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Harmonic Response of CFRP Tensegrity System in a Suspen-dome

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Abstract

Wind-induced excitation causes structure to vibrate which leads to instability. This paper focuses on the performance of CFRP tensegrity system in a suspen-dome subjected to wind load by assuming such load as harmonic. A comparison is made with the traditional steel tensegrity system, in order to justify the integrity of CFRP cable application in a suspen-dome system. A finite element software, namely ANSYS, was implemented for the simulation by analyzing a physical model of 4 m span and 0.4 m height. Results show that CFRP tensegrity system has similar performance as steel tensegrity system and can be used as a substitute for steel.

Keywords: suspen dome, tensegrity system, CFRP cable, steel cable, harmonic load

1 Introduction

Researchers have been critical about the dynamic behavior of structural systems in order to achieve stability and safety [1-4]. Wind loading is usually dominant in structural loading on roofs of large buildings. It is paramount to fully understand the behavior pattern of the structure in respect to dynamic effect such as wind load. This kind of load increases the amplitude of the structures' vibration along the wind direction.

Wind is a random and dynamic phenomenon that occurs in space and time in structural systems. The importance of dynamic resonant response to wind for large span roofs is dependent on the natural frequency of vibration which is in turn dependent on the mass, stiffness properties and the damping [5]. However, the use of stiffening cables often increases the stiffness of a system sufficiently to reduce resonant contribution to a minimal proportion [6]. A structural system such as a suspen-dome [7] must have sufficient strength and adequate stiffness to resist wind-induced forces. The response of the geometrical structure under wind loading is crucial. Therefore, the need to understand such performance is required. The structural performance of wind load can be realistic by assuming such loads as harmonic [8]. Sustained cyclic load produces harmonic response in a structure. When natural frequency of a structure coincides

with the forcing excitation frequency, resonance occur causing maximum displacement. The harmonic regime is a representative of many excitation cases encountered in engineering practice, such as vibration induced by imbalance, and torsional vibration in engines [9].

From history, damage to structures by severe winds has been a fact of life and solution to resist wind forces is required. With the upcoming development in the utilization of CFRP cable in space spatial structures [10-14], it is salient to understand the behavior pattern of such structure induced by wind.

In this paper, harmonic response technique was adopted on ANSYS software for a suspen-dome prototype constructed with CFRP as the tensegrity system and comparison was made with steel tensegrity system based on natural frequency and maximum displacement, in order to justify the implementation of CFRP cables in a suspen-dome.

2 Literature review

In this section, a brief explanation of wind loads on large roofs, harmonic response and theory of harmonics are presented in some detail.

2.1 Wind flow over large span roofs

Wind is the terminology used to describe air in motion and it is usually applied to the natural horizontal motion of the atmosphere. A constant flow of wind can suddenly gust to a rush of air. This sudden variation in wind speed plays an important part in determining a structure's oscillation. The flow of wind is not steady and fluctuates in a random fashion. Because of this, wind loads imposed on buildings are studied statistically [5]. Wind load effect on a large roof has some significant difference in comparison with its effect on smaller roof; the resonant effects, although not dominant can be significant. Upward and downward external pressures are also significant. Domed structures are sensitive to wind load distribution hence the possibility of critical unbalanced pressure distribution must be considered [6]. When considering dynamic response of a structure to wind, distinguishing between the resonant response or near the natural frequency of the structure is necessary. The fluctuating responses at frequencies below the first or lowest frequency are usually great contributors [6]. However, because of the huge fluctuating components in wind loading on large roofs, the statistical correlation between pressure separated by a sizable distance is nanoscopic.

2.2 Harmonic Assessment

The response of the single degree of freedom systems to harmonic excitation is a consequential subject matter in structural dynamics. Apart from the fact that excitations are encountered in engineering system, for example force caused by unstable revolving machinery, the reaction of structures is understood based on harmonic excitation. This provides an insight to what degree the system will respond to any other type of force [13]. Forced harmonic vibration theory has a functional implementation in earthquake engineering because of its structural dynamics.

2.2.1 Theorem

Within a structural system any sustained cyclic load will produce harmonic response[15-16] as illustrated in Figure 1.

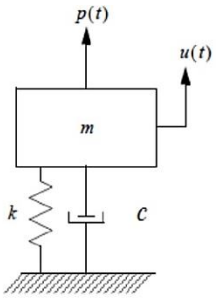


Figure 1: A system subjected to harmonic excitation [16]

A harmonic force is represented as [15]:

$$P(t) = P_0 \sin \omega (t) \tag{1}$$

where P_o is the amplitude, ω is the exciting frequency and t is the period of excitation.

The governing differential equation for forced harmonics vibration for damped system is given as [17]:

$$M\ddot{U} + C\dot{U} + KU = P_0 \sin \omega (t) \tag{2}$$

Solving the Equation (2) for initial condition, $U = U(0) and\ \dot{U} = \dot{U}(0)$ and the complimentary solution is the free vibration response given as:

$$U_c = e^{-\xi \omega_n t}(A \cos \omega_D t + B \sin \omega_D t) \tag{3}$$

$$A = U_0, B = \frac{\dot{U}_0}{\omega_n} - \left(\frac{\left(\frac{P_0}{k}\right)\left(\frac{\omega}{\omega_n}\right)}{\left(1-\left(\frac{\omega}{\omega_n}\right)^2\right)} \right) \tag{4}$$

where

$$\omega_D = \omega_n \sqrt{1 - 2\xi}, \tag{5}$$

The solution for Equation (3) is given as:

$$U_P(t) = C \sin \omega t + D \cos \omega t \tag{6}$$

where

$$C = \left(\frac{P_0}{k}\right)\left[\frac{(1-\xi^2)}{(1-\xi^2)+2\xi(r)^2}\right] \tag{7}$$

$$D = \frac{-P_0}{k}\left[\frac{2\xi r}{(1-\xi^2)^2+(2\xi r)^2}\right] \tag{8}$$

The total response is given as:

$$U_t = e^{-\xi\omega_n t}(A\cos\omega_D t + B\sin\omega_D t) + C\sin\omega t + D\cos\omega t \tag{9}$$

3 Model Verification

A small-scaled suspen-dome was designed according to Chinese specification [18-20] with a span of 4 meters and a rise of 0.4 meters, as shown in Figure 2. The tensegrity system is made of the struts, radial and hoop cables. The tension members were constructed with CFRP.

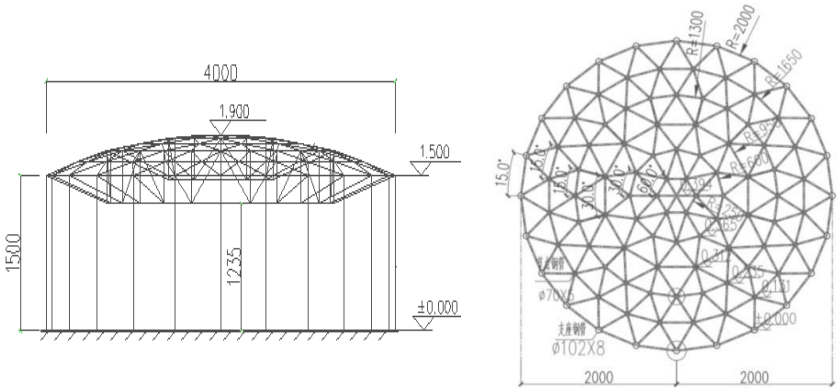


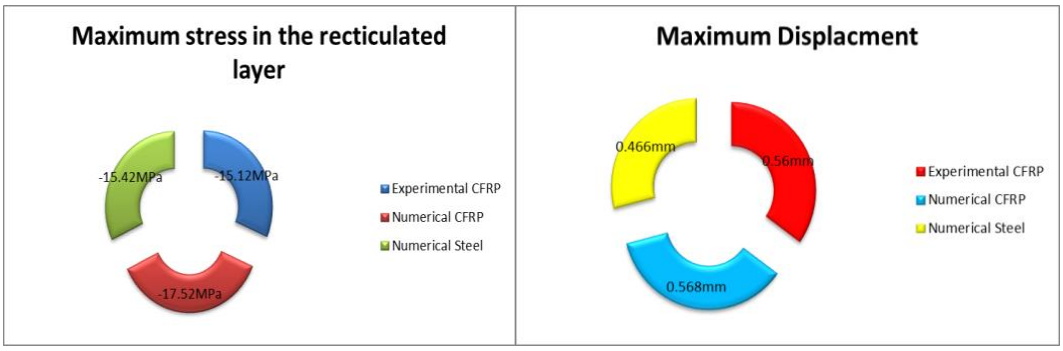
Figure 2: Model and reticulated single layer plan



Figure 3: Construction and deflection dial indicator layout

With the successful construction of the prototype as illustrated in Figure 3, experimental static performance was compared with numerical analysis via ANSYS software to validate the application of CFRP cables as a tensegrity system in a suspen-dome. Contrast between experimental and numerical findings for CFRP and steel cables was established. Figure 4(a) illustrates the maximum stresses generated on the single reticulated layer at high imposed load.

Similarly, Figure 4(b) shows the maximum displacement at specified nodes obtained for analysis.



(a) (b)

Figure 4: Contrast of maximum values for stress and displacement

In addition, forces generated internally within the cables had similar values. It can be concluded that the digital analysis using ANSYS achieved a similar trend with the experimental findings with an excellent accuracy [21]. With positive findings obtained for the static investigation, it is paramount to further investigate the integrity of the structure, especially in dynamics which is a common practice. Although dynamic analysis is computationally extensive, complex and expensive compared with static analysis, numerical simulations are essential to observe the structure's performance before experimentation on the structure, in order to establish guidelines.

4 Numerical Technique

This section explains in detail the Finite Element Analysis (FEA), material properties utilized, and loading conditions.

4.1 Finite Element Method

With the vast development of software, the calculation of the behavior of suspen-dome application can be realistic and economical. The ability of CFRP structure to withstand critical loading can be evaluated by computational method. The two materials (steel and CFRP cables) are subjected to finite element analysis. Basic assumptions for the structure include cables are elastic and the tensegrity members are pin-jointed. The complexity of the suspen-dome structure allows results for three-dimensional FEM (Finite Element Method) analysis to be more comprehensive and reliable than results of empirical formula. The analysis was conducted with ANSYS 10 finite element software package [22]. The algorithm for the analysis is illustrated in Figure 5.

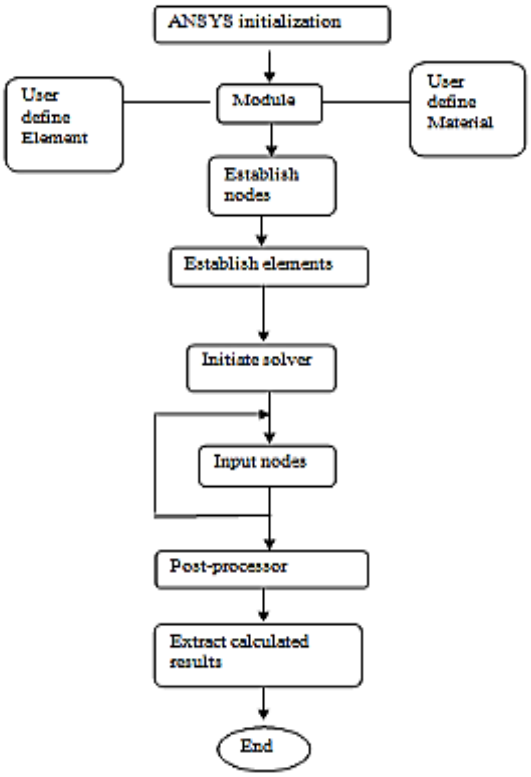


Figure 5: Simulation Algorithm

4.2 Model and Mesh

The finite element digital model is illustrated in Figure 6. Fixed boundary condition was assigned at the edge of the model. Beam 188 was incorporated for the single reticulated layer while link 10 was incorporated for the cable system. A mesh of 1mm x 1mm was utilized. CFRP cable was modeled as an anisotropic linear-elastic material and an isotropic elastic-plastic material was assumed for the mechanical behavior of steel cables.

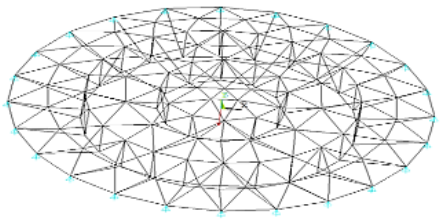


Figure 6: Finite element model

4.3 Material Properties

The mechanical properties of the materials used for the simulation are shown in Table 1.

Table 1: Material properties for the suspen-dome members

Member	**Elastic Modulus (MPa)**	**Density (kg/m^3)**
Steel Tensegrity System	$1.8x10^5$	78.5
CFRP Tensegrity system	$1.6x10^5$	16.0
Single reticulated layer	$2.05x10^5$	78.5

Material properties used in the analysis are subjected to certain loads which have an impact on the structural behavior of the suspen-dome system.

4.3.1 Dimensions

The dimension for the tension members is illustrated in Table 2.

Table 2: Illustrates the dimensions of the tension members

Cable	**ϕ Radial (mm)**	**ϕ Hoop (mm)**
Steel	8	10
CFRP [21]	5	7.9

The length for the hoop cable was 2.6 m and radial cable was 44 mm.

4.4 Loading

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 dynamic load. The wind load coefficient was computed based on the codal provisions from the relevant standard GB50009-2012 [18]. The wind load on the structure was assumed to be sinusoidal and applied at nodes. All loads are assumed to have similar frequency and the maximum amplitude is identified by the static load intensity. Damping of 5% is considered for the models through the dynamic analysis.

5 Results and Discussion

Mode superposition method was employed for the analysis of harmonic response. The system frequency response domain is often utilized for experimental identification for a dynamic system. Prior to the method, modal analysis was carried out as a pre-requisite by using reduced method for mode extraction. Secondly, the system was assumed to be excited through external loads, namely loads that had time variation. An assumption made was that forces applied for a

time period were enough for transients to vanish [13], so that the only response is a forced motion.

5.1 Modal Analysis

The structure's natural frequencies were obtained because when the structure excites at one of these frequencies, and the resonance occurs, this prevents the structure from fulfilling its desired function. Hence, resonance should be avoided because vibration generates dynamic stress and strain which causes fatigue and failure of a structure [23].
Modal analysis was computed and the natural frequencies and modal periods evaluated. Six mode values were extracted as illustrated in Figures 7 and 8.

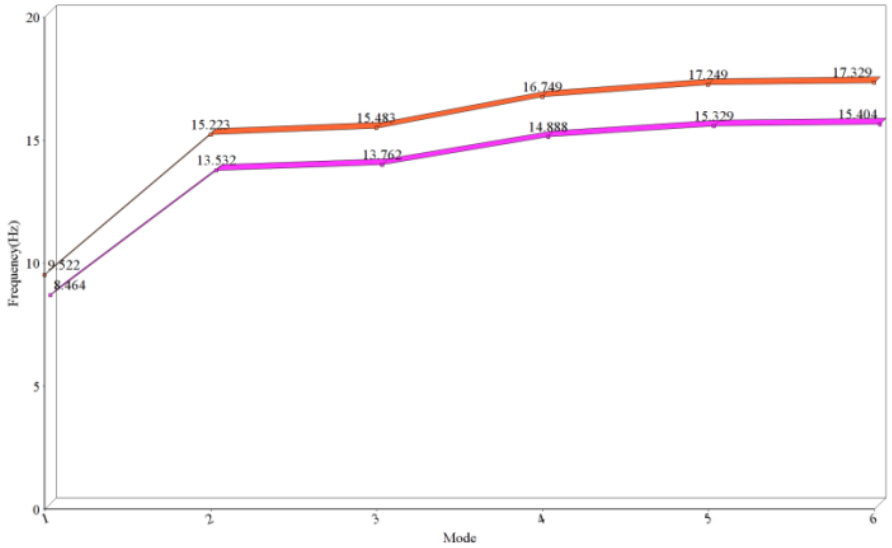


Figure 7: Natural frequency response (red = steel, purple = CFRP)

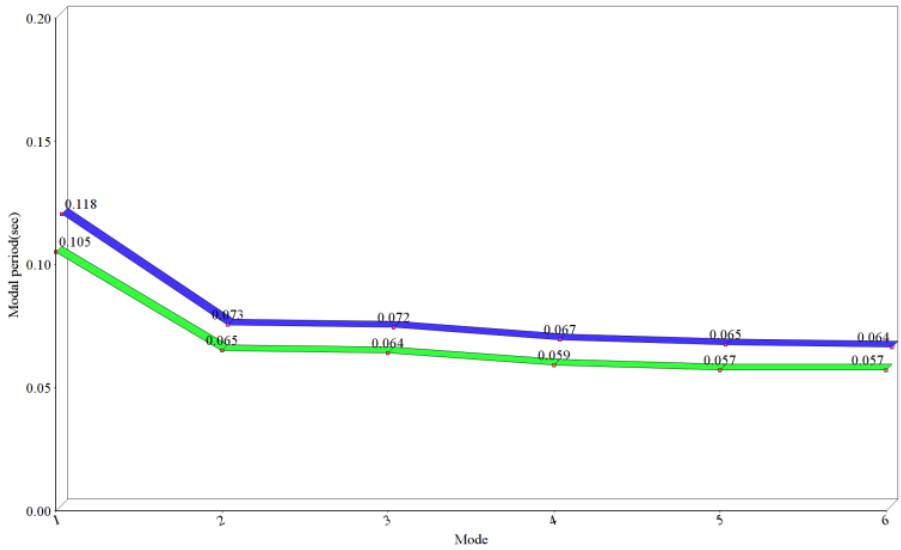


Figure 8: Modal period response (green = steel, blue = CFRP)

The displacement of the whole structure with steel tendons was 0.021 mm and that of CFRP was 0.029 mm at first modal period. The value for CFRP was 0.118 sec which is not a high value indicating that the whole structure is stiff enough. From the first six modes, it can be observed that the integrity of the roof with CFRP cables is very good and has similar behavior as that of steel cables. Similarly, Figures 9 and 10 illustrate the sixth mode for the structural system; both CFRP (Carbon Fiber Reinforced Polymer) and steel had similar structural shape.

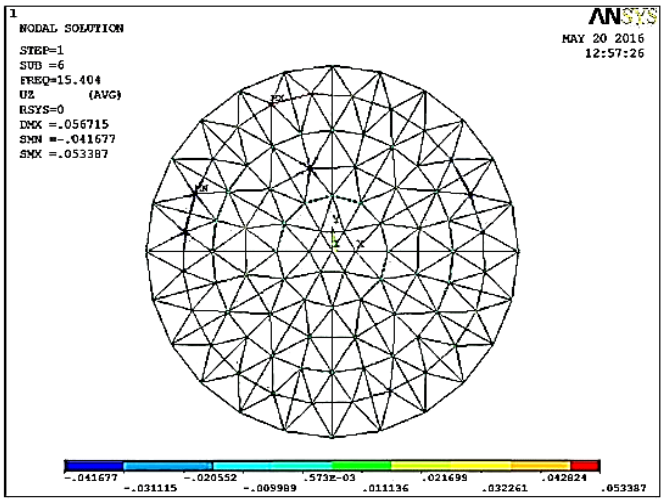


Figure 9: Sixth mode for CFRP

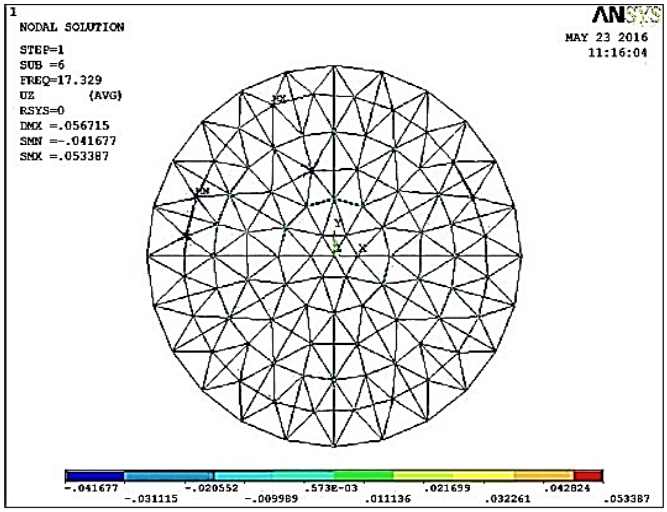


Figure 10: Sixth mode for steel

Frequencies obtained from the analysis were relatively low. The fundamental frequency of CFRP tensegrity system from the modal analysis was approximately 15.404 Hz, as shown in Figure 9, which is sufficiently similar to steel (Figure 10) with frequency of 17.329 Hz. The difference was 12% compared to steel, which still falls into the acceptable criteria within design. This satisfies the assertion of Cheng and Lau [24] which states that the modal frequencies and order don't affect the motion of the cable. Substituting steel cable with CFRP has a stiffening effect on the structure.

5.2 Harmonic Response

The harmonic response was performed using mode superposition method on ANSYS. The response was obtained from the modal analysis in previous section and by considering the center node of the structural system to draw out conclusive findings for design process. The wind load on the structure was assumed to be sinusoidal and applied at nodes. All loads are assumed to have similar frequency and the maximum amplitude is identified by the static load intensity. The first mode and lowest frequency value was used in performing the harmonic response analysis from the modal solution because it is associated with wind and wave forces [6]. Due to the symmetrical nature of the structure any node or element can be represented by one of the typical nodes or elements. However, the node at the mid-section of the structure was considered because the effect is concentrated at the central part of the single reticulated layer. Figures 11-16 illustrate the typical response curves for the center node of the structure for both CFRP cables and steel cables at *x*, *y*, and *z* axis.

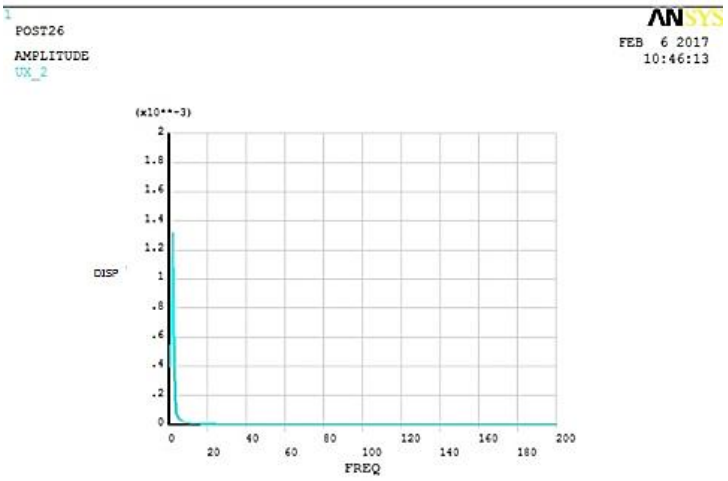


Figure 11: Typical response curve for the centre node (steel) *x*-axis

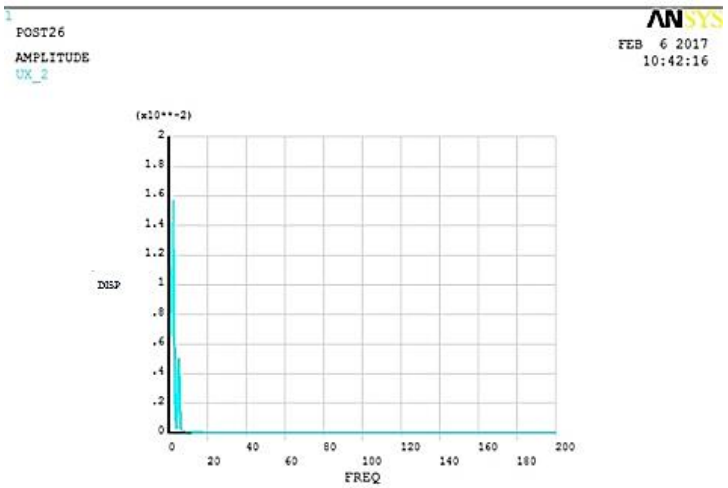


Figure 12: Typical response curve for the centre node (CFRP) *x*-axis

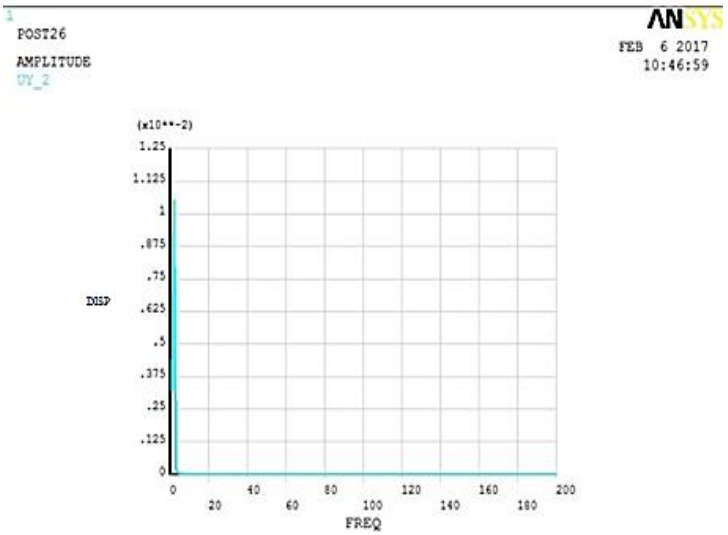


Figure 13: Typical response curve for the centre node (steel) *y*-axis

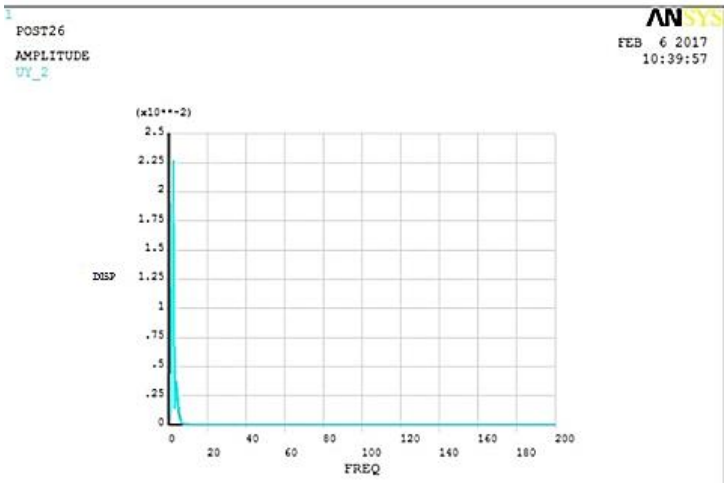


Figure 14: Typical response curve for the centre node (CFRP) *y*-axis

It can be observed that the peak frequency occurred at 0.2 Hz. At the *x*-axis, the maximum displacement was 0.016 mm for CFRP and 0.0135 mm for steel, at the *y*-axis, the maximum displacement was 0.0115 mm for steel and 0.0225 mm for CFRP, and at the *z*-axis, the maximum displacement for CFRP was 0.0128 mm and that of steel was 0.0087 mm. When one cable is at resonance, the other is at a different frequency which acts to dampen the resonance vibration, hence the total vibration amplitude is kept small for both steel and CFRP, thanks to the nature of tensegrity systems. It was also observed that all amplitudes reduced as natural frequencies increased. Internal forces in the cables and bars are not significant under vertical frequency for both materials.

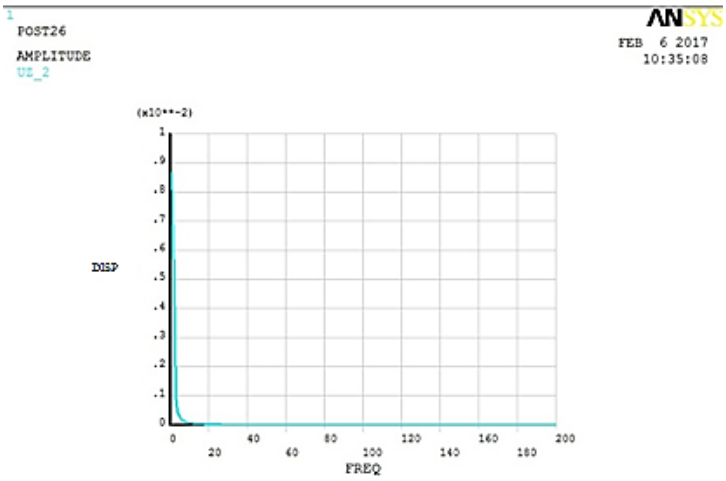


Figure 15: Typical response curve for the centre node (steel) *z*-axis

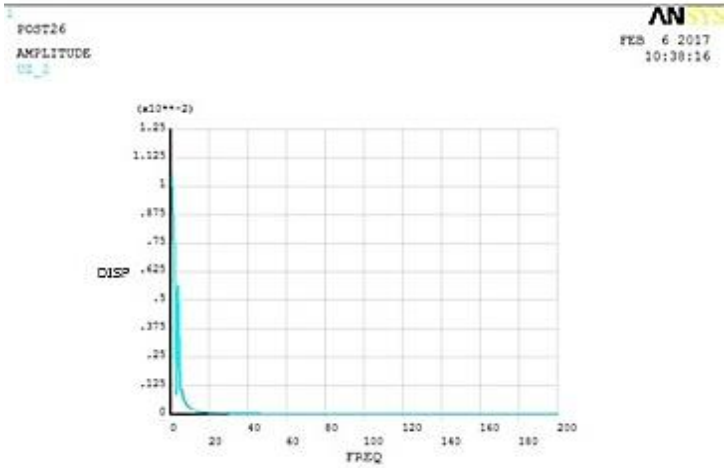


Figure 16: Typical response curve for the cenre node (CFRP) *z*-axis

6 Conclusion

Numerical analysis of the tensegrity system model was proposed to predict the dynamic mechanical response of the suspen-dome. From the simulated results, the following conclusions are drawn:

- CFRP is highly stable and has a good damping behavior.
- The vibration of CFRP cable is similar to that of steel, validating its exceptional mechanical properties of high stiffness-to-weight ratio and less curvature under gravity load. Such behavior resists vibration.

From a technical point of view, the harmonic response was assumed as wind induced response, the behavioral pattern of the suspen-dome with CFRP tensegrity system correlated well with that of steel system irrespective of the natural frequency difference. This is a realization that CFRP cables can resist wind forces and the novel material is suitable for designing of suspen-domes.

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