables have obviously become the best alternative choice in the design of bridgeworks for Civil Engineering structures as reviewed by Olofin and Liu [1]. Exploring the material in other cable structures has been limited. A suspen dome which is a composite structure made up of a single reticulated layer and a tensegrity system which is a cable structure has become popular in the present world [2]. The need to explore more properties of the structure is required in order to make conclusive findings for researchers and designers. In order to explore such excellent mechanical properties for a suspen dome, a study is performed, first and foremost to comprehend the ultimate load bearing capacity of carbon fiber reinforced polymer cable due to its anisotropic nature in order to compare the result with the corresponding behavior of steel cables. Carbon fiber reinforced polymer cables may experience severe damage when subjected to certain load conditions. Under such conditions, the load imposed area deforms and alters the material behavior resulting in a decrease in residual strength and subsequently a risk of total failure.

The purpose of the study is to determine the extent to which carbon fiber reinforced polymer cables as a tensegrity system in a suspen dome structure can sustain their capacities under high impact load bearing condition with a finite element model; namely, the Beijing Olympics Stadium using ANSYS software for its simulation and comparing results with that of its counterpart steel.

Newton-Raphson method was used for the initial loading and when the load was close to ultimate load. Then arc length method was employed to cross pass the critical point. The methods are restricted to static analyses with proportional loads for deflections based on the actual member sizes which were performed with as much accuracy as possible for the constructed model to predict structural response under various loading conditions in order to put forward some design recommendations.

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LITERATURE REVIEW

In today's world long span structures are becoming trendy, the need to explore lightweight, high stiffness and low cost material are required to fulfil such requirement. Steel cables have been known for centuries to be the best choice of material for cable structures. Of recent, carbon fibre reinforced polymer cables have taken a toll in competing with steel cables with its exceptional mechanical properties. To explore such properties in other cable structures apart from bridgework, Yue *et al*. [3] investigated the application of carbon fibre reinforced polymer cables on roof cables; namely, the wheel spoked and roof façade and concluded it was more economical and material usage was limited as compared to steel. Similarly Olofin and Liu [4-6] investigated the application of carbon fibre reinforced polymer cables as a tensegrity system in a suspen dome and concluded that applying the material increases the stiffness and stability just as steel.

An overview on buckling load

Local buckling is greatly affected by the stiffness, loads on the adjacent elements and the flexural strength of the joint in most cases it is likely to occur in single-layered space frames [7] which leads to global buckling. An approximate formula for local buckling load was proposed by Lind, applicable to triangular network with all elements of same cross-section [8].The formulas are expressed in Equations 1-3.

For a uniform load, the critical load is given as:

$$Q_{cr} = \frac{E_t}{1+\alpha^2/\left(8\pi^2\right)}\left(0.47\frac{Al^3}{R^3}+3\frac{BI}{Rl}\right) \tag{1}$$

where $\alpha = l^2/(rR)$, *r* is the radius of gyration, A is the area of an element, *B* is the non-dimensional bending stiffness of the grid near a joint, I is the moment of inertia, *R* is the radius of curvature of the mid-surface of the framework, *l* is the length of the element, *h* is the rise and E_t is the tangent modulus.

For concentrated load, the critical load is given as:

$$W_{cr} = \frac{3EAh^3}{l^3}\left\{\frac{8B}{\alpha^2}+0.241\left(1-1.595\frac{8B}{\alpha^2}\right)\right\} \tag{2}$$

Valid if αis greater than 9(approximately), and

$$W_{cr} = 0.0905EAl^3/R^3 \tag{3}$$

Valid for a regular pin-jointed structure.

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METHODS

This section describes in details the study material, procedures and methods used for the analysis.

Principle of comparison and design

In this case study, the following properties were compared:

i) The ultimate load bearing capacity of the models,

ii) The hoop and radical cables in tension.

During the comparison the following were used as guidelines:

i) Initial geometry loads and boundary condition of steel and carbon fiber reinforced polymer tensegrity systems are same,

ii) The external load conditions of steel and carbon fiber reinforced polymer suspen dome are kept the same,

iii) Each cable reached its ultimate tensile strength,

iv) The deflection limits of steel and carbon fiber reinforced tensegrity systems are reached.

Numerical technique

The purpose of finite element analysis is to create mathematically the behavior of an actual system. The analysis is an accurate mathematical model for the physical prototype. Figure 1 illustrates the flowchart of the occurrence of a progressive collapse in a suspen dome.

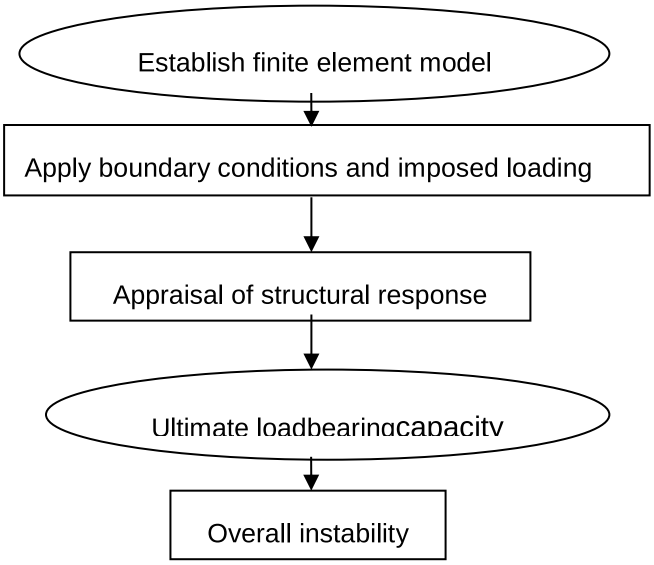

Fig.1-Identification flowchart for occurrence of a progressive collapse in a suspen dome

Description of investigated structure

Based on appropriate simplification, the physical dimensions of Beijing Olympic Badminton Gymnasium suspen dome are given as follows [9-11]: the span of the model is 93m and 8m high, fixed and hinged as shown in Figure 2.

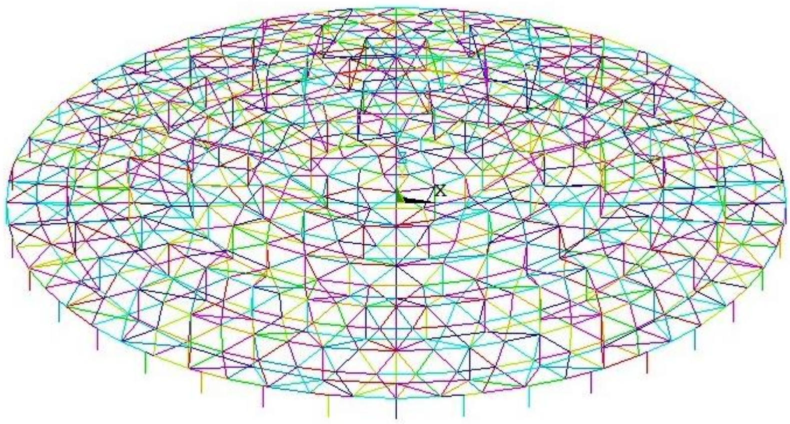

Fig. 2 - Model design of Beijing Olympic Badminton stadium

The single layer reticulated shell is a ϕ219x10 circular steel pipe with Q345 steel circular tube of ϕ168 x 8 for strut and a yielding strength of 345N/mm^2.The permanent and live loads of the roof are 0.85kN/m^2 and 0.5kN/m^2 respectively for initial simulation. Based on static equivalent principle, the uniformly distributed load is equivalent to a vertical concentrated load on each node of the upper single layer of the reticulated shell. According to Wenjiang et al. [12], in general, for a suspen-dome with N_r rings, the suggested pre-stress force ratio is given as N_r: N_{r-1}: N_{r-2}….:1. For the model, 1.8 x 10^5 N/mm^2 was adopted for the pre-stressed cable with distribution ratio of 5:4:3:2:1 from the outer to the inner hoop. The area and material properties are illustrated in Tables 1 and 2 respectively.

Tab. 1 - Details of hoop cables and radial cables

		Hoopcable			**Cable diameter**	
		HS1	HS2~3	HS4	JS1	JS2~4
Cable						
	Cross-sectionarea(mm^2)	7658	2730	1179	1179	726
	The equivalent axial stiffness(MPa)	9898	3258	1524	1524	938
	Strength(MPa)	6950	2478	1070	1070	659

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Tab.2 - Material Properties

	Modulus of elasticity (E)/GPa	Density /kg/m^3	Tensilestrength /MPa	Design strength(*f*) /MPa	Poisson ratio	The temperature coefficient of expansion (α)/K^{-1}
Sectionsteel	206	7850	550	315	0.3	12×10^{-6}
Steel Cable	180	7850	1670	835	0.3	12×10^{-6}

Material type proposed

Aside from the geometric configuration and stiffness of the tensegrity system, the static performance of the suspen dome is essentially governed by axial mechanical properties of the cables. As hinted earlier, carbon fiber reinforced polymer cables is proposed to replace steel ones. Based on the structural dimensions of Beijing Olympic Badminton stadium suspen dome, the structural scheme of the tensegrity system made up of carbon fiber reinforced polymer cables would involve material properties illustrated in Table 3.

Tab.3 - Material Properties Proposed for carbon fibre reinforced polymer cables

	Modulus of elasticity (E)/GPa	Density /kg/m^3	Tensile strength /MPa	Design strength (*f*)/MPa	Poisson ratio	The temperature coefficient of expansion(α) /K^{-1}
Radical and hoop cables	160	1600	2300	920	0.3	6.8×10^{-7}
Strut	390	1600	2740	920	0.3	6.8×10^{-7}

Exploiting the relative high tensile strength of carbon fiber reinforced polymer cables and avoiding the unfavorable influence of their relatively low elastic modulus can improve the structural mechanical property of the system.

Element and mesh selection

A suspen dome structure is made up of series of beams and truss elements. Two types of elements were selected for the analyses of the structure, namely: LINK 10 and BEAM188.

LINK 10 element is a uniaxial 3-D elastic truss element with tension only (or compression only) capability. The element has three degrees of freedom at each node: translation in x, y and z directions of the nodal, translation in node x, y and z directions [13]. BEAM 188 is an element to analyze slender to moderately thick structures. It is a quadratic 3-node beam element in 3-D, having a six to seven degree of freedom at each node [13].

The single reticulated layer is meshed using BEAM188 and the tensegrity system is meshed using LINK10 (Bar element). A reasonable mesh of element size 1mm x 1mm was implemented for both cases. The model consists of 1785elements and 621nodes. Carbon fiber reinforced polymer cables were modeled as an anisotropic linear-elastic material and an isotropic elastic-plastic material was assumed for the mechanical behavior of steel cables.

Loading and Boundary conditions

The joints of the upper single layer are rigid joints. The degrees of freedom for the supporting joints are restricted as the boundary conditions. The upper single reticulated shells are under uniform loads. The dead, live, seismic, temperature values were considered alongside with all pertinent load combinations as specified in Chinese standard codes [14-16].

RESULTS

Firstly, results obtained from carbon fiber reinforced polymer model were compared with steel model to see the influence of the advantages of carbon fiber reinforced polymer. Carbon fiber reinforced polymer and steel models were analyzed at different imposed load for the whole system. In addition, the reactions of the radical and hoop cables were considered due to the snap effect.

Load bearing capacity of the models

Elastic design is based on full calculated loads. The minimum load causing buckling depends on the mechanical and geometrical characteristics which include section, length, young modulus and end support conditions. The load displacement curves for loading conditions on the models to achieve their ultimate bearing capacities are illustrated in Figure 3.

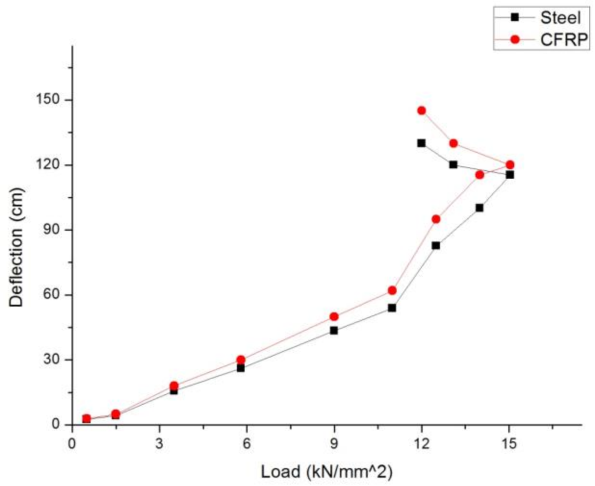

Fig. 3 - Load-displacement curve of the suspen dome at maximum load

In the elastic phase, the two curves are consistent. The suspen dome showed a linear nature in the initial loading period for both carbon fiber reinforced polymer and steel cables due to the pre-stressed nature of the tensegrity system. When carbon fiber reinforced polymer reaches its maximum elastic phase it fails whereas steel cables can still withstand additional load due to its strain hardening effect. The elastic ultimate load bearing capacity for steel was 15.0kN/m^2 and that of carbon fiber reinforced polymer was 18kN/m^2. Pre-stressed carbon fiber reinforced polymer increased the stiffness of the structure with an ultimate capacity a little bit closer to steel. This is advantageous when improving the serviceability of the structure is desired.

The performance of carbon fiber reinforced polymer also increased as a result of its high ultimate strength. Any additional load on carbon fiber reinforced polymer cable model would yield to elastic-plastic which means instability of the structure and a progressive collapse will occur. In reality, non-linearity and imperfections prevent real structure from achieving its theoretical capacity.

Stress behavior of the suspen dome members

Figure 4 illustrates the typical nodes and elements of the structure. Due to the symmetrical nature of the structure any node or element can be represented by one of the typical nodes or elements.

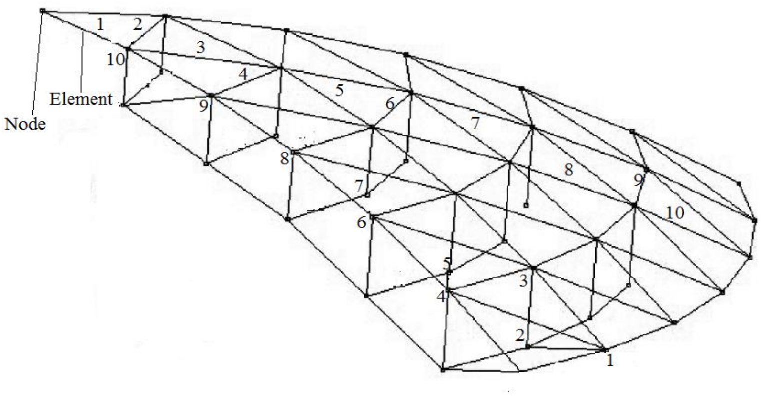

Fig. 4 - Typical numbering of nodes and element

Buckling always occur at members near the support point of the suspen dome. It is necessary to strength the members near the support to avoid buckling which can lead to the instability of the whole structure. At maximum load bearing capacity of steel cables, as shown in Figure 5, stresses are generated at a quarter part of the outermost ring whereas the maximum stresses for carbon fiber reinforced cable just occurred at a point.

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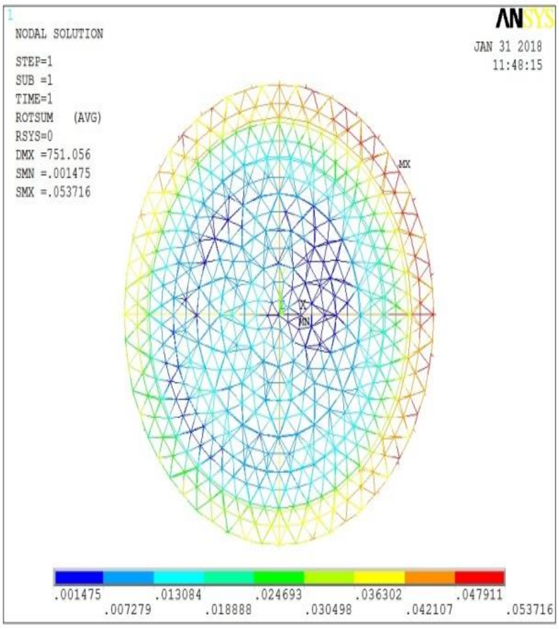
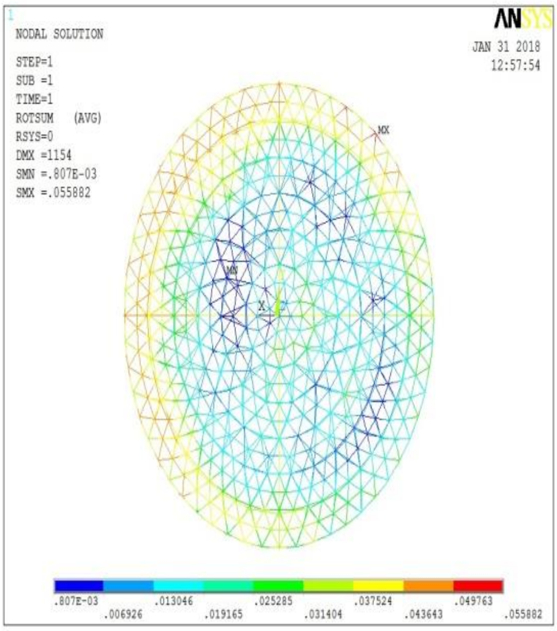


Steel



Carbon fibre reinforced polymer

Fig.5 - Comparison of maximum load bearing capacity contour

In Figure 6, it is observed that the force experienced in carbon fiber reinforced polymer cables in relation to element is similar to that of steel cables; they both had a linear form showing that carbon fiber reinforced cables had the tendency to withstand force transfer better than steel based on applied load.

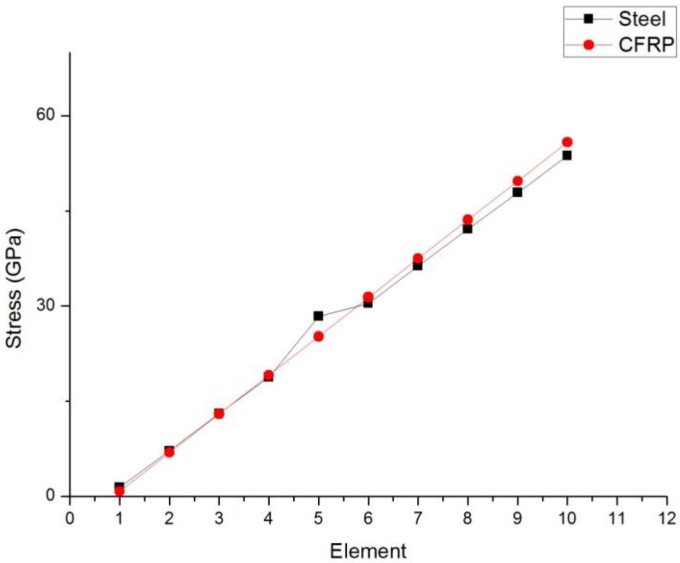


Fig.6 - Comparison of stresses at maximum load bearing capacity in element

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Comparison of deflection in nodes

The maximum deflection occurs at the midpoint of the system within the perimeter axis of node 10. The deflection values for carbon fiber reinforced polymer are higher than those of steel cables with a percentage difference of 10% as illustrated in Figure7. This is as a result of relatively small ultimate strain and low elastic modulus of carbon fiber reinforced polymer applied. A high stiffness could have been incorporated to reduce the effect of deformation sensitivity. However, this did not have much impact on the overall behavior pattern of carbon fiber reinforced polymer tensegrity system in the suspen dome as shown in Figure 3 and Figure 6. Relatively, a high pre-stressed carbon fiber reinforced polymer cable does not increase the elastic stiffness, bringing about the issue of exploiting the relatively high tensile strength of carbon fibre reinforced polymer cable and effectively avoiding the unfavorbale conditions of its relatively low elastic modulus.

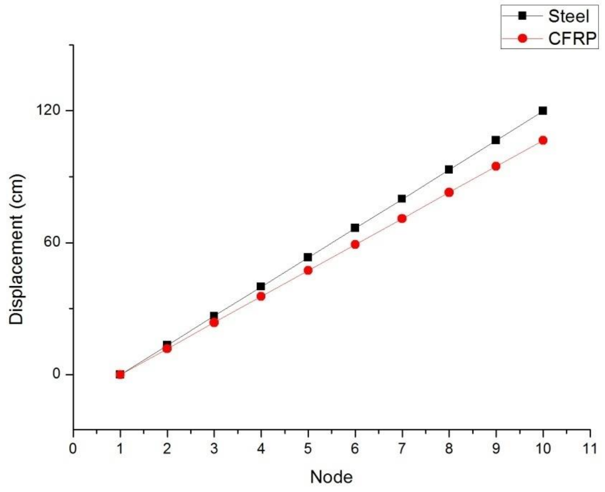

Fig. 7 - Comparison of displacement in at maximum load bearing capacity in nodes

Influence of internal forces on hoop cables

Internal forces of the cable segment are considered. The pretension of the initial hoop cable would have great influence on the next cable. The internal forces at different locations in the cable differ due to the friction between the cable and joints. The outermost hoop cable (hoop1) is considered because it has the most significant influence on the mechanical properties of the suspen dome. Based on the findings of Zhu et al. [17], the hoop cable rupture would result in the failure of the whole tensegrity strut assemble; meaning that the hoop cable has more influence on the displacement and internal force of the structure than the ridge cable.

Figure 8 illustrates the position of the hoop cables within the suspen dome. Results based on the internal generated force in the hoop cables are illustrated in Table 4.

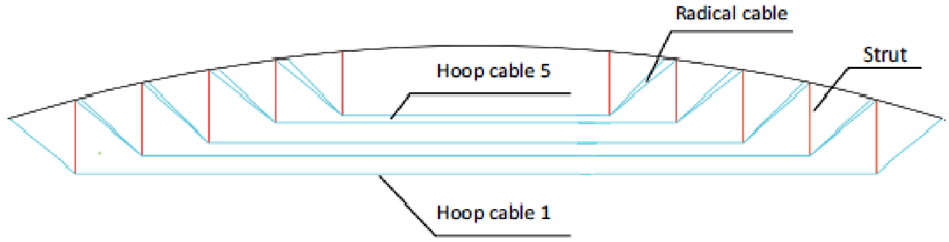

Fig. 8- Position of hoop cables

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From the results obtained as illustrated in Table 4, carbon fiber reinforced polymer cable has proven its capability when compared with steel. The outer most hoop for the steel has more effect on the suspen dome structure and the inner hoops have relatively low effect on the structure which is similar to that of carbon fiber reinforced polymer tensegrity system. In addition to this, carbon fiber reinforced polymer hoop cables had similar internal generated force and stresses as compared to steel when the ultimate bearing capacity was reached.

Tab 4 - Internal Forces of Hoop Cables at maximum load bearing capacity (kN)

	Steel	**CFRP**
Hoop 1	21280	21460
Hoop2	11704	11916
Hoop3	11218	11370
Hoop4	7134	8126
Hoop5	2148	2180

Influence of internal forces on the radical cable

The internal forces of the radical tension member obtained had small values for all the hoops except for hoop1. Only the internal force of hoop1 in relation to radical tension member was considered because the change of internal forces of the radical tension member is similar to the change of the internal force of the hoop cable which affects the internal forces of the radical member directly since internal forces of the radical member are generated due to pretension in the hoop cable [18-19]. Table 5 shows that the generated internal force of the radical cable carbon fiber reinforced polymer is in agreement with that of steel with only a very minimal difference.

Tab.5 - Internal force of radical cable at maximum load bearing capacity (kN)

Steel	5129.3
CFRP	5131.7

CONCLUSION

This study examines the most likely cause of structural failure of a suspen dome with carbon fiber reinforced polymer as the tensegrity system by observing the node point which is the weakest component in the structure that is expected to yield when loads are imposed on it. However, from the analysis, carbon fiber reinforced polymer cable improved the ultimate bearing capacity of the system at the support end due to its high tensile strength which has similar values with steel despite a little difference in their load bearing capacity.

Given the results obtained from carbon fiber reinforced polymer tensegrity system, one can conclude that it gives rigidity and stiffness to the single reticulated layer. Hence a super stability of the system is guaranteed when the tensegrity system is designed with carbon fiber reinforced polymer cables.

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