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Numerical Modal Analysis of a Suspen Dome with Carbon Fibber Reinforced Polymer Tensegrity System

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Abstract

This paper reports the result of a simple suspen-dome model created to study the behavior of a Carbon Fibre Reinforced Polymer (CFRP) tensegrity system as a replacement for steel tensegrity system in a suspen dome through modal numerical analysis. Based on the structural vibration theory and the theory of finite element model (FEM), the finite element model of the structure was established with ADPL- ANSYS. The vibration mode and frequency calculated for the steel tensegrity system were compared with those of carbon fibre reinforced polymer to validate the carbon fibre reinforced polymer tensegrity system.

Keywords: Suspen-dome, Finite element method, Carbon Fibre Reinforced Polymer tensegrity system, Steel tensegrity system, Modal analysis.

1. Introduction

A suspen dome is a unique structure made up of two systems, a reticulated single layer and a tensegrity system developed by Prof. Kawaguchi and his team in 1993 as shown in Figure 1. Materials used in its design are subjected to certain loads which have an impact on the structural behavior. As engineers' lay emphasis on structures' behavior, it is paramount to predict the dynamic behavior of the structures at the design stage. The preliminary design stage will determine whether the project is worth pursuing.

When a material such as steel bar is hit a hammer, a sound can be heard due to the fact that steel vibrates at its resonant frequency. If the bar oscillates at the resonant frequency, it is noted that the vibration amplitude of the bar becomes very large. Hence, when a structure is designed, it is important to know the resonant frequency. The analysis to obtain such resonant frequency and the vibration mode of elastic body is known as mode analysis. [1]. It is necessary to analyze the vibration of structures in order to predict the natural frequencies and the response to the expected excitation. The natural frequencies of the structure must be found because if the structure is excited at one of these frequencies, resonances occur with vibration amplitudes, dynamics stresses and noise levels. Resonance prevents structures from fulfilling their desired functions. Accordingly resonance should be avoided because vibration creates dynamic stresses and strain which cause fatigue and failure of the structures.[3]

Modal analysis is the most fundamental of all types of dynamic analysis; it allows a given design to avoid resonant vibration and gives the engineer an idea of how the design will respond to different dynamic loadings. The development of finite element methods, alongside the progress in computer technology, has allowed structural designer to use software packages in simulating structural behavior.

This paper presents a comparative modal analysis on the behavior pattern of a carbon fibre reinforced polymer tensegrity system with that of the traditional steel tensegrity system based on the natural frequencies and the modal shapes of the suspen dome. The model simulation was carried out on ANSYS 10 software package.

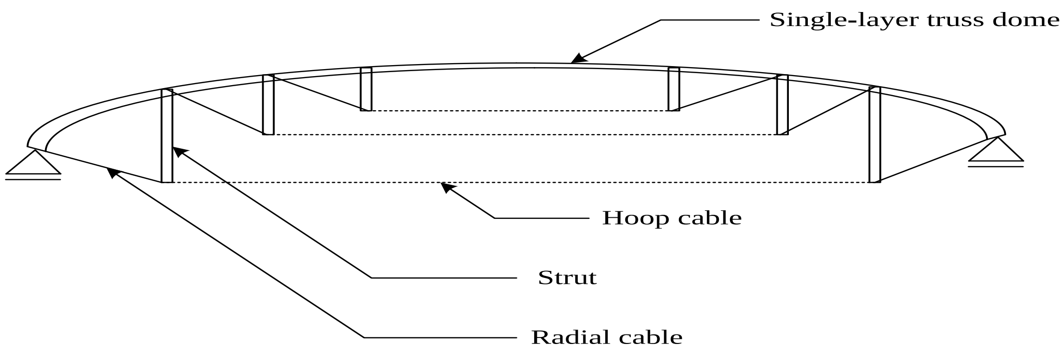


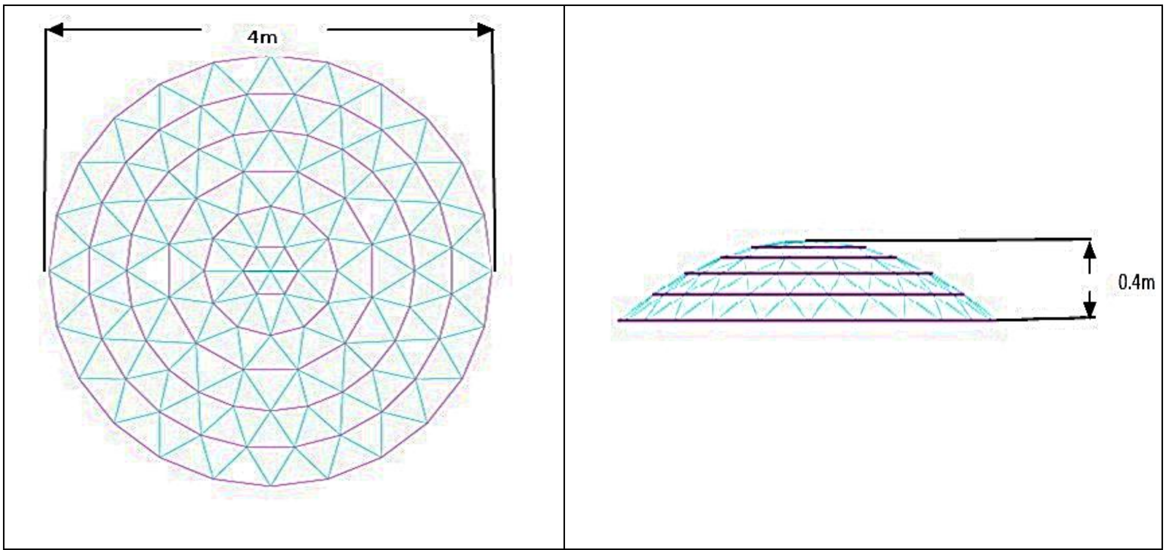
Fig. 1: Suspen-dome (Structural system)

2. Material and methods

The section describes the model and parameters employed in the analysis, it also includes a review on modal analysis. In addition, it examines how the finite element of the model was established and the steps involved for analysis of the model are explained.

2.1 Project Overview

A simple suspen dome was designed, with a span of 4 metres and a rise of 0.4metres as shown in Figure 2 (making a rise-span ratio 0.1) which satisfy the span to rise ratio recommend by Kitiporncha [6].. The sections of the element are made up of cables and pipes. The single layer reticulated dome was 20mm by 1.2mm in diameter and thickness respectively; whereas the cables that make up the tensegrity system, which constitute the hoop, radial and strut, are 8mm in diameter. Studies from Wenjiang *et al.* [7] explained though the structure is popular but there are no standard procedures to design suspen-dome structure. In most cases, a complex system can be represented by a simple model with the use of appropriate assumptions to determine the behavior pattern of such structure. Suspen dome are highly efficient prestressing structures, the prestressing forces in the cable has a major effect on the structural performance. Prestressing systems,by applying inverse force to the structure increase the load-bearing capacity so from the economical point of view its cost effective. [8]. Owing to the fact that the structure is prestressed, the modal analysis was carried out on prestressed structures. The material properties used for the analysis of the two proposed suspen domes are illustrated in Table 1.



(a)Roof plan: Main span 4metres | (b) Roof section: Rise 0.4metres

Fig. 2: Sketch illustrating the geometry of the suspen dome(Test Model)

Table 1: The Material Properties for the Model

Modal Type	Material	Structural Member	Elastic Modulus(MPa)	Possion ratio	Density(kN/m^3)
Type I	Steel	Strut Hoop cable Radical cable	2.05×10^4	0.3	78.5
Type II	CFRP	Reticulated single layer	1.6×10^4	0.3	16.0
		Strut Hoop cable Radical cable	2.05×10^4		78.5
		Reticulated single layer			

2.2 An overview of modal analysis theory

The natural frequencies and mode shapes are important parameters in the design of a structure. According to Subramanian space structures can be large in plan, relatively flexible and may have relatively low natural frequencies. However, natural periods may be close to external dynamic excitations, making the structure more sensitive to dynamic effects. The dynamic response of a structure depends on the nature of the external dynamic action, boundary conditions, the stiffness, mass and damping characteristics of the structure [2]. If a structure possesses damping, the damping can be modeled similar to that in the system shown in fig.3.

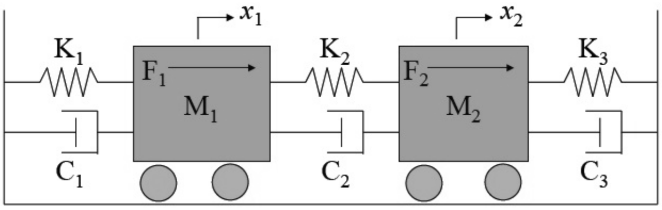


Fig. 3: Two degree of freedom damped model with force excitation

The modal analysis can be expressed in matrix form as:

$$[M]\{\ddot{u}\}+[C]\{\dot{u}\}+[K]\{u\}=\{F\} \quad (1)$$

Where [M] = mass matrix, [C] = damping matrix, [K] = stiffness matrix, $\{u\}$ = displacement vector of each node, $\{\dot{u}\}$ = velocity vector of each node, $\{\ddot{u}\}$ = acceleration vector of each node

Ignoring resistance, a dynamic equilibrium equation can be obtained as:

$$[M]\{\ddot{u}\}+[K]\{u\} = 0 \quad (2)$$

Taking $[u(t)] = \{\varphi\} \sin wt$, solving the differential equation

$$([K] - \omega^2[M])\{\varphi\} = 0 \quad (3)$$

Where ω = natural frequency of the system, $\{\varphi\}$ = vibration modals of the structure for equation (3)

2.3 FEM Model Establishment

Modeling is one of the crucial steps in structural analysis. The model could reflect the structural stiffness and mass system accurately but effect can occur in the calculation accuracy due to basic assumptions. The boundary conditions, mass and structural stiffness are considered in modal analysis because they can directly incline to the structures characteristics. The selection of element type is listed in Table 2

Table 2: Element type selection

Structure	Element type
Tensegrity System (strut,hoop and radical cable)	Link 10
Single layer reticulated dome	Beam 188

The finite element method approximates the real structures with a finite number of degrees of freedom. The model, after meshing, is subjected to various loads specified, based on FEM theory. The suspen dome was established with ANSYS APDL shown in figure 4.

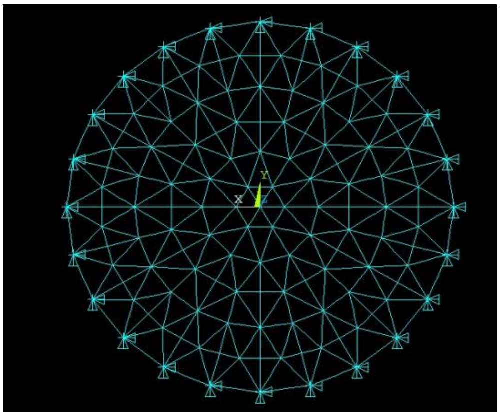


Fig. 4: FEM model of the suspen dome

An initial force in cables has little effect on the dynamic characteristics of the structure [5]; though loads are specified, they are can be ignored in modal analysis. Non-linear material properties are ignored.

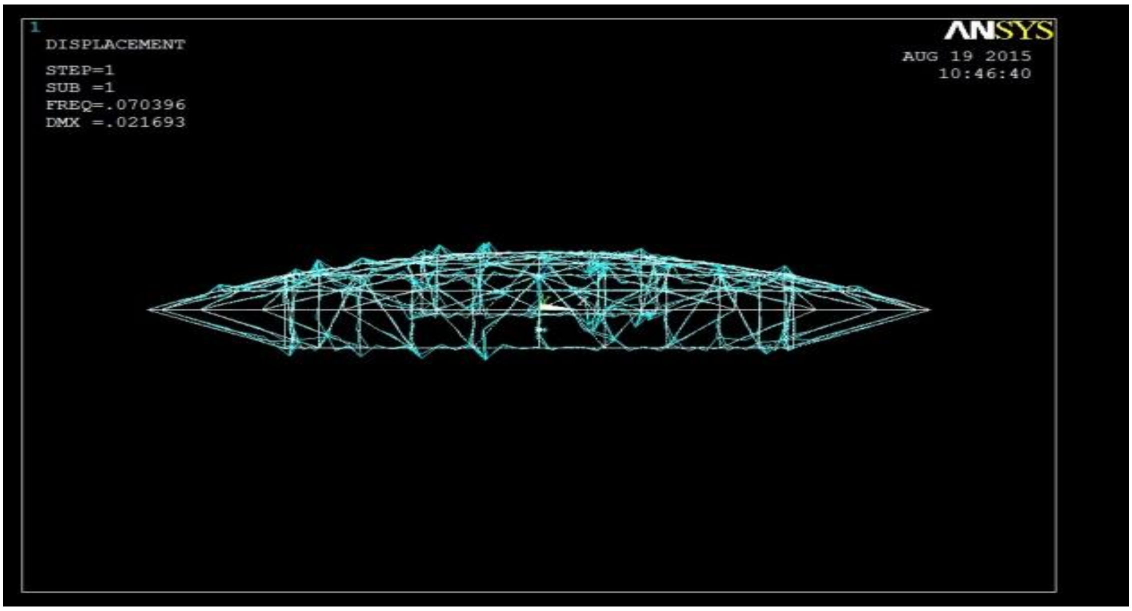
2.3.1 Modal Analysis and FEM Calculation

Methods of modal analysis include Subspace method, Block Lancoz method etc. In this numerical analysis, subspace method is adopted for its large symmetric eigenvalue problem, the convergence error takes default value and the iteration is 7. Calculating all natural frequencies of the structure is not usually necessary because the frequencies will not be excited and may give small resonance amplitudes due to high damping for that particular mode [3]. Natural frequencies and mode shapes constitute the starting point for harmonic or transient analysis when using superposition method. The number of natural frequencies and modes that the suspen dome possesses equals the number of degrees of freedom of the suspen dome: this is to ensure that the frequency of any applied period loading will not coincide with the modal frequency which attracts resonances and leads to large oscillation.

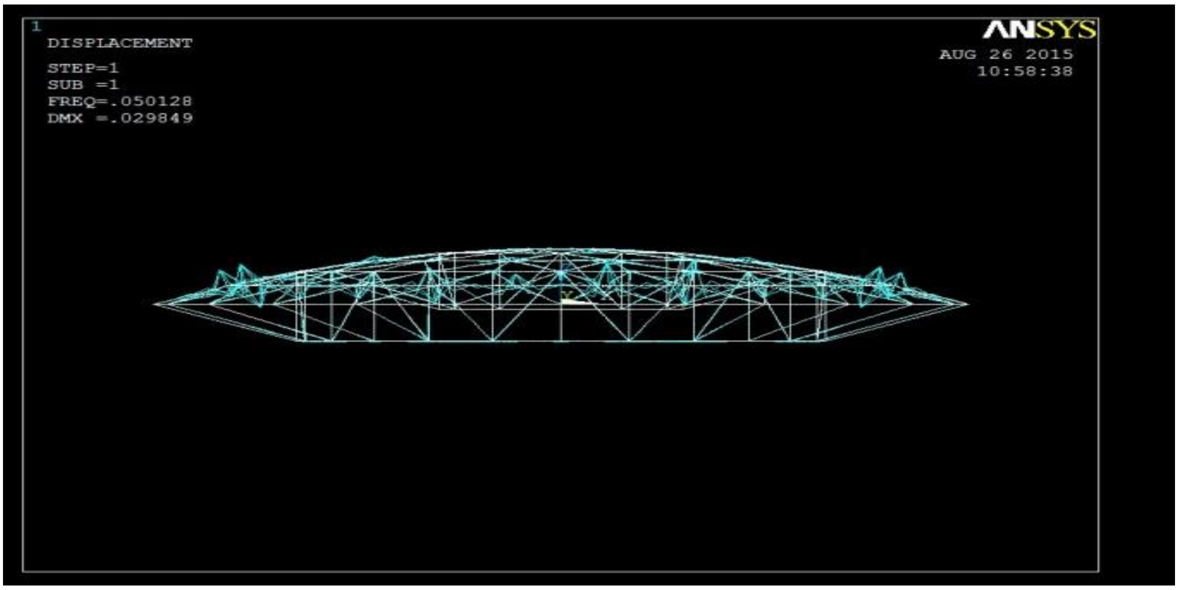
3. Results and Discussion

Frequencies obtained from the analysis were relatively low. The modal shapes are shown in fig 5.The natural frequencies of steel tensegrity in comparison with carbon fibre reinforced polymer tensegrity values including percentage difference are shown in table 3 and the comparison by graph is illustrated in fig 6

Figure 5 illustrates the analyses generated at displacement amplitude at given points in the suspen dome as a function of the forcing frequency, similar images were obtained for the next steps of vibration mode. The displacement remained constant but the frequency varied with little difference, including percentage differences, as illustrated in Table 3. However, the structures move with similar frequency, they all attained their maximum displacement at same interval of time though they do not move in the same direction. The analyses also show that the natural frequencies of carbon fibber reinforced polymer are lower compared to steel ones, which implies that stiffness characteristic of carbon fibber reinforced polymer is better than that of steel, the stiffness of the material is measured by the modulus of elasticity. From fig 4, it can be observed that a deformation mode occurred at the bottom (hoop cable) of the tensegrity system for Type I fig 5(a) whereas there was no deformation for Type II, fig 5(b).



(a)



(b)

Fig 5: First step-vibration mode for (a) Type I and Type (b) II

Table 3: Natural Frequency Values

Steps	Type I Frequency(Hz)	Type II Frequency(Hz)	Percentage Difference(%)
1	0.070396	0.050128	28.7914
2	0.070939	0.050313	29.0757
3	0.071478	0.051040	28.5934
4	0.073445	0.051231	30.2458
5	0.074544	0.051238	31.2648
6	0.076068	0.051305	32.5538
7	0.076559	0.056916	25.6573

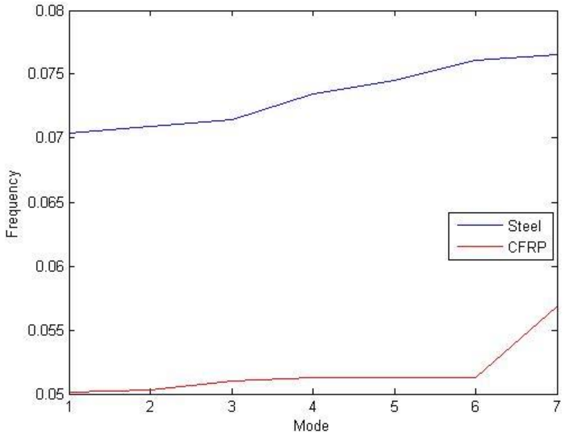


Fig 6: Comparison of Natural Frequency

From Fig 6, the step for both model are complex coupled vibration mode, the mode shapes shows that the higher the step number, the more complex the mode shape. From Table, 4 the cycle time for steel tensegrity at first step is 14.2054s compared to that of carbon fibber reinforced polymer tensegrity system which is 19.9289s, its graphical illustration is presented in Fig 7.This shows that the cycle time for carbon fibber reinforced polymer tensegrity system is longer than that of steel tensegrity system. The long cycle indicates that carbon fibber reinforced polymer tensegrity system is more flexible than steel tensegrity system. The structure's flexibility can be an advantage for unbalanced loading scenarios; structures will deflect to relieve applied loads. .

Table 4: Cycle time value

Steps	Type I Cycle time/s	Type II Cycle time/s
1	14.2054	19.9489
2	14.0966	19.8756
3	13.9903	19.5925
4	13.6156	19.5194
5	13.4149	19.5168
6	13.1461	19.4913
7	13.0618	17.5698

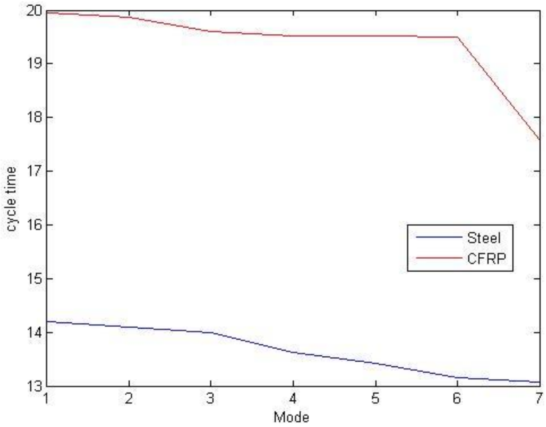


Fig 7. Comparison of cycle time

3.1 Previous Research Work

The application of CFRP as a tensegrity system for a suspen dome is a new line of research; although Hara [9] studied the behavior of a spherical FRP dome. However, studies related to suspen dome with steel as the material have been undertaken before. Some of such studies and their results are compared with the results of the current study where steel and CFRP are applied side by side as illustrated in Table 5.

Table 5: Comparison with previous study

Authors	The Study of Each	Materials Applied
Wenjiang et al(2003)	Investigated the static and dynamic behavior of the outmost ring stiffened suspen dome structure and that of the general suspen dome structure. The results showed that stiffened suspen dome is as efficient as the general suspen dome, however, for the stiffened suspen dome, less material is needed for construction at lower cost.	Steel
Subramanian(2006)	Stated that Kawaguchi conducted a vibration test on a full size dome the results showed no significant difference between the natural frequency characteristics of the suspen dome and the single layer truss dome	Steel
Behnam et al(2012)	The study compared the single layer dome with a suspen dome under different	Steel

	load combinations. The authors concluded that the suspen dome had bette performance characteristics compared to single layer domes	
Current study(Olofin and Liu)	A suspen dome with carbon fibre reinforced polymer (CFRP) as the tensegrity system, considered in the preliminary study was compared with a suspen dome of same design but with steel tensegrity system. The results showed that CFRP tensegity system performed better than that of steel. This result should make designers of suspen dome prefer CFRP tensegity system to that of steel.	Carbon Fibre Reinforced Polymer(CFRP) and steel

4. Conclusion

In the present work, modal analysis with ADPL-ANSYS was established for a small suspen dome model. The results in this paper can be used as a basic data for a suspen dome with carbon fibber reinforced polymer tensegrity system's dynamic response analysis. Carbon fibber reinforced polymer tensegrity system performance and behavior can be compared to steel tensegrity system and can be used as a replacement for steel.

The suspen dome FEM model established can be a reference to similar structure modeling, and the analyzed results can provide useful reference for the safety design of other suspen domes. With the preliminary results, further investigation can be carried out on the model such as mode superposition, harmonic or transient analysis. The results can serve as a guide towards investigating the experimental methods for the model.

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