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Dynamic Characteristics and Vibration Response of CFRP Cable-Based Beam-String Structures: A Comparative Numerical Investigation

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Abstract

Beam-string structures (BSSs) use a combination of a flexural beam, a string, and connecting struts to form a long-span structure. The string may take the form of a cable, strut, or other structure. The dynamics of BSSs is impacted by many factors, including geometrical configuration, member properties, mass distribution, prestressing, and geometric imperfections. In this research, the natural frequencies and associated vibration modes of BSSs for different cable representations were numerically evaluated. Euler-Bernoulli beam elements were used to create a reduced-order finite element model of BSSs in Python. Equivalent vertical tangent springs, representing cable elements, were placed at quarter-span locations. The baseline length of the beam was 12 m and the beam and cable material was considered to be of the same type with Young's Modulus E = 200 GPa. The Cable was considered to be prestressed with a force of 200 kN. The cases considered were: (i) a steel cable of area 600 mm², (ii) a CFRP cable of area 600 mm², and (iii) a CFRP cable of area 800 mm², representing an axially rigid steel cable case. The first natural frequencies were computed to be 12.170 Hz, 12.005 Hz, and 12.304 Hz for cases (i), (ii) and (iii), respectively. In this study, the identity of the cable material was of less importance in determining the modal rankings. Considerable changes in the first natural frequency were observed for prestress changes in the range of 100 kN to 300 kN. Other effects, such as creep of the cable and the longitudinal constraint of the beam, were neglected. The results were obtained from computation models and simplified versions of what could be predicted by a comprehensive computational model or from physical experiments. Full-system ANSYS simulations, predictions of extreme event responses, and experimental measurements were not performed. Results show that it is possible to compare designs in a fair manner and indicate what types of models and measurements would be necessary to make informed decisions on the selection of prototype-specific vibration-control systems.

Keywords: beam–string structure; CFRP cable; steel cable; natural frequency; vibration mode; prestress; modal analysis; structural dynamics; reduced-order finite-element model.

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1. Introduction

Consideration must be given to various actions and limitations including strength, serviceability, durability, construction, self-weight, and vibration when designing long-span structural systems. Beam-String Structural Systems (BSS) satisfy the aforementioned requirements through the combination of a beam and a lower tension system which is defined by a string and struts. The dynamic behavior of a BSS is a function of the geometry and mass distribution of the system as well as the initial stress and the stiffness of the components of the system. Of particular interest is the passive constraint or prestress which affects the path and magnitude of the system response to external actions. It is important to take into account all of the above when determining the dynamic response of a BSS.

This paper accomplishes the third objective of the research proposal, which is to evaluate and compare the modes of vibration of BSSs using CFRP or steel cables, using finite element analysis. According to the proposal, the field activities and prototypes to be presented in this paper are selected and represented using finite element analysis. It must be emphasized that it is not the intent of this paper to address every field activity or prototype described in the proposal. Rather, this paper represents and interprets within the confines of the model and computer program implemented, a clear and limited element of comparison of finite element modes.

Steel cables are a mature reference. Fabrication and anchorage of stiff materials of significant mass are well established. Corrosion of steel requires maintenance. CFRP cables are light and corrosion resistant, but behaviors of cables dominated by anchorage and connections are fiber architecture and design dependent. Reports on FRP cables for cable stayed bridges suggest that the material is a promising candidate, yet challenges due to the behavior of interacting and combined systems remain (Yang et al., 2020).

For dynamic systems, there exists a further partition of mass and stiffness. The natural frequencies of a system can be determined by solving the generalized eigenvalue problem $K\varphi = \omega^2 M\varphi$, where φ is the mode shape, ω is the circular natural frequency, and K and M are the stiffness and mass matrices respectively. It is worth noting that in any system, increasing the stiffness generally increases the frequencies of natural vibrations. However, increasing the mass of a system may decrease the frequencies if the stiffness is constrained. Steel, being a stiff and dense material, has a dominant role in determining the frequency of natural vibrations of a cable stayed bridge. Replacing steel with a lower density and higher stiffness material, like CFRP, generally decreases natural frequencies of the system. It is important to keep in mind that during a comparison of equal rigidity, changing the mass of a system can lead to very different conclusions.

As stated in the literature, one should not assume that vibration of an individual cable element of a structure and vibration of the overall supported structure are the same. It has also been reported in the literature that cable modes, which are often ignored, can be coupled with deck or beam modes. A one-element representation of a cable element may not capture coupled modes of a more complex cable structure (Abdel-Ghaffar & Khalifa, 1991). Natural frequencies of CFRP cables have been reported to be different from steel cables. Damping behaviors of CFRP cables are also different from that of steel cables, and can be different for the same cable, depending on the direction and amplitude of vibration (Yang et al., 2015). While a reduced-order BSS model can be effectively used to assess the effects of coupled cable systems on the overall structure, the model cannot capture all modes of the cable systems, local anchorage deformation, torsional modes, and out of plane behavior of the cable systems.

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This work accomplishes three things. First, a reproducible method to perform a modal analysis, including an explicit representation of system geometry, materials and mass, is proposed. Second, the work reports results of modal analyses for steel and CFRP systems, including estimated natural frequencies and modes. Finally, it provides the limitations of the model and how these influence the understanding of vibration control and service limit state of the systems. This work does not intend to simulate the response of a prototype structure, and it does not provide an earthquake response analysis. The authors provide an analysis of the limitations of modal analysis of structures and provide insights on assumptions made in modeling and construction of engineering systems.

The rest of this paper is organized in the following way. Section 2 provides a review of BSS dynamics, modal response, prestress, vibration of CFRP cables, damping, seismic response, and the distinction between component and system levels of evidence. Section 3 describes the computational method, defines model parameters, describes comparison cases, presents solutions for eigenvalues, and describes sensitivity and verification analyses. Section 4 describes the model. Section 5 presents the results of numerical analyses. Section 6 presents an interpretation of results and defines the limits of the model. Section 7 defines the limitations of the model, and Section 8 presents the conclusions and describes the next steps of a more comprehensive study.

2. Literature review

Five interrelated topics define the scope of the related literature on this study: (i) mechanics and free vibration of beam-string systems; (ii) importance of prestress and geometric stiffness; (iii) modal damping of CFRP cables; (iv) dynamic behavior and seismic response of cable structures; (v) verification of finite element models and assessment of vibration control. Variability of models studied explain why complete overlap of literature within interrelated categories does not exist. A modal test of a cable identifies the modal properties of the cable under a given set of physical constraints, and does not prove or disprove the modal behavior of an assembled beam-string system (BSS). Likewise, a shaking table test of a steel beam-string system (Steel BSS) does not prove or disprove a CFRP beam-string system (CFRP BSS) model.

2.1 Beam–string structural behaviour

From a coupled structural behavior perspective, camber in an assembled BSS may be attributed to prestress in the string. Equilibrium can be classified as symmetric, antisymmetric, vertical, lateral or torsional. Importance of the string in a hybrid string structure is discussed in Saitoh and Okada (1999). Behavior of a BSS under tensioning, service loading, and ultimate loading is discussed in Xue and Liu (2009). Both these papers stress the need to consider prestress in conjunction with physical layout and geometry of the structure.

The proposal builds upon previous research in the BSS group on natural frequencies and periods, on mode shapes and on the consideration of three-dimensional effects of earthquake actions. These areas of research are related to the studies of the role of prestress and string elements in the hybrid systems, and are, therefore, complimentary to each other (Kato & Nakazawa, 1995; Saitoh & Okada, 1999). The proposal also reviews the influence of system parameters such as the rise to span ratio of braces, system constraints, number of braces, and traveling wave effects. The proposal focuses on the effect of system stiffness and the system's redundancy on the load path and system response. The proposal presents a framework to understand modal

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properties of hybrid systems. The authors do not attempt to model all variants of the geometric systems. Some of these issues require a larger structural model with specific excitation signals.

2.2 Modal analysis and eigenvalue mechanics

In the case of linear structures, the free vibration equation is given by Mü + Ku = 0, where M and K denote mass and stiffness matrices respectively. For a vibrating structure, M u = φ sin (ωt), and therefore, Ku = ω^2 M u. In this case, the system of equations Ku = 0 has a nontrivial solution if the determinant of K − ω^2M equals zero. The values of ω that satisfy this condition are the natural frequencies of the system and the vectors of the eigenvalues are mode shapes of the system. It is good practice to normalize the eigenvectors, as their amplitudes are arbitrary. The meaningful output of the eigenanalysis is the shape and not the amplitude. There is, however, the exception where a specific forcing function is applied. In this case, the shape, frequency, and amplitude of the forced vibration is given by modal analysis (Clough & Penzien, 1993; Chopra, 2017).

Care should be taken when using mode numbers. The first mode is the least restrictive mode of the constraints and mass of the system. In general, higher modes of the system are allowed; however, they can approach lower modes if the system is changed. Mode numbers should not be used to indicate the same physical mode across different models, unless the mode shapes are compared. Various techniques can be used to verify modes; one of them is the modal assurance criterion. This technique requires that modes be correlated to the same degrees of freedom and that the normalization be consistent. In this study, comparison of mode shapes indicates that dominantly bending modes of a reduced beam are observed, not modes of the global BSS.

2.3 Prestress and geometric stiffness

The equilibrium configuration of a stressed structure is changed by the application of prestress. The configuration may differ from the unstressed state. Linearized vibrations of prestressed structures are modeled using the stiffness of the surrounding material. The configuration of a structure may be rendered unstable due to the presence of compressive forces. There are several instances where an increase in a natural frequency can be observed as a result of a change in the state of a member, mode shape, boundary conditions, and the form of the stiffness. Therefore, conclusions on changes to natural frequencies should be drawn using a sensitivity analysis for a given model, rather than a design rule.

The proposal mentions research into the effect of lower-string prestressing on the natural frequencies of bridge at-tune sensors (BSS). We have followed the emphasis on this research in the proposal. In the simplified version of the model described in this report, prestress is taken into account by geometrically relating equivalent vertical tangent springs. Thismodel does not account for a nonlinear, iterative procedure for determining the equilibrium of the structure. Thus, any change in frequency measured during the simulation of prestressing should not be taken to represent the actual change in natural frequency of a fully prestressed BSS. In reality, a number of factors, including initial camber, strut compression, and cable and connection geometry and limitations may come into play.

2.4 CFRP cable dynamic properties

Axial Effective modulus may be used to approximate EA in an global analysis. However, such an approximation does not account for transverse stresses, failure of fibers at the matrix-interface, and contact at the anchorage. Further, such simplification does not capture local, high bending stresses that may occur due to mis-modeled cable geometry. FRP cables have a number of potential advantages such as significant weight

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reduction as compared to conventional steel cables and corrosion resistance. However, in the opinion of the authors, a number of challenges still exist, especially regarding incomplete understanding of the mechanics of cable elements and the nature of connection between cables and other elements of the structure.

Experimental studies have investigated both in-plane and out-of-plane vibrations of reduced scale FRP cable models. Furthermore, studies have determined natural frequencies and examined damping. It has been reported that CFRP and BFRP cables can exhibit different types of damping behaviors in each direction. It has also been reported that FRP damping cannot be generalized by a single, lump-sum value. Modal tests on a 135 m CFRP cable bridge have shown that damping is heavily dependent on the modal frequency, order, and the level of vibration, and thus, cannot be generalized. Based on these studies, it is necessary to perform a modal analysis and measure the damping of the product, or justify why damping is not needed based on the amplitude, especially if the product contains CFRP.

2.5 Steel and CFRP comparisons in cable-supported bridges

Numerical and experimental studies on cable-stayed bridges are helpful types of evidence in this case. Xie et al. (2014) performed a study on the static and dynamic behavior of a cable-stayed bridge. Xie et al. (2017) conducted both numerical and experimental studies on a short span cable-stayed bridge, as well as a 648 m bridge with a combination of steel and CFRP stays. The results of these studies showed that the effects of nonlinear cables and structural system play an important role on the modal response of a structure. From these studies, it can also be seen that the balance of stiffness and mass is related to modal response. However, the geometry and load path of a cable-stayed bridge and a Balanced Singer Span bridge is completely different. Therefore, results of modal analysis of a cable-stayed bridge cannot be applied to a Balanced Singer Span bridge without analyzing the other components of the structure (i.e. Beam, String, and Restrainers).

Results from numerical studies on bridge components showed that decreasing mass of a component can cause an increase in a modal frequency of that component; but if the mass is significantly reduced, the effect can be on a modal frequency of a completely different component of the bridge. From the studies, it can also be concluded that there are no general rules to state that the use of CFRP in a bridge structure will always increase the modal frequencies of the structure. The authors of the studies evaluated the balance of stiffness and mass and compared the results to the numerical studies.

2.6 Cable vibration and structural coupling

Cable vibrations can occur from winds, rain-wind interactions, traffic, moving supports, or from external dynamic loads such as earthquakes. The response of a cable system depends on the frequencies contained in the excitation, the tension and sag in the cables, damping, and the interaction of the system with the supported structure. Abdel-Ghaffar and Khalifa (1991) showed how non-negligible cable vibrations can result in coupled-mode oscillations that are not resolved when each cable is analyzed independently. Sun et al. (2022) analyzed different stay-cable vibration mitigation methods, and mentioned the importance of non-zero damping and multimodal control. Stay cables, like other suspension and bridge system components, haveModal coupling with other support structure components, and the appropriate control strategy must be designed for the system.

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Volume 2, Issue 5, September-October 2026

2.7 Seismic response and dynamic stability

In the case of earthquake excitation, the natural frequencies of the system are of little importance. Of greater relevance are the characteristics and duration of the ground motion, system damping, mode shape participation, nonlinear behavior and flexibility of the system, and initial prestress. A modal analysis can help identify natural frequencies and associated mode shapes, but it should not be misinterpreted or used to anticipate the response of a system to earthquake loading. Limitations of the modal analysis can only be overcome by using the response-spectrum or time-history analysis. The current document cites research studies on dynamic stability and seismic response of BSSs, considering effects of brace number and prestress. Other effects that should also be considered within the context of seismic response analysis of BSSs are traveling waves and geometric and material nonlinearity.

2.8 Vibration control and serviceability

To improve serviceability, design changes may involve stiffness or mass changes, provision of damping, changes to cable tension, changes to structural configuration, or reliance on active control. Design changes should be assessed based on response, for example, peak acceleration, displacement, vibration in the built environment, or fatigue. An increase in natural frequency of a structure may result in excitation in another frequency band. Undamped structures may always exhibit resonance. The same response amplitude may be achieved by reducing the system damping. Xu et al. (1999) demonstrated the importance of modal damping in bridge stay cables using oil dampers. This study does not cover damper design. Rather, it identifies modes that will assist in design of vibration control systems.

2.9 Research gap and positioning

The proposal outlines a requirement to analyze CFRP and steel cable systems using finite element analysis (FEA). Relevant studies on basic building block systems (BSS) are available; however, these studies do not provide a direct modal validation dataset for a BSS using CFRP cables. This research addresses a methodological research gap. A numerical comparison is required to separate equivalent area from equivalent axial rigidity of the cables. The comparison should incorporate the mass and prestress of the cables. Numerical results for bridge components and bridge tests should not be used to validate a BSS. The results of this analysis will allow the authors to understand the behavior of the BSS. It is beyond the scope of this research to determine if the results of the analyses will be acceptable.

3. Research methodology

3.1 Study design

This study is a modal comparison of equivalent systems. The first case considers a BSS using steel cables at 600 mm2. The second case considers a BSS using CFRP cables at 600 mm2. The third case considers a BSS using CFRP cables at 800 mm2. The first two cases represent equivalent area substitution. The third case represents the influence of equivalent axial rigidity, while the area and mass of the cable remain variable. It is not the intent of this comparison to perform a design in which all elements are equivalent.

This model is implemented in Python via NumPy and SciPy. It relies on industry-standard, accessible finite-element and eigenvalue-analysis approaches (Bathe, 2014; Cook et al., 2002). It was not performed in ANSYS. This study is based on a research proposal that considers ANSYS as the primary tool to create a complete

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Volume 2, Issue 5, September-October 2026

system finite-element model. Because of this, the authors provided a preliminary reduced-order analysis model that can be replicated using the equations and assumptions included in the research proposal. Understanding the physical meaning of the computed frequencies is contextual to the element and model scope of the analysis. The goal of the model is to present a controlled system and evaluate various influences. The model is not intended to replace a detailed and thorough prototype model and/or make any claims of frequency validation related to design.

3.2 Geometry and structural idealization

The span of the reference beam is 12 m. The beam is modeled using 48 Euler-Bernoulli beam elements. Thus, the number of nodes is 49 and the degree of freedom at each node is 2 (vertical displacements and rotations about the axis of cross-section). The support conditions are such that the rotations about the axis of cross-section are free and the support in the vertical direction is simple at both ends. Two equivalent vertical tangent springs are placed at quarter and three-quarter spans of the beam (x = 3 and 9 m, respectively). As explained in the case of the cable supports, the 6 m horizontal distance and 1.5 m vertical distance used below are assumed effective geometry for the condensed stiffness of the cable system, and not the actual distance from the springs to the cable anchors. The effective length of the inclined line is Lc = √(36 + 2.25) m. Thus, the model considers that the contribution of the cable system is represented by the springs placed at x = 3 m and x = 9 m, and the stiffness of the springs is determined from the effective geometry of the system. It is to be noted that this type of modeling, in which a rigid body system is modeled by using a lesser number of degrees of freedom, is a type of approximate modeling. This type of modeling does not represent the full system.

Certain assumptions have been made in this model. Ultimate loads and displacements account for idealization. Individual strut degrees of freedom, cable sag and shape changes, connection slip, local anchorage, torsional degrees of freedom, out-of-plane modes, and mode coupling have not been considered. In this regard, the system can be approximated as planar. The modes computed are idealized bending modes and should not be misleading interpreted as full three-dimensional BSS modes. The simplified springs represent modes of interest and allow assessment of the effect of prestress and cable stiffness.

3.3 Material and mass assumptions

The density of the steel cable has been taken as 7,850 kg/m3 and modulus of elasticity as 200 GPa. The density and modulus of elasticity of the CFRP cable have been taken as 1,600 kg/m3 and 150 GPa, respectively. For equal area CFRP and steel cases, the cable cross-sectional area has been taken as 600 mm2. For equal rigidity CFRP case, cable cross-sectional area has been taken as 800 mm2.

Beam stiffness is fixed to E = 200 GPa. I = 8.0×10^{-4} m^4. Cross-sectional area Abeam = 0.02 m^{-2}. The density is ρ = 7850 kg/m^{-3}. Mass is assumed proportional to area for an Euler-Bernoulli beam, therefore, an estimate for beam area is modeled with an assumption not validated in the prototype.

The mass matrix is modeled with the standard Euler-Bernoulli mass matrix for a beam element. A mass representing a cable is modeled as a lumped mass between the two springs. Cable-equivalent mass is defined as ρAL, where A is the effective area of the two inclined segments, and L is the total segment length of the two inclined segments. Comparing cable-equivalent mass captures the differences in mass between CFRP and steel. Ideally, a cable has independent transverse vibrational modes and mass is modeled as a continuous distribution. Considering these approximations, we see that for very large elements, with large spring constant compared to mass matrix elements, the mode will correspond to the physical deflections of the element.

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Volume 2, Issue 5, September-October 2026

3.4 Stiffness formulation

The formula for estimating the equivalent vertical tangent stiffness is given by k_v = (EA/Lc)c_v^2 + (T/Lc)c_h^2. Here, EA is the axial rigidity of the cable, Lc is the effective inclined length, and T is the parameter of initial prestressing. The expressions c_v = 1.5/Lc and c_h = 6/Lc represent all of the effective segment used in the simplified stiffness and are not related to the physical segment of cable between the quarter span spring node and an anchor. The vertical translational degrees of freedom are considered at x = 3 m and x = 9 m in the plane of the cable. The expressions for the stiffness ideally represent the effects of prestress and geometry of the cable. It is noted that these terms do not represent a conventional geometrically nonlinear modeling approach, which utilizes the principles of equilibrium, to analyze the state of the system. It is assumed that the geometry is not significantly distorted due to the effects of large amplitude deformations.

The stiffness matrices derived from the Euler-Bernoulli beam theory are used to obtain mass and stiffness matrices for each element. The element matrices are, subsequently, integrated into global matrices. The translational degree of freedom of the beams in the vertical direction at the ends of the beams are constrained. The corresponding degrees of freedom in the horizontal direction are not constrained. The rotational degrees of freedom are not considered. It is assumed that the eigenvalue solution provides the vibration modes of the structure about the idealized state and it does not represent large amplitude deformations that may cause failure of the structure.

3.5 Generalized eigenvalue solution

The undamped free-vibration problem can be expressed as $K\phi j = \omega j^2 M\phi j$. For this problem, we solve the symmetric generalized eigenvalue problem to find the smallest positive eigenvalues and corresponding eigenvectors. The frequencies are found to be $fj = \omega j / (2\pi)$. The mode eigenvectors are expressed in terms of all degrees of freedom and then normalized. This is done in order to represent the largest displacement as one. This normalization allows us to produce mode shapes on a consistent scale. It is important to note, this normalization does not represent any physical magnitude. We compare modes across various case studies and make conclusions based on differences we see. It should be kept in mind that this model does not capture lateral or torsional modes.

It is assumed that the mass matrix is always positive definite for the system of interest; and with the assumptions made on lumping cable masses and modeling beams, the stiffness matrix is also positive definite. The eigenvalues and eigenvectors of the first eight modes are calculated, and the first six modes are reported. The main output of the analysis is the undamped natural frequencies of the modes. It should be noted that the eigenvalue problem was undamped; and therefore, if damping is of interest, it would have to be modeled explicitly. Although, in various cases, damping measurements are reported; and in those cases, damping of the model is presumed to be the same as that reported.

3.6 Prestress sensitivity

The effect of varying prestress on the results is studied in this section. Therefore, the value of prestress is changed from 100 kN to 300 kN with an increment of 50 kN. The first natural frequency for each case was computed. The objective of this study is to understand the effect of prestress on the lowest mode. This is not an analysis of uncertainty in design, an optimization study, a seismic study, or a complete nonlinear analysis of prestress. Relative trend is of interest, therefore, all cases are analyzed using the same equation.

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Volume 2, Issue 5, September-October 2026

3.7 Cable-stiffness sensitivity

Equal area and equal axial rigidity provide a means of comparison based on two criteria of stiffness. In the case of steel, equal area is met at EA = 120 MN; equal area in CFRP is met at EA = 90 MN and CFRP with 800 mm2 meet it at EA = 120 MN. In equal rigidity, the mass of the cables is not balanced; in the examples examined, the CFRP cable and the equivalent systems meet equal rigidity, and therefore, positive stiffness of the springs in the model. Comparing cases with various moduli of cables and keeping mass constants provides a better case.

3.8 Model verification and numerical checks

The assembled matrices were confirmed to be symmetric and matrices K and M were confirmed to be positive definite, using the methods described in Section 3.8. The eigenvalues of the extended stiffness matrix of the constraint equilibrium system (including the constraints) were determined to be positive. Numerical checks were performed on the frequencies of the system, to assess the behavior of the finite element discretization. These checks involved refining the finite element mesh.

Numerical stability of the beam discretization for the reduced order BSS model was assessed by performing a mesh check. A refinement of the discretization of the beams from 12 to 48 elements, while holding all other assumptions fixed, was performed to assess the frequencies of the first six modes. For the assessment of numerical stability, the assumptions of the model were such that springs were placed at quarter-span locations. The 12 element mesh assessment indicated the frequencies of the first six modes of the structure to be 12.170 Hz, 43.437 Hz, 97.820 Hz, 176.335 Hz, 271.883 Hz, and 386.683 Hz. The 24 element mesh assessment indicated the frequencies of the first six modes of the structure to be 12.170 Hz, 43.435 Hz, 97.797 Hz, 176.202 Hz, 271.417 Hz, and 385.414 Hz. The 48 element mesh assessment indicated the frequencies of the first six modes of the structure to be 12.170 Hz, 43.435 Hz, 97.796 Hz, 176.193 Hz, 271.387 Hz, and 385.330 Hz. The differences in relative frequencies between the 24 element and 48 element mesh assessments for modes 1 through 6 were 0.00002%, 0.00028%, 0.00146%, 0.00485%, 0.01115%, and 0.02176%, respectively. Dispersion of spring positions to quarter-span locations of the beams was assumed. Numerical stability of the beam discretization for the six modes of the BSS is validated by the assessment of mesh checks.

3.9 Dynamic response interpretation

For the model described herein, the main outputs are natural frequencies and mode shapes. It should be noted that, with the exception of an external forcing function, this model contains no representation of either mechanical or material damping. Consequently, outputs such as peak acceleration, transient response, or fatigue demand are not computed by this model. Additional outputs such as modal participation factors and modal response are computable with an adequate representation of mass and stiffness (including damping) and the relevant boundary conditions. For the purposes of this report, the focus of any considerations of vibration control will be on the implications of the modal model and not on the performance of any control elements.

3.10 Reproducibility and reporting

It is considered that the reported assumptions, computational procedure, and all inputs to the model (i.e. material properties, mesh size, restraint types and positions, spring positions, eigenvalue solver method, and prestress sweep) are reported in sufficient detail to allow the computational procedures to be repeated. Figures and tables are extracted directly from computer output. The reported results were obtained from the reduced

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order model implemented in Python. Measured data were not modeled or simulated. The literature was reviewed in order to help the author interpret the results. The author referenced older literature to support qualitative statements.

4. Theoretical basis

4.1 Linearized free vibration

The linearized equation of motion of a system with generalized displacement vector u is given by M uid + C üd + K_T u = p(t), where M and C are the system matrices of the mass and damping terms, respectively, K_T is the tangent stiffness matrix, and p(t) is an externally applied load. In free vibration, C and p(t) are not considered. The response is assumed to be of the form u = φ exp(iωt). Thus, (K_T - ω^2 M) φ = 0. The solution of this equation yields the natural frequencies and corresponding mode shapes. In a structure with initial stress, K_T may include geometry stiffness, and as a result, the selected initial stress may be part of the dynamic model instead of a static load to be removed for the performance of a modal analysis.

A similar approach for a reduced model of beam and equivalent springs has been employed in this study. Bending of the beam and rotation of the springs represent the bending and sagging of the cables, respectively. The two degrees of freedom (masses) are located at the positions where the cables are supported. The rigorous form of the coupled problem of the beam and the equivalent springs represents the steady state vibrations of the system. The solution of the problem gives natural frequencies and associated mode shapes of the system.

4.2 Stiffness and mass effects

The natural frequency of a single degree of freedom oscillator is given by ω = √(k/m) where m is the mass and k the stiffness. For structures with multiple degrees of freedom the relationship becomes more complicated and is given in terms of coupled eigenvectors of a certain matrix eigenvalue problem. This relationship is similar to that of a single degree of freedom system. This similar relationship should not be used to analyze each member of a coupled system of structural components (BSS) separately. In an assembled structure, the effects of stiffness are reflected in the mode shapes and the distribution of energy of the system. Mass, on the other hand, affects the modal inertia of the system. Thus changes in the system frequency are due to changes in stiffness, mass or both.

In the presence of an equal axial load EA is equal. This does not mean that the two cables are of the same mass, of the same tensile strength, of the same damping, of the same thermal and anchorage compliances, or of the same nonlinear behavior. If EA is equal, the stiffness of the two members is equal, and by definition, the frequency of the two members is also equal. Any perceived contradiction of equal stiffness should be investigated to determine if the mass of the system has also changed.

4.3 Prestress and tangent stiffness

Tensioned cables provide both material and geometric stiffness. Geometric stiffness depends on the orientation of the member and the direction of the load. Equilibrating forces due to prestress affect compression in beams, action forces in struts, and the geometric configuration of the structure. In the model, geometric stiffness due to prestress is represented by a positive term that is dependent on the horizontal direction cosine and the ratio of the prestress to the length of the member. Increasing the prestress in the model

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Volume 2, Issue 5, September-October 2026

causes the stiffness to increase. In the model, the inclusion of prestress causes an increase in the fundamental frequency of vibration of the structure. It is not justified to state that all BSS frequencies increase due to the inclusion of prestress. This is dependent on the geometry of the structure and the action forces in the members.

4.4 Mode shapes and participation

A mode shape indicates the displacement of various parts of a structure for a particular mode of vibration. The amount that a particular mode participates in response to a given excitation of the structure is indicated by the modal participation factor. A low frequency mode can be totally absent in the response of the structure if the excitation does not contain energy at the natural frequency of the mode. On the other hand, a high frequency mode can be coupled strongly to the response of the structure if the excitation contains a significant portion of energy at the natural frequency of the mode. The model is limited in that it does not consider the participation of the structure in response to excitation in other planes of the structure.

4.5 Damping and resonance

Damping describes the rate at which free vibrations die out and the maximum amplitude of the forced response near resonance. In the case of a single mode with subdued damping, the resonant amplification is in direct relation to modal damping. In a structure, the location of the stiffness and mass determine the frequency of vibrations. Computing natural frequencies from a structure with undamped Eigen frequencies gives no information on the amplitude of response. CFRP damping depends on several factors including modal order and the direction of the vibration and hence the causal relationship between CFRP and structure. Therefore, no definite statement for or against CFRP damping is made in this study.

4.6 Modal verification and validation

Verification ascertains whether the mathematics of the system is implemented and solved correctly. Validation ascertains whether the system represents the behavior of the real world to an acceptable degree of accuracy. There are several degrees of freedom in the discretization of the system and in finite element analysis. Verification can be checked by ensuring equivalence in matrix dimensions, dimensional checks, or stability of eigenvalues. An adequately converged solution has to be checked to ascertain that the finite element discretization of the system adequately captures the essential features of the physical system. Comparison of FE results with experimental data can be made, only if the aforementioned conditions are satisfied.

5. Numerical results

5.1 Baseline modal frequencies

At a prestress value of 200 kN, the first natural frequency for the steel equal-area case is 12.170 Hz. For equal-area CFRP, the first natural frequency is 12.005 Hz. For equal-axial-rigidity CFRP, the first natural frequency is 12.304 Hz. Compared to steel, the equal-area CFRP first natural frequency is reduced by 1.35%. The first natural frequency of the equal-axial-rigidity CFRP case is increased by 1.10% compared to the steel case. These results represent the effects of the reduced-order model, the BSS (beam-spring-mass) system, and its associated lumped elements. Therefore, these results should not be generalized to a full BSS.

The lower first natural frequency for CFRP cases compared to steel is expected and is mainly due to the lower assumed axial rigidity and cable mass. In this study, if the CFRP case tends to have a reduced equivalent stiffness, the first natural frequency will tend to be reduced, even if the mass is reduced. Compared to the steel

International Journal of Advanced Multidisciplinary Research and Innovation
E-ISSN: 3107-6157 editor@ijamri.com
Volume 2, Issue 5, September-October 2026

case, the equal-axial-rigidity case tends to have a reduced first natural frequency due to lower density and larger effective area. This shows that a material substitution should be considered by considering the effects of stiffness and mass together, as opposed to considering the effects of modulus or density separately.

The first six cases illustrate the effect of changes to the material and case of the vibration absorber. The first three cases illustrate changes associated with the position of the mass and the stiffness of the equivalent springs in the model. The fourth case is relatively insensitive to changes in the material and case of the vibration absorber. Higher modes of the model exhibit this behavior, since the shape and displacement of the beam over the length of the model vary. This behavior is exhibited by different modes of the model depending on the location of the springs; however, this behavior should not be extrapolated to other three-dimensional BSS models without justification.

The calculated frequencies of the first six modes are reported in Table 1. Mode order is determined by case. Since the model represents a planar beam with only vertical translational degrees of freedom and rotation about the vertical axis, modes are not classified. Modes are described as bending modes of the planar beam representation.

5.2 Mode-shape observations

The first mode-shape is dominated by global bending. Maximum displacement is zero at the supports, and maximum displacement at midspan is at the bottom. Other areas exhibited smaller displacements. It is expected that the three cases will exhibit similar mode shapes as they all share the same geometry and support conditions. Differences in the mode shapes are attributed to differences in flexibility (stiffness) and lumped mass (or mass at quarter span). Two structures with identical mode shapes do not necessarily have the same modal frequencies, and equivalently, structures with the same mode shapes do not always have the same frequencies.

As one proceeds to subsequent modes, more nodes and changes in the spanwise curvature are exhibited. The influence of the stiffness elements (springs) is determined by the location of their attachments to the beam, and accordingly, the regions of highest vertical displacement. Some of the higher-mode patterns may include torsional motions of the system; however, the current model and reduced system does not allow for such motion. Therefore, the limitations of the present model and the mode analysis preclude any conclusions regarding a physical system. Rather, such analysis is an indication of the adequacy of the beam–spring system model implemented.

5.3 Prestress sensitivity

The effect of varying the prestress parameter on the structure is considered next. Here the prestress parameter was varied from 100 kN to 300 kN, in increments of 50 kN. For both steel and CFRP, the first natural frequency of the structure increased. For steel, the increase was from 12.154 Hz to 12.186 Hz. For equal area CFRP, the increase was from 11.989 Hz to 12.022 Hz. Similarly for equal-axial-rigidity CFRP, the first natural frequency increased from 12.288 Hz to 12.320 Hz. The increase in frequencies across the full sweep in all the cases was about 0.27%. The positive term related to prestress in the adopted spring constant equation governs the Prestress variation.

Although the variation in the natural frequency of the structure due to prestressing is small, this does not indicate the insignificance of prestress in a real BSS. A real BSS comprises an array of cables/struts/tendons,

International Journal of Advanced Multidisciplinary Research and Innovation
E-ISSN: 3107-6157 editor@ijamri.com
Volume 2, Issue 5, September-October 2026

a deck/sheet, and a filled/strengthened space between the deck and the stiffened sheet (the space could contain part of the fluid that the BSS intends to improve the transport of). As the construction of a real BSS progresses, the equilibrium configuration could change and mode switching, for example, could occur. The goal of the current analysis is to understand the sensitivity of the first natural frequency of the BSS to the prestressing force. The analysis does not indicate the behavior of a real BSS during the entire construction and tensioning process.

5.4 Comparison of equal area and equal axial rigidity

In the equal-area comparison, the area of each cable stays constant at 600 mm2. Therefore, to compare equivalent nominal areas, other parameters of the system are also held constant. With respect to spring stiffness, EA = 90 MN for the CFRP case, and 120 MN for the steel case. Consequently, CFRP exhibits less spring stiffness. The first natural frequency for the CFRP case, based on this assumption, is less than the equivalent frequency for steel. An equal-rigidity comparison provides a more realistic representation, given the EA of the CFRP case is increased to 120 MN. Consequently, the first natural frequency of the CFRP case becomes greater than the first natural frequency of the steel case.

The purpose of this case study was to provide the basic methodology for representing cable systems. The emphasis is placed on mass and equilibrium. In this regard, the study is successful. The disparity of the two cases of CFRP also illustrates the need for precision when equal-stiffness conditions are required. Equal ideal axial rigidity of the cable systems is not equal transverse rigidity of the systems. Spring constants include geometric factors and stress components. In this representation, Cable 1 has the same EA as Cable 2. However, the system could include other factors such as the geometry of the cables, their position with respect to the structure, and other flexible connections. In such a case, the order and values of the modes of the system could be different.

5.5 Prestress and modal ordering

First-mode frequencies were obtained for the CFRP equals A and C sections for both steel and CFRP samples across the entire prestress range. No mode crossing was observed in the first-mode frequency values reported here. The remarks herein are limited to the first modal analysis. If higher modes are closely spaced, full mode-tracking analyses should compare various modes, including mode shapes. In cases where multiple eigenvalues are closely spaced, frequency ordering may not identify the corresponding physical modes. To determine if pairs of physical modes are corresponding, the correlation of mode shapes is necessary, as well as a consistent mapping of degrees of freedom.

5.6 Mesh and numerical stability

A 48-element beam model was used to obtain the modal analysis results. The frequency-based mesh assessment in Section 3.8, compares the first six frequencies of discrete beam models consisting of 12, 24 and 48 elements. Numerical stability of the frequencies was determined based on the results of the 24 and 48 element beam models. Convergence of mode shapes was not established based on the assessment reported here. As noted, mesh refinement does not prove the equivalent-spring model, and tightening the mesh does not alleviate irreconcilable limitations of the model.

5.7 Dynamic response scope

Numerical outputs from the model are natural frequencies and mode shapes. Time-history responses, acceleration spectra, earthquake input, damping calibration, and harmonic force responses have not been

International Journal of Advanced Multidisciplinary Research and Innovation
E-ISSN: 3107-6157 editor@ijamri.com
Volume 2, Issue 5, September-October 2026

reported. Therefore, results cannot be used to validate a claim on peak accelerations, vibration comfort, fatigue, seismic demands, or percent reductions in dynamic response. These evaluations require a definition of the excitation and damping in the system. These are important considerations because a change in frequency can improve or worsen a structure's response to a particular excitation. Results from the model identify mode shapes and frequency ranges. While the results from the model do not represent a performance assessment in vibration control, they can be used to define the modes and frequencies in the structure, and can help frame a case for vibration control.

Table 1. First six calculated natural frequencies

Mode order	Steel, equal area (Hz)	CFRP, equal area (Hz)	CFRP, equal EA (Hz)
1	12.170	12.005	12.304
2	43.435	44.308	44.386
3	97.796	98.918	98.854
4	176.193	176.193	176.193
5	271.387	274.490	274.224
6	385.330	394.048	393.270

Table 2. First-mode prestress sensitivity

Prestress parameter (kN)	Steel, equal area (Hz)	CFRP, equal area (Hz)	CFRP, equal EA (Hz)
100	12.154	11.989	12.288
150	12.162	11.997	12.296
200	12.170	12.005	12.304
250	12.178	12.014	12.312
300	12.186	12.022	12.320

International Journal of Advanced Multidisciplinary Research and Innovation
E-ISSN: 3107-6157 editor@ijamri.com
Volume 2, Issue 5, September-October 2026

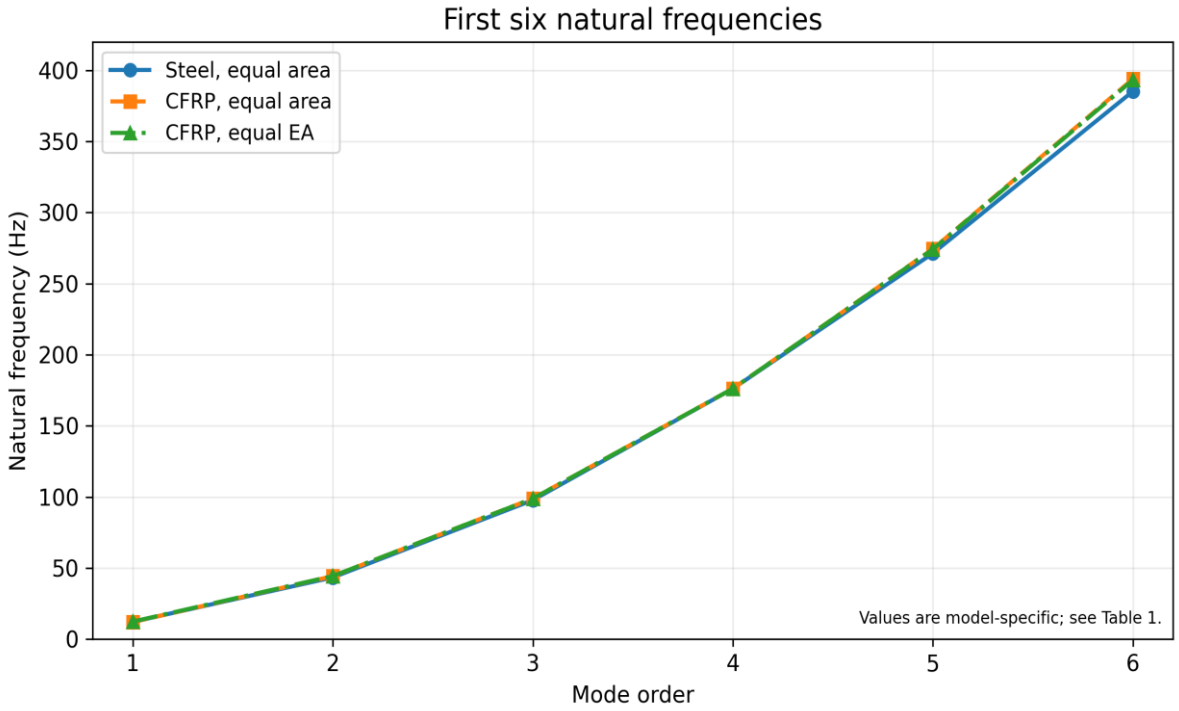


Figure 1. First six natural frequencies for the three comparison cases.

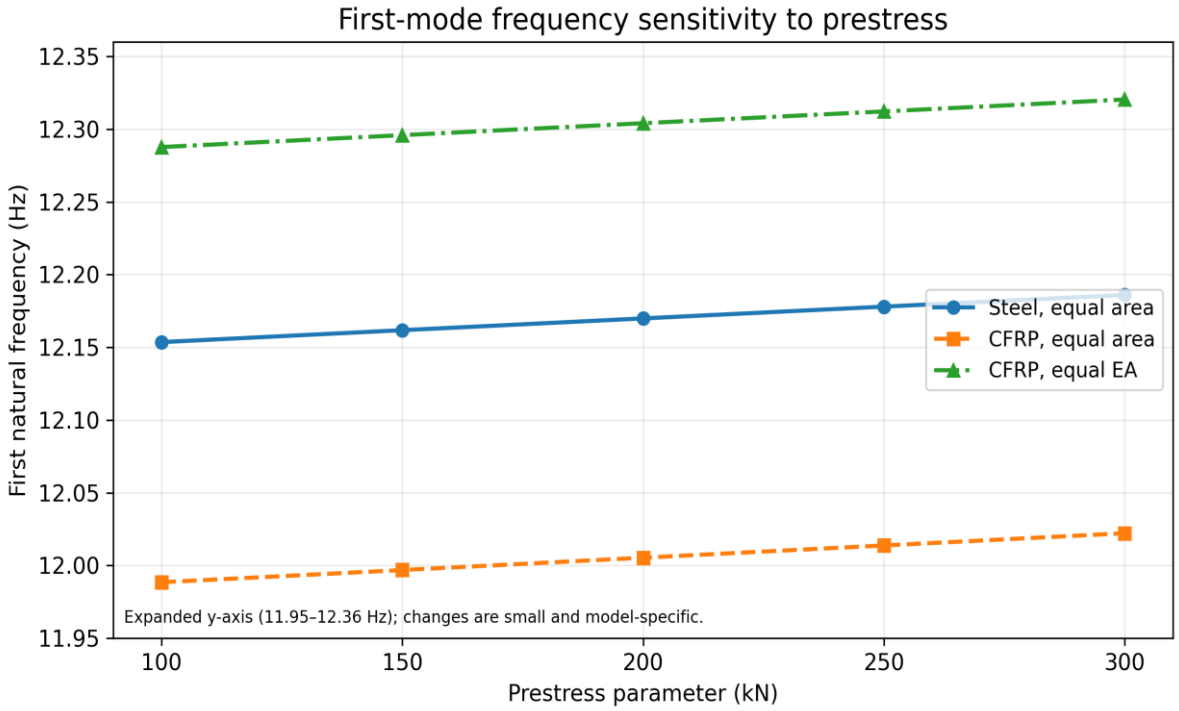


Figure 2. First-mode frequency sensitivity to the prestress parameter (expanded vertical axis).

International Journal of Advanced Multidisciplinary Research and Innovation
E-ISSN: 3107-6157 editor@ijamri.com
Volume 2, Issue 5, September-October 2026

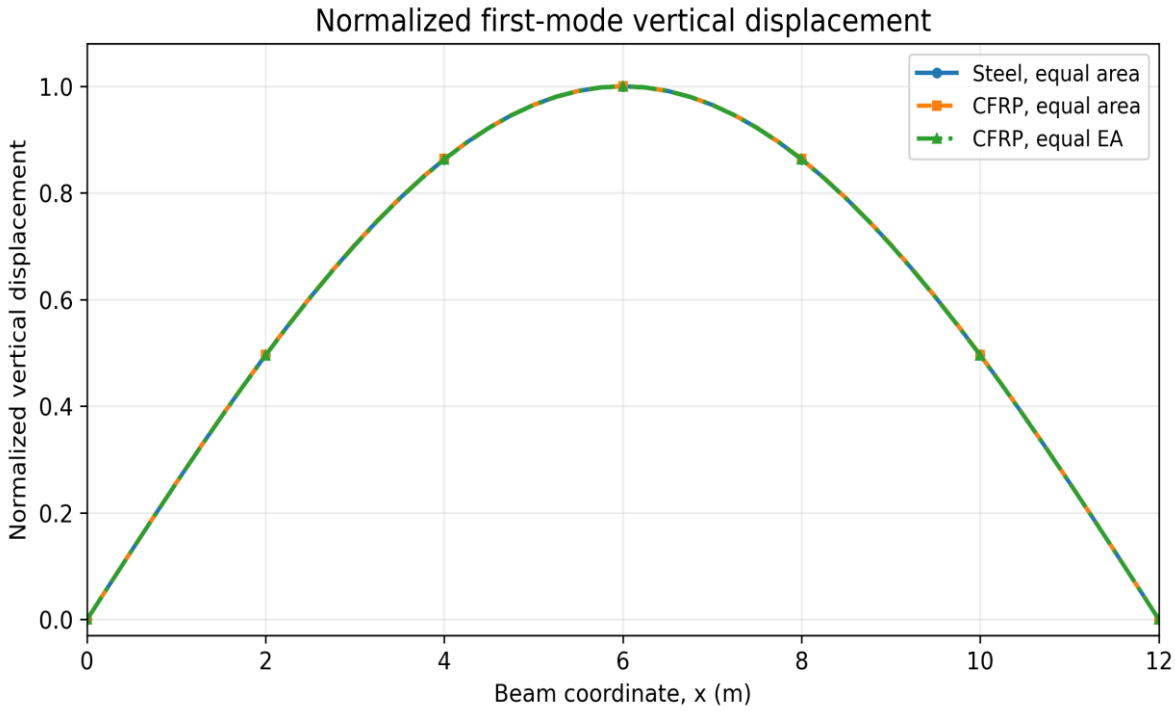


Figure 3. Normalized first-mode vertical displacement profiles for steel and CFRP cable-based beam-string configurations.

The profiles represent the first-mode eigenvectors and therefore have a similar shape due to common supporting conditions. The horizontal extent of the profiles corresponds to the amplitude of the eigenvectors.

6. Discussion

6.1 Interpretation of the first frequency

The numerical model estimates the first frequency of the equal-area CFRP and the steel laminates. The first frequency of the equal-area CFRP is lower than the steel frequency estimate, which is consistent with the assumption of a lower CFRP modulus. While CFRP is significantly lighter than steel in the model, the effect of the lighter mass is outweighed by the removal of an equivalent steel spring in the model, making the first mode frequency of the CFRP case lower. The equal-axial-rigidity CFRP case gives a first frequency that is higher than the steel case, with the lower CFRP mass case contribution being lower than the steel case. Again, the conclusion depends upon model details and is not applicable in all cases.

Replacing a steel structure with CFRP in a model meets the broad structural dynamics principle that changing stiffness and inertia affects the frequencies of a system. Replacing a steel structure with a lower mass and lower stiffness structure does not guarantee a lower frequency, and the mode shape of the structure can be affected. Replacing steel with a structure of equal axial rigidity does not make the two structures dynamically identical as there are numerous other system characteristics that differ. To determine equivalence of a system, the modelers should identify the design requirements and evaluate mass and stiffness in relation to the modes of the system.

International Journal of Advanced Multidisciplinary Research and Innovation
E-ISSN: 3107-6157 editor@ijamri.com
Volume 2, Issue 5, September-October 2026

6.2 Mode shape and structural configuration

The first few normalized mode shapes are similar for all cases; therefore, the dominant global behavior for all cases is lateral beam bending within the span of the beams. The differences in the frequencies are due to local stiffness and mass of the springs. It is instructive to examine the effects of different material models in a numerical experiment. The remainder of the effects are attributed to structural configuration. For the entire system, the rise-to-span ratio of the struts, the spacing of the struts, and cable and suspender (sag) lengths can be varied. Support conditions, unmodeled constraints, and fixity conditions can also affect the behavior of the cable system. Variability of these parameters will effect the mode shape of the system and the participation of the cable system. The effects of these variables on the system behavior will be investigated using a parametric study.

Modeling lateral and torsional effects of a structure requires a fully three-dimensional model. A model of a structure that represents all degrees of freedom and is sufficiently nonlinear and large to represent input from earthquakes can be prohibitively expensive and computational inefficient. For symmetric structures, symmetric mode shapes will couple to the cable system to a similar degree, and antisymmetric mode shapes will couple to the cable system to a lesser degree. The mode shapes obtained in this study will be used to qualify the behavior of the system, and to compare to more rigorous studies.

6.3 Prestress as a dynamic parameter

In the model, the increase in the first mode frequency, within the range of considered prestressing, is less than 0.27%. Although for the current formulation of springs this may be neglected, this should not be the general case. That is because introduction of prestress may influence equilibrium conditions, and consequently, member forces and effects, geometrical stiffness, and instability of the structure. Variation of the level and order of cable-tensioning during the construction of a real BSS may alter strut compression, support reactions and even the initial geometry of the system. This is not considered in the present model. In general, in order to analyze the effect of prestress on the modes of vibration, it is necessary to first obtain a prestressed equilibrium.

6.4 Implications for vibration control

Modal analysis does not necessarily enable selection of the best vibration control systems. The factors which influence the decision include type of excitation, the response which is to be controlled, type and level of damping, and which modes participate in the response. Depending upon the type of excitation, different modes may predominate. For vibration control systems, the designer should consider excitation spectrum and multiple modes of vibration (e.g., Sun, 2022).

The study is able to determine how the first few natural frequencies of the simplified model change with respect to cable stiffness, cable mass and initial cable tension. A quantitative evaluation of the damper requirements is not possible with this approach. It is not appropriate to assign damping values to FRP cable systems based on material category, as differences in the damping values have been found to depend on the direction and amplitude of cable vibration (Yang et al., 2015). Any future models that account for vibration need to include values or represent damping with a model and address the range of variation of the systems response.

International Journal of Advanced Multidisciplinary Research and Innovation
E-ISSN: 3107-6157 editor@ijamri.com
Volume 2, Issue 5, September-October 2026

6.5 Seismic implications

In seismic assessment, modal analysis is an initial step that determines natural frequencies and mode shapes that are used in modal response spectrum analysis. Demand in the response spectrum is determined by several factors, such as mass and damping participation, spatial distribution and effects of structural nonlinearity. The study refers to studies of BSS that analyze the effects of earthquake actions in one and three dimensions. The studies identify the effects of structural restraint and prestress braces. Like mentioned above, these cannot be fully expressed in a planar model of beams and springs. As such, this paper does not analyze seismic responses of BSS structures and does not make any claims regarding seismic performance of these structures against BSS structures that use other cabling materials.

6.6 Transfer of evidence from cable-stayed bridges

Analysis of CFRP cable-stayed bridges allows the determination of relevant information on cable stiffness and mass and identification of bridge modes and coupling. Beams, pylons, and stays with restrainers are part of a different structural system from a BSS beam, strings, and struts. Analysis of bridges may inspire the choice of input parameters and provide insights on mechanics, but will not verify BSS modal frequencies. Measuring frequencies of cables of a BSS will not verify modes of the BSS and will provide information on the cable and its constraints.

6.7 Robustness and uncertainty

The frequencies computed in this study are dependent on several factors including the geometry of the beams, density of the beams, modulus of cables, area of cables, density of cables, geometry of springs, and parameters of prestress and conditions of supports. It is assumed that the input factors will be determined with certainty. uncertainties on these parameters will not be reflected in the analysis. A change in any of the parameters within the defined limits should be considered in a robustness check. Changes in support compliance and connection stiffnesses may shift frequencies of a BSS, and may be of concern for verification of global modes of the BSS.

Uncertainty should be associated with the engineering judgment. If the difference in frequency between the CFRP and steel cases is less than the uncertainty due to realistic variations in the material and support systems, then the available evidence from the modal analysis would not provide strong evidence to support a material selection decision. A stable difference, however, among the various design cases and considering the excitation and serviceability limits, would provide evidence to support a material selection decision. Our analysis focuses on understanding the differences between the various design cases, including the modal frequencies, and therefore would not quantify uncertainty.

6.8 Design interpretation

From a design analysis perspective, the performance function to be satisfied by the material being selected should be articulated first. For serviceability, the limit cases may be specified as displacements or accelerations, the associated forcing functions, and the associated frequency ranges. For seismic design, participation of modes and degree of structural system nonlinearity should be accounted for. For cable vibration, the influence of various constraints, damping and coupling to other structures should be evaluated. For the material selection case, the basis of comparison should be equal stress, equal strain or equal area, and the results of the comparison should be presented in terms of system mass, system stiffness, and modal properties, and the design and integrity constraints. Again, for a material selection case, several modal numbers may be needed to arrive at a system-level decision.

International Journal of Advanced Multidisciplinary Research and Innovation
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Volume 2, Issue 5, September-October 2026

7. Limitations

The main constraint is using a reduced-order model. The beam has been modeled using Euler-Bernoulli elements and the cable-strut subsystem has been idealized using a pair of equivalent vertical tangent springs and a mass representing a lump of cable. This model can only capture the global bending of the system and does not model slip at the joints or flexibility of the anchorage. In addition, this idealization does not capture the deformation of the cables, or distributed vibrations of the cable. Lateral and out-of-plane movements are also ignored. Reported modes of vibration cannot be considered as a complete set of BSS modes.

Also, it is to be noted that the input data provided for this study was highly idealized. The values presented for the dimensions of the elements of the system do not represent measured values for a physical system, and therefore, should not be considered as design or construction data. A mass of 0.02 m^2 has been assigned to the beam for the purpose of the present study. A detailed design study should assess the impact of the idealized values used in the present work and replace them with realistic values. If the actual cable system does not assume an ideal equivalent axial system, the model should be updated to reflect the changes.

There are three main limitations concerning the linearized undamped eigenvalue formulation. The model is unable to compute any response to external loading, whether due to an external dynamic load or an earthquake. Material damping ratios are not determined or defined in the model. Therefore, this study is not able to show any reduction in amplitude of response, increased damping, or improved fatigue life of the system.

The limitation is also reflected in the lack of response-amplitude reduction in the fatigue life, which is due to the neglect of energy dissipation in the system. The model would also need to account for the effects of nonlinearity due to large deformation of the system, as well as changes in the equilibrium configuration of the system.

The Cable-Stayed structures modeling study also neglects measurement validation. The verification of the results depends on the relation of the modeling assumptions to the real world. A difference in modeling assumptions from what is seen in the real-world system will also decrease the fidelity of the predicted results. Additional assumptions and definition of tolerances will be important when claiming generalization of the numerical results.

8. Conclusions and recommendations

This study developed a reduced-order Python finite element model to analyze modal behaviors of cable systems made of steel and carbon-fiber reinforced polymer (CFRP). The model employed Euler-Bernoulli beam elements and approximated the system mass and stiffness with vertical springs located at quarter-span positions. Each cable was modeled as a lumped mass. The model was simpler than the detailed finite element model (FEM) developed in ANSYS proposed in the original research. The results of the model described in the present study should not be interpreted as results of ANSYS or experimental data.

The calculated first natural frequencies were 12.170 Hz, 12.005 Hz, and 12.304 Hz, corresponding to the steel cable of 600 mm2 cross-sectional area, CFRP of the same cross-sectional area, and CFRP of 800 mm2 cross-sectional area, respectively. In the equal-area comparison, the first natural frequency of CFRP was 1.35% lower than that of steel. In the comparison of equal axial rigidity, the first natural frequency of CFRP was 1.10% higher than that of steel. These differences are valid for the current model and parameters.

International Journal of Advanced Multidisciplinary Research and Innovation
E-ISSN: 3107-6157 editor@ijamri.com
Volume 2, Issue 5, September-October 2026

During the parametric study, where prestress was varied from 100 to 300 kN, the first natural frequency of steel remained approximately 12.154 to 12.186 Hz. In the case of equal-area and equal-axial-rigidity CFRP, the first natural frequency was in the range of 11.989 to 12.022 Hz and 12.288 to 12.320 Hz, respectively. These results are expected from the equivalent spring constant approximation. In general, a higher prestress produces a higher natural frequency. However, these results should not be extrapolated to make general conclusions about the natural frequencies of bonded structural systems (BSSs).

The main design consequence is methodological. If we are to compare cable systems, equivalence criteria need to be specified, and both stiffness and mass of the systems should be considered. Equal area and equal axial rigidity address different issues and do not balance anything else, including damping, limitting strength, anchorage behavior, or nonlinear behavior. Natural frequency does not indicate performance of a vibration control system. A detailed analysis of the behavior of the system (i.e. forced response or seismic analysis) requires definition of the excitation, modal behavior of the structure, damping, and nonlinear behavior of the system.

For next steps, using the proposed ANSYS pathway and a suitable finite element model, the closest equilibrium position of the cable system should be determined. Consideration should be given to all other elements, particularly flexibility of the cable, mesh and mode convergence, and balanced mass, and the connection of the cable to the structure. A verified model should be compared to the behavior of a working prototype and a clear definition of the damping should be provided for each mode. Vibrations in all modes, including torsional and lateral modes, should be investigated.

It can be concluded that the results of the computational study show that for a balanced evaluation of stiffness and mass of a system, evaluating the behavior of steel and CFRP cable systems is considered equivalent. The study provides a basis for the evaluation of dynamic behavior of a system. Distinction between exploratory computational studies, full system simulations, and experimental validations has been maintained.

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