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Comparative Static Performance of Carbon Fibre-Reinforced Polymer and Steel Cables in Beam-String Structures: Finite Element Analysis and Numerical Verification

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Abstract

Beam-string structures (BSSs) utilize cables to achieve long span structures. Stiffness and mass of cables are system properties that depend on material of construction. This study emulates steel and carbon fiber reinforced polymer (CFRP) cables to assess their effect on behavior of BSSs. A general-purpose computational software environment was interfaced with Python to programmatically generate and solve a BSS model subjected to static loading. Steel and CFRP cables were embedded in a reusable, reduced order, finite element model (ROM-FEM). The ROM-FEM incorporates Euler-Bernoulli beams and equivalent springs to represent cable segments. The baseline model consists of a 12 m span, loaded by a 10 kN/m uniform load, and prestressed by a 200 kN load in the CFRP cable. In the steel cable case, the mid-span displacement was 2.835 mm. In the CFRP case, mid-span deflection was computed to be 3.590 mm. This represents an approximately 26.6% increase, attributable to the Steel-CFRP stiffness assumption. A 800 mm2 cross sectional area for the CFRP cable reduced computed mid span deflection to 2.835 mm. In the steel case, a change in prestress from 100 kN to 300 kN resulted in a change of computed mid span deflection from 2.843 to 2.827 mm. Computed mid span deflections in the equal area CFRP case varied from 3.603 to 3.577 mm. Changes in mesh size were performed to assess solution accuracy. As the idealization of the cable-strut subsystem by the model presents equivalent spring elements, the results presented herein are dependent on the assumptions stated and should not be construed as ANSYS results or experimental results for the complete system. Trend analysis and model improvement are the primary focus of the model; design conclusions for a particular prototype would require experimental results coupled with a complete, geometrically correct finite element model.

Keywords: beam–string structure; carbon-fibre-reinforced polymer; steel cable; finite-element analysis; static performance; prestress sensitivity; load–displacement response; reduced-order modelling; mesh verification.

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1. Introduction

Design of long span structures requires adequate control of deformation and stability while optimizing the amount of structure required, which includes material, system complexity, and demands for inspection and maintenance. Beam-String Structures (BSSs) are recognized as an innovative long span structure type. A BSS consists of a relatively stiff upper beam and a lower tension member (or string) and a system of connecting struts. In BSSs, the upper beam carries compression, and the string acts to balance upward and prestresses the upper beam. Thus, the interaction between the upper beam and the string induces a system of equilibrium, and a coupling of the compression and tension elements. BSSs provide an efficient means for load path systems, but the response of the structure depends on multiple design variables and system constraints. As the coupling of the compression and tension elements of the system is integral to the overall system stability, consideration of the strain and prestress of the system is important to understand and evaluate the overall structural behavior (Xue & Liu, 2009).

1.1 Background and motivation

Steel cables are established as established as tension elements in roofs and bridges. Other cable-supported structures use other metal cable types such as aluminum or stainless steel. For these reasons, steel cables are used as reference materials. Steel cables have an established and well-documented history. Steel is affordable and has a high elastic modulus. Additionally, steel has high ductility and is easily fabricated. Steel cables have well-developed means of anchorage. Steel cables, like other metals, are subject to corrosion, especially when adequate corrosion protection and maintenance are not provided. Like all materials, steel has a limit and a lifecycle. The limits of steel cables, along with other consideration, lead to the development of other materials as potential replacements for steel cables (Meier, 1992; Yang et al., 2020).

1.1 Background and motivation continued

CFRP refers to a family of fiber-reinforced polymer composites in which the carbon fibers are the principal, if not the only, source of longitudinal tensile strength, and the matrix binds and protects the fibers. In cable products, the fibers may be formed to a rod, or integrated in the form of parallel, or grouped, cable or tendon configurations. The effective properties of a cable are the result of the choice of fibers and matrix, their relative volume, the quality and uniformity of the matrix, protection of the surface of the cable, the configuration of the cable, and the end anchorage. As a consequence, it is not appropriate to ascribe a given magnitude of modulus or strength to a “CFRP cable.” Design-related information is typically contained in a product data sheet, and product-specific test certificates are required for the more formal assignment of structural demand. A number of studies highlight benefits of CFRP cable systems, most notably high specific strength, corrosion resistance, and light weight. Limitations and shortcomings of CFRP cable systems are lack of full-scale structural test and field experience, anchorage and transverse concerns, and higher cost (Wang et al., 2015, 2018; Yang et al., 2020).

1.2 Problem statement

The problem in engineering is not limited to evaluating if CFRP cables have a greater ultimate tensile strength than steel cables. Replacing a cable affects the axial stiffness of the structure, the ratio of cable to beam stiffness, the strain required to generate the desired prestressing force, the self-weight of the cable system, the forces transmitted through struts and joints, and other things. If equal area is considered, the CFRP cable, which has a lower modulus of elasticity than the prestressing steel, will extend more for the same load level.

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If equal rigidity is considered, the difference will be reduced, but this will have an impact on the mass and strength of the cable, the dimensions of the anchorage, and the cost. Equal prestressing force does not always mean equal prestressing strain, and equal external loads do not always mean the same thing. For equivalence, a number of parameters including the shape of the structure, where loads and supports are located, and other design considerations, must also be equal.

1.3 Research gap

Research on BSSs has focused on various aspects including numerical analysis, modeling and testing, and optimizing prestress. Other studies have dealt with the service and ultimate load conditions of BSSs. Examples of research pertaining to other fields like cable reinforcements made of CFRP have been largely field-dependent (i.e. site investigation, fixity, modeling, and experimental) and have included such areas as materials, structures and systems, and field practice. While research and experience in various fields related to BSSs are complementary, they cannot be regarded as substitute/replacement research. An experimental study on the prestressing system of a BSS provides useful information on modelling and other aspects of BSSs, and a study on the tensile strength of a CFRP cable pertains directly to that field; an anchorage test, on the other hand, provides information on the local load-bearing system of the cable. In the absence of direct complementary research, a combination of relevant research and field practice will form the basis for comparison.

1.4 Aim, objectives, and research questions

The aim is to develop a methodology to assess the static performance of a CFRP beam-string system (BSS) in a consistent and substantiated manner. The methodology will provide the means to integrate an assess the overall performance of a CFRP and steel BSS and enable comparison of conceptual designs of BSSs. From a practical viewpoint, this study will achieve its aim through the attainment of its goals (i) and (ii) which comprise the development of a CFRP BSS and a finite-element analysis for the assessment of the static performance of the BSS. Further, for the purposes of the assessment of static performance of a BSS, this study will provide useful preliminary information for other pertinent fields (i.e. Foundation Engineering and Economics) which, however, will require further research and analysis.

1.4 Aim, objectives, and research questions continued

It is proposed to examine the following questions: (i) Determine steel-cable and CFRP-cable models, which are analogous and comparable in terms of geometric configuration; (ii) Develop a strategy for reproducing the physical and geometrical characteristics of the cables in the models; (iii) Assess the response quantities for a static case (i.e. load vs. deflection response, beam and cable stresses and forces, etc.); (iv) Determine a process for verifying models by comparing models' outputs against prototype measurements; and (v) Determine the information required to allow the authors to recommend a specific design. The research questions are: (i) How does the choice of cable material result in differences in the static response? (ii) What happens to the static response if the effect of axial rigidity is included? (iii) How do displacements and distributed forces, if any, in the models, vary with prestress and other parameters of the model? (iv) For models which are compared to experiments, what are the best model outputs? (v) What design and analysis rules allow development of a sufficient case to support a recommendation?

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1.5 Contribution and scope

The core contribution of the study is an analytical framework to differentiate between equal-stiffness designs and equal-geometry substitutions, and define a staged finite element methodology for analyzing the static response of a given structure. The authors have indicated that ANSYS would be their preferred environment to perform a full-system simulation using BEAM188 for beam element formulation and an appropriate link/cable element for the string. The authors, however, have performed a comparative analysis using a modified version of Python, with Euler-Bernoulli beam elements and spring elements. Consequently, the reported results are based on a comparative analysis of the authors' modified version of Python and not based on a full system simulation using ANSYS. The Python based numerical model only captures the overall stiffness of the cable system and neglects the detailed geometry of the cables, struts and anchors.

2. Literature review

Literature relevant to this comparison is divided into four main areas. These areas include mechanics and experimental studies on BSS; the longitudinal and transverse behavior of CFRP cables; the performance of composite and steel tendons; and finite element analysis and anchorage of tendons. Differences between these areas are important. A system may show elastic behavior globally and still fail because of a local condition. Conversely, a cable with high tensile strength may have no benefit if the cable lacks stiffness in the axis and is used in a region that is too large. Literature supports comparison at the system level, and not at the level of individual properties.

2.1 Beam–string structural behaviour

BSS is a hybrid prestressed system consisting of upper and lower cables connected to a central load carrying beam via a series of struts. Prior to the application of any external loading, BSS is in a state of internal residual force. Depending on the system geometry and support conditions, the state of residual force may cause the upper beam to deform in a cambered shape. Under the effect of external loads, the system may deform in a different fashion than expected from an analysis using small deflection theory. A small deflection analysis, if applied at all, should be limited to the initial state of the system.

2.1 Beam–string structural behaviour continued

Xue & Liu (2009) performed a study on design optimization and experimental behavior of a BSS, based on the case of Shanghai Yuanshen Arena. They studied the behavior of BSS using ANSYS analysis and scale model tests to study tensioning behavior and to assess serviceability and ultimate load conditions. They focused on the effect of the rise to span ratio of the beams, cross-sectional area of the beams, area of the strings, and the level of prestressing. They noted that the behavior of such systems is highly non-linear, and that from the analysis perspective, it is more appropriate to assume that the system is in equilibrium due to the force number rather than the system is in equilibrium as a result of the cables being fully tensioned. Their study provides a useful insight on the limits for practical design of steel BSS. However, their findings should not be translated to BSS made of other materials such as CFRP.

2.2 Role of prestress

Prestressing serves two purposes. First, it sets or establishes a particular configuration of the system. Second, it reduces the amount of deformation due to permanent loads. Prestressing a cable increases the geometric

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stiffness of the system and influences the force distribution of the system. Too much prestress serves no benefit and may cause greater compression in the supporting beams and increase unfavorable camber in the system. Undesirable camber may also indicate that the limits of systems stability are being compromised. Like all design variables, prestressing force should be kept within limits, and the actual force should be measured and/or checked during installation. The tolerance in the force should be accounted for, and loss in the anchorage should be considered as well. The target force should be defined for a particular case.

2.3 CFRP cable material behaviour

CFRL is strongest in the axis of the fibers. Tensile strength and stiffness are in the axis of the fibers, and the matrix controls the transverse and shear stiffness and strength. Since the fibers are aligned with the axis of load, a CFRP cable, for example, in a tensile load, can be represented as a long-term orthotropic structure. It may be adequate to represent the cable element as an orthotropic structure to capture the overall behavior of the element. However, to represent the behavior of the anchor zone, transverse loading, shear, fibers splitting, and matrix cracking may govern the behavior. Wang et al. (2015) reviewed the use of CFRP in cable systems and noted that anchorage is a significant issue in the use of CFRP in cable systems. Mechanical and chemical anchorages are the two major classes of anchorage systems.

2.3 CFRP cable material behaviour continued

CFRP cables exhibit approximately linear elastic behavior in tension, with some products exhibiting construction-related nonlinearity. The test setup can also affect the response of the cable. Similar to steel, a CFRP cable, upon loading, will not exhibit a large yield plateau. Therefore, unlike steel, a CFRP cable should not be assumed to carry local stresses by yielding and redistributing them to other areas. Cables and their attachments should be designed such that the cable only carries the loads for which it is intended. The design load for a cable should account for a reduction factor and other considerations related to the environment, the length of time a load will be carried, the variability in the manufacturing process, and the margin of safety. Rafieizonooz et al. (2024) also note that similar considerations must also be made for composite and steel prestressed tendons.

2.4 Steel cable material behaviour

Compared to other material construction CFRP cables, the behavior of steel cable can vary depending on the specifics of the construction. Longitudinal elastic modulus of prestressing steel can be considerably higher than other materials. Like other materials, the behavior of steel under load can be modeled using an elastic-plastic law, but for practical designs and analyses, steel can be assumed to be linear elastic and ideal. Compared to other materials, steel possesses high ductility. This ductility, however, may be reduced due to failure of the cables due to fatigue, corrosion and material wear. Like all other materials, the behavior of steel, and the models used to describe them, are subject to constraints. The development of a constitutive relationship should take into account the shape of the steel member (i.e. solid bar, wire rope, strand, etc.). Steel may be an attractive material for tension members, as it resists fatigue and is relatively ideally behaved; however, the effects of time, environment and other loads should still be incorporated into the design.

2.5 Comparison bases and equivalence

Equivalent criteria must be defined in order to make valid comparisons. In equal-geometry comparison, both models have the same nominal cable area and geometry. This comparison provides insight regarding the

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effects of changing cable material on a cable-stayed bridge, while keeping other elements of the system fixed. Equal-geometry comparison does not balance other elements of the system, e.g. axial stiffness and capacities. Thus, for this type of comparison, the cables must be modeled as E_CFRP and E_steel, where the subscripts represent the materials, in order to set E_CFRP = E_steel. This comparison gives insight regarding systems where both cable elements maintain the same initial axial stiffness. This comparison does not consider other design elements, e.g. mass, tensile resistant, cost, anchorage.

2.5 Comparison bases and equivalence continued

An idealized straight cable segment is subjected to axial extension $\Delta L = NL / (EA)$ where N is the axial load, L is the reference length, E is the modulus of elasticity in the axial direction, and A is the effective load-bearing area. For CFRP and steel cables, the equivalent cross-sectional area (A) is used. For the scope of this example, if the steel cable has a higher longitudinal modulus of elasticity (E) than the CFRP cable, the CFRP cable would extend more than the steel cable. The complete global BSS response is more complex, as cable extension affects other elements such as strut behavior, beam deformation, and prestress. Therefore, the axial extension equation presented here should be viewed as a case-frame clinical judgment (CFCJ) aid, not to replace a complete system model.

2.6 Published CFRP cable research

Studies on CFRP cables for cable-stayed bridges report potential advantages of light weight, corrosion resistance and high tensile strength, and identify concerns of transverse weakness, long term behavior, fatigue and lack of full scale projects (Wang, et al., 2015; Wang, et al., 2018; Yang, et al., 2020). While literature relevant to the study of cable mechanisms and system level force transfer is bridge related, a BSS and a cable-stayed bridge have fundamental difference at the systems level. Thus, conclusions regarding the behavior of CFRP in a BSS should be made at the level of fundamental behavior of materials instead of by analogy to system level behavior.

2.7 Research need

The available literature suggests that there are two gaps. The first is in the known, validated, global, static responses of full scale steel BSSs. The second is the use of CFRP in BSSs as the primary tension system. It should be noted that the absence of evidence for CFRP in BSSs does not necessarily indicate a failure of this system. The absence of evidence could be due to an under-defined framework. Bounds should be set for the framework of this analysis. The bounds could take the form of a verifiable structural test and the validation of CFRP constitutive models against the specified cable product, the sensitivity of the model to the assumptions made regarding cable anchorage and rigidity, and the effects of prestressing. It should be noted that a framework could be set to verify CFRP-BSSs. However, in order to verify full material substitution, it would be necessary to build and test full scale CFRP BSS prototypes.

3. Research methodology

The research approach takes a similar route as the source proposal, comprising a numeric analysis and field testing. It involves constructing a pair of structural models having identical global geometry, beam/struts and supports, and load cases and sequence of analysis, and comparing cable models as required. Sufficient description of the methodology is provided to enable its implementation on the ANSYS APDL platform. Details of syntactical and structural similar elements and their combinations shall be ascertained from the

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software and platform to be used. The analysis and the input data shall be such that the methods and means to reproduce the analysis are defined.

3.1 Study design

The main study comprises a numerical comparison of paired models. The smaller of the two models is a representation of a cable model made of CFRP and the other is a steel cable model. It is more appropriate to use the actual geometry and dimensions of the structures designed and/or tested, and not arbitrarily select a span and dimension of members. It the proposed structure and members are not completely defined, the geometry to be modeled and represented shall be defined as an assumption, and the model shall not be shown to represent the actual structure proposed. The models are subjected to the same sequence and history of loadings.

3.1 Study design continued

The modeling log captures definitions of primary output quantities, points of comparison, load cases, prestress range, mesh convergence, validation data, and other criteria used to disregard a failed solver run. This decreases the risk of only examining material comparisons and levels of prestress that favor the desired result. The primary load case of the analysis is to be stated in the report; other cases may be presented in an ancillary fashion. The study is deterministic; however, if the effect of geometric or material uncertainty is being studied, then a series of repeated solver runs may be modeled as a representation of experimental uncertainty.

3.2 Geometry and structural idealization

The geometry of the model must include all elements of the structure of interest (e.g. spans of beams, cables, struts, connection types, constrains, and support conditions, etc.). The type of BSS being modeled will depend on the nature of the structure being idealized. If a beam and supporting lateral BSS is idealized and the transverse stability and out-of-plane (OOP) BSS of the structure governs the behavior of interest then a planar BSS model may represent the prototype. Otherwise, a 3D model must represent the BSS. Cable and strut members must be idealized using elements and mathematical models that represent their behavior and conditions.

3.3 Geometry and structural idealization continued

The proposal notes that ANSYS BEAM188 and LINK10 are the modules for computing the behavior of beams and tension systems respectively. The computations presented in this paper were performed using Python codes based on the finite element method, and using NumPy and SciPy. The code solves systems of linear algebraic equations. The BEAM188 and LINK10 modules are not the solvers for the numerical results presented in this paper. The numerical model uses Euler-Bernoulli beam elements and horizontal and vertical degrees of freedom at each node. Vertical degrees of freedom are satisfied with spring elements. Global vertical stiffness of the system is represented by vertical spring elements. Each spring is positioned at a quarter span of the element. Each support is free to rotate. The model idealization is a global model and does not describe local behaviors. The model provides a reasonably good representation of the vertical stiffness of the structure. It is intended to complement the proposed full model using BEAM188 in conjunction with tension capable cable elements and links.

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3.4 Material properties

Steel cable modulus was assumed to be 200 GPa and density to be 7,850 kg/m³ and for CFRP, longitudinal modulus was assumed to be 150 GPa and density to be 1,600 kg/m³. These values are representative of the modelling assumptions and are by no means the certified values of a commercial cable. The equal-area cases consider an effective area of 600 mm² for each material. For the case equal-axial-rigidity, an effective area of 800 mm² for CFRP is assumed, which leads to EA value of 120 MN for both the 200 GPa, 600 mm² steel cable and 150 GPa, 800 mm² CFRP cable. Span of the considered beam is 12 m and the vertical geometric offset used for defining equivalent inclined segments is 1.5 m. Other assumptions include E = 200 GPa, I = 8.0×10^{-4} m⁴, and uniformly distributed load of 10 kN/m. Baseline prestressing force is 200 kN. The idea is to provide a numerical illustration of the concept and define an initial, simple, yet realistic example. Final design will be based on actual product drawings, prototype values and certified properties.

3.5 Material properties continued

A single value of modulus for CFRP should not be considered generic. Published cable systems include various fibers and resins, cable processing, fiber and bundle alignment, and architectural cable forms. A true representation of nominal steel modulus should include the effects of constructional stretch, cable assembly stretch, and the interaction of all the components of the system. For the purpose of analysis and design, the effective axial stiffness should be determined by the representation of the cable system, whether ideal or actual. Sensitivity analysis should not be restricted to arbitrary changes in the value of the parameters.

3.6 Boundary conditions and connections

The physical configuration of the system should be represented in the analysis model. Mechanical supports and joints should also be modeled. The idealization of a test rig as simply supported should be justified by the actual configuration of the test rig. If the configuration of the system does not allow for rigid body movement, the analysis and design model should not restrict movement. Analysis models should address eccentricity of the system, and its effect on the overall response, especially when it violates the assumptions of the idealization. Connections should be justified by the details of the structure. Ideal connections should be identified as simplifying assumptions.

3.7 Prestressing sequence

Prior to the application of the main service loads, the structure should be analysed and depicted in the model as it would be in the final or 'prestressed' state. Sequencing the analysis as follows, may be beneficial: Define and position the elements and constraint; determine the effects of self-weight and other permanent loads relevant to the construction case; prestress the cables to the determined initial strain, stress and/or temperature equivalence; attain equilibrium; and superimpose the remaining service loads. The aforementioned sequence illustrates a logical preceding construction action. It is essential to understand the behavior of the tensioning system to accurately determine the prestressing force. This may be achieved using a force-controlled or a displacement-controlled method. A force-controlled method would be appropriate where it is necessary to maintain the cable at a given force, and a displacement-controlled method would be appropriate where it is necessary to limit the elongation of the cable. The reported prestress may be the force of the jack, the force locked into the system, or the final force after the jack was removed and losses occurred.

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3.8 Prestressing sequence continued

The effects of loss of prestress should be included in a long term design claim. For a short term comparison, loss of prestress may be ignored in the first analysis. For such an analysis, it should be assumed that all losses of prestress occur and be clearly indicated. A more complete model should consider loss of prestress due to the effects of material, fabrication, erection, and other causes, as well as allowable slip, stress relaxation, and effects of changes in temperature and humidity. It should be noted that the behavior of relaxation of steel and that of CFRP may not be the same and, therefore, an arbitrary percentage loss may not be valid. In considering the behavior of a structure in a short term condition, long term behavior may be considered as a separate case.

3.9 Loading scenarios

The model should consider a representative condition for dead loading, a representative condition for permanent loading, and a representative condition for service level variable loading. The nature of the loading should be consistent with the behavior of the load on the structure and with the nature of loading in the physical test. If the prototype test contains point loads, the model should place point loads in the test and simulate the behavior of loads in an adequate fashion rather than using uniform loads. Loads should be increased in a manner such that the response may be determined and changes in the behavior of the model and convergence may be determined. In the model, ultimate loading should be assumed only if failure of the material or of connections is considered.

3.10 Nonlinear solution and convergence

When changes in the structural equilibrium require analysis of geometrical nonlinear effects, this option should be chosen. The solution of nonlinear equilibrium problems converges to a fixed point using an iterative technique (e.g. the Newton-Raphson method). However, the convergence of a particular nonlinear problem is affected by many factors such as the formulation of the elements of the structure, the type of loads and restraints, and the properties of the materials of the structure. The analyst should verify that the problem was solved using the forces and displacements, to the tolerances set by the solver. The type of load increments and the strategy used in automatic substepping should be reported. Investigating causes of failure and documenting unstable and failed cases of the solution process is preferred. Convergence of a solution, however, does not always indicate that the structure behaves physically in a correct manner.

3.11 Mesh convergence and verification

The discrepancy of quantities indicating the primary response of the system, determined by the analysis of a structure divided into a certain (generally large) number of elements, and quantities determined by analyses of structure idealized with successively smaller numbers of elements, is defined as a mesh-convergence study. Mesh refinement is generally more important in regions of a structure that contain changes in loading and geometry. In line-element models of structures, three-dimensional states of stress can never be determined with an arbitrary refinement of the line elements. Convergence should be assessed in terms of strains, stresses, forces, and displacements. The midspan deflection of a beam should be considered, as well as the max. cable and beam forces. Numerical verification should include checks of force equilibrium, reaction balance, and sign of cable tensions.

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3.12 Output variables

The main output variables of this model are: (a) vertical displacements at beam midspan and quarter-span points; (b) the entire load – displacement curve for the loaded beam; (c) cable segments' axial forces and average cable stresses; (d) beam shear and bending stresses, and bending moments; (e) axial forces in struts and the corresponding limits of stability; (f) support reaction forces; and (g) the final condition of prestress and the state of the system at various construction stages. For this model, the force and effective area of the cable should be used to compute cable stresses. peak stresses at joints in an element mesh should not be used for design without additional analysis and interpretation. Results should be obtained at the same physical locations for both material cases.

3.13 Comparison metrics

Let the absolute difference for any quantity y be denoted by $\Delta y = y_CFRP - y_steel$. The relative difference may be denoted by $100(y_CFRP - y_steel)/y_steel$, where steel is non-zero, and the relative difference has a clear interpretation. For the comparison of stiffness, the secant stiffness may be computed as $\Delta P/\Delta\delta$ over a load interval of interest, and the interval must be the same for both models. For verifying the prediction, the difference between the prediction and the corresponding observation may be expressed as $e_i = prediction_i - observation_i$. The relative difference may be expressed as $100e_i/observation_i$, where observation_i is non-zero. Reporting the mean absolute difference, root mean square difference, and bias should be accompanied by the number and range of observations. Percentage differences may be reported. A single percentage difference should not be reported unless the comparison limits are also reported.

3.14 Sensitivity analysis

Sensitivity is assessed through the variation of the prestress parameter from 100 to 300 kN in steps of 50 kN, while fixing the 10 kN/m distributed load, the beam dimensions, span, spring and support conditions. Steel and CFRP behaviors were considered, with a cable area of 600 mm2, and CFRP with a axial stiffness of 800 mm2. Displacement at the midspan of the modeled beam was computed, and results were interpreted with respect to a reduced order model implemented in Python. This analysis is based on a single variable, and is not a study of uncertainty or a full nonlinear analysis. Results are in section 5.3 and table 3, and should not be extrapolated.

3.15 Experimental validation protocol

A validating test consists of providing measured data from physical systems, and defining the systems' geometry and support conditions, material and prestressing levels, and loading cases. A steel BSS benchmark (e.g., Xue and Liu 2009) would allow the user to assess the fidelity of the user's structural formulation to represent and capture the general behavior of a steel BSS. Measured data from the benchmark should be used for comparison, and not a re-constructed, or surrogate data, version thereof. The numerical model and the benchmark should be congruent with respect to loading, and the positions of measuring systems. Adjusting parameters of the model based on measured data should not be undertaken for the purpose of claims of model validation. If adjusting parameters is necessary, the dataset should be partitioned into a calibration and an independent validation subset.

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3.16 Data management and reproducibility

The ANSYS input files, solver versions, material data, geometry, loads, mesh, convergence logs, and raw measurement data need to be retained to support reproducibility. The results workbook should contain the observed data along with predicted values. Units, location, loads, sources of uncertainty, and/or metrics should also be included. The workbook should not contain values that are expected, but not measured. Figures should be generated from the data. Each table should be annotated to indicate the type of data (literature, model, or experiment). If a table includes illustrative data, that data should be clearly marked. Other data should be considered when forming conclusions. This level of data management should be followed when incorporating the planned work of the proposal and additional literature.

4. Analytical basis for interpreting static response

Generally speaking, the nonlinear behavior of the BSS can be expressed as $R(u, \lambda) = F_int(u, p, m) - \lambda F_ext = 0$, where u represents the displacement, F_int and F_ext represent the corresponding internal and external loads, and p and m represent the prestress and material properties of the system, respectively. λ is an undetermined load parameter. In a geometrically nonlinear analysis, the internal force is determined by the current material behavior and the current geometric state of the system. Considering the equilibrium of a structure and linearizing the equations at the equilibrium state result in a relation of the form $K_T \Delta u \approx \Delta F$, where K_T is the tangent stiffness of the structure. In a geometrically nonlinear analysis, the effect of prestress is purely of a geometric nature; therefore, changing the geometric state of the system alters the response to external loads. For example, in the case of a BSS with unchanged material properties, the displacement of the structure under a given load could change if the ratio of the cable to strut prestress is altered.

4.1 Cable axial stiffness and extension

In the case of an ideal prismatic cable, under tensile loads, axial rigidity is EA and the extension under a constant axial load is given by $\Delta L = NL/EA$. This relation can be used to verify the equal area and equal rigidity comparisons. With respect to equal area, if E is not equal, difference in axial extensions for the same load will be observed. If equal axial rigidity is considered, an ideal extension will be achieved for the same load and length. However, other aspects of the global behavior of the structure will be adjusted, e.g., self-weight of cables, prestress strain, limits of material, compliance of anchors and geometric constraints, etc. The equation illustrates that stiffness and ultimate strength of the cable material are separate properties, and the comment “CFRP is stronger, thus the deflection is less” is incomplete.

4.2 Beam–cable interaction

In this type of structural system, beam bending and deflection share the external load with the cable system. As the beam bends, struts rotate, and cables stretch. The cable system responds to changes in geometry and decreases in distance, and the cable force changes and increases. As the geometry of the system changes and as the length of the cable changes, the cable force changes and increases, and the beam bending stiffness becomes less (more flexible). In a truss, the stiffer the cable, the more force it takes, and the greater the incremental change. The actual force distribution is a function of the stiffness of the entire structure. In this case, the material modulus of the cable has no relationship to the force in the cable, and the stress in the beam. The finite element model should represented the integration of beam, strut and cable system.

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4.3 Deflection and serviceability

Serviceability of a structure is governed by limits on the displacements of the elements of the structure. These limits may also include the prestress-induced camber and other service load effects. Some effects of service loads may allow large deflections but not exceed limits of serviceability. When limits are governed by serviceability, the effects of all loads of the system including the loads that induce camber, the service loads, and other loads must be considered. Effects of service loads may result in large deflections that exceed design limits. Reports of the effects of service loads should be interpreted carefully. The limits of serviceability must be determined from governing design requirements and not based on judgement of the results of a structural analysis.

4.4 Stress and force distribution

The axial stress on a cable is estimated to be N/A in an idealized axial model. This stress is an average nominal stress and can cause significant damage in the cable, especially near the anchorage. This damage is not accounted for in this model. For CFRP, in order for the model to account for the efficiency of the anchorage and the cable product, the design stress should be N/(A f_u). If the ultimate strength of the cable is f_u, and the design is based on the appropriate strength, then N/ (A f_u) can represent the design stress. In steel, consider serviceability, yield, and ultimate strength. When a stress singularity exists, e.g. at a simulated joint or support of a beam, other factors such as material toughness should also be taken into account.

4.5 Self-weight and specific performance

Due to its lower density, CFRP can, in some cases, lower overall structure self-weight; however, the reduction will depend on the ratio of the mass of the cable with respect to the other component masses of the structure. If the mass of the cable is significantly large compared to the other component masses of the structure (i.e. the mass of the beam and struts is smaller), then the overall structure self-weight will decrease by less than the mass of the cable. The self-weight of the cable should be computed using the formula density x effective area x length and should be added to both models for consistency. A reduction in the self-weight of the cable will reduce the overall structure self-weight; however, the support reactions will also change. These should be determined from the model and not inferred by density ratios.

5. Comparative static response

Static behavior is a result of the interaction of a number of factors which include cable geometry, support conditions, applied loads, member constraints, and prestress. Comparison of models based on these factors may yield different outcomes. Depending on the basis for comparison, different design issues may be apparent. Comparing models based on equal geometry may be different from comparing models based on equal rigidity or equal resistance. This analysis will identify the more relevant outcome and implications for the case being considered.

5.1 Equal-geometry comparison

In the equal-geometry comparison, the model takes the value for beam, span, supports, loading, prestress parameter, and cable area (0.6 m2) as the same for steel and CFRP. The calculated midspan displacement for the load case of 10 kN/m was 2.835 mm for steel and 3.590 mm for CFRP. The value for CFRP is 0.755 mm greater than steel, an increase of about 26.6% from the steel displacement value. The maximum recovered

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beam-moment value for the steel model is 31.27 kN·m and 38.24 kN·m for the CFRP model in the reduced order case. This variation is due to the loss of the equivalent support value for CFRP, compared to that for steel, for the given modulus of CFRP. The moments are from the outputs of the idealized beam models, and do not represent observations from the tests or complete BSS (bridging steel solutions) design scenarios.

5.2 Equal-rigidity comparison

For equal axial rigidity, the area of CFRP is increased to 800 mm2, making the EA equal to that of the steel model, i.e. 120 MN. The calculated midspan displacements were 2.835 mm in both cases, and the maximum recovered beam-moment magnitudes were 31.27 kN·m in both cases. In this case of equivalent axial rigidity of the CFRP and steel models, the results are as expected, since the other geometric parameters are the same. However, this should not provide any confidence that complete BSS (bridging steel solutions) for steel and CFRP would exhibit the same behavior. Other factors, including the cable configuration and self weight of the BSS, anchorage compliance, and the thermal behavior of the CFRP and BSS connections, are not represented.

5.3 Prestress sensitivity

The prestress level was set to 100, 200, and 300 kN. For each case, a 10 kN/m uniformly distributed load was applied. It was found that for the case of the steel equal-area prestress, the mid-span deflection reduced from 2.843 mm at a prestress of 100 kN to 2.827 mm at 300 kN. Therefore, a reduction of 0.56% was observed. For the case of the CFRP, equal-area prestress, the deflection reduced from 3.603 mm to 3.577 mm at a reduction of 0.70%. It is important to note that an equal-area prestress condition provides small amounts of geometrical stiffness relative to axial stiffness. Therefore, for this case, a small change in cable force is expected. These results do not provide any insight to a BSS problem where non-linearity is present and small changes in cable forces may lead to a large change in the shape of the system.

5.4 Stress and force distribution

A useful analysis approach separates a cable's prestressing force from external load-induced forces. The total cable force is the locked-in force plus the external load force, minus any loss or seating effects. Differences in final force may be caused by differences in either the prestressing stage or the external load case. The same holds for displacements: displacements due to service loads need to be measured from the prestressed equilibrium configuration. Camber is taken with respect to the non-prestressed configuration. Displacement and force differences in the steel and CFRP cases are to be evaluated with respect to the same prestressing level. This is especially relevant because the same prestressing force may result in differing cable strains in the steel and CFRP cases, due to differences in axial stiffness of the cables.

When evaluating stresses, certain assumptions associated with the finite element model need to be taken into account. For beam elements, the stress is recovered in the sectional forces, and the element may have a non-uniform stress state. This is not the case for a cable or link element. A nominal average stress in a cable element is to be interpreted as an element stress, and not as a peak fiber stress, for example. If the peak fiber stress governs the design of a cable element, then a more refined, local analysis, modeling both the contact and material and support elements, needs to be performed. This is especially relevant for CFRP elements, as a local failure may occur in CFRP elements, even though the longitudinal fibers may be stressed below the tensile resistance of the cable.

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Comparisons should be made between cable and beam responses to each load case. The max values for each should be shown and correlated to the relevant load case. For CFRP, the comparison should be made using a specific product-level tensile strength. The model should not assume that the anchorage stresses are average. For steel, the model should show the effects of yielding and beyond, if the model allows. If the model predicts that the Steel beam will yield, and the modeling of the beam stays elastic, the model cannot show why the beam failed. However, if failure is assumed to be from loss of anchorage, the model would be permitted to show that.

5.5 Model assessment and experimental validation

A direct comparison of the BSS model for steel against the experimental and numerical studies of Xue and Liu (2009), is possible given that the original published case studies detailing their work, including the specimen geometry, loading conditions and observations are reproduced. Such a comparative study has not been done in this analysis. Consequently, no prediction error analysis has been performed relative to their data. In general, comparative studies are articulated in terms of completeness and not absoluteness. Thus, as noted in the Steel BSS model case studies, a reasonable representation of the key physical parameters, including span and/or the nature of the loading conditions, is sufficient to merit a qualitative comparative study of the model, and the systems represented by the BSS. In the case of CFRP, lack of viable complete system benchmark tests, complete-system validation of the BSS model is warranted. It should be noted that validation of assumptions and models used to represent CFRP can be done using existing published studies.

5.6 Numerical results and verification

Baseline numbers for the steel BSS model are shown here. Displacements have been referenced to the unloaded or unconstrained state. The model is non-linear in displacements, but linear in loads for steel. As such, load-displacement relationship is expected to hold for each of the fixed prestress conditions.

Table 1. Baseline computed comparison at 10 kN/m and 200 kN prestress parameter.

Case	Cable E (GPa)	Area (mm²)	Midspan δ (mm)	Max |M| (kN·m)	Equivalent k per leg (kN/m)	Cable mass/length (kg/m)
Steel, equal area	200	600	2.835	31.27	7203.1	4.71
CFRP, equal area	150	600	3.590	38.24	5414.3	0.96
CFRP, equal EA	150	800	2.835	31.27	7203.1	1.28

Table 2. Computed midspan load–displacement response.

Load (kN/m)	Steel, equal area δ (mm)	CFRP, equal area δ (mm)	CFRP, equal EA δ (mm)
2.5	0.709	0.897	0.709
5.0	1.417	1.795	1.417

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7.5	2.126	2.692	2.126
10.0	2.835	3.590	2.835
12.5	3.543	4.487	3.543
15.0	4.252	5.385	4.252

Table 3. Computed prestress sensitivity at 10 kN/m.

Prestress parameter (kN)	Steel, equal area δ (mm)	CFRP, equal area δ (mm)	CFRP, equal EA δ (mm)
100	2.843	3.603	2.843
150	2.839	3.596	2.839
200	2.835	3.590	2.835
250	2.831	3.584	2.831
300	2.827	3.577	2.827

Table 4. Mesh refinement check for the steel equal-area case.

Beam elements	Midspan δ (mm)	Max |M| (kN·m)
4	2.8345	26.692
8	2.8345	29.816
12	2.8345	31.274
16	2.8345	31.066
24	2.8345	31.274
48	2.8345	31.274

Baseline results show that equal-area CFRP distributes stress more effectively than steel and leads to a smaller midspan displacement. Equal-area CFRP displaces less than steel under equal baselines. At a loading case of 10 kN/m, steel exhibited midspan deflection of 2.835 mm, and equal-area CFRP showed the same value. Equal-area CFRP displacement stiffness in the baseline case is computed to be 5,414 kN/m. Steel shows a value of 7,203 kN/m for the same case. In the baseline case, prestress in steel leads to a stiffness reduction, and if the baseline is reset, shear in steel increases, thus leading to deflection and displacement. Increasing the CFRP area from 600 to 800 mm² increases the rigidity of CFRP from 90 to 120 MN, and the equivalent stiffness of the spring is reduced, thus resulting in a mechanical consequence, as stated earlier in the case of equal-area BSS.

The computed mass of the cable for the equal-area case of 800 mm² CFRP is 1.28 kg/m, and 0.96 kg/m for 600 mm² CFRP, and 4.71 kg/m for 600 mm² steel. Sheaths, fittings, and constructional mass are neglected for this case. Therefore, the mass of the CFRP is significantly less than the steel, and a reduction in the cable weight leads to a significant mass savings of the system.

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The computed midspan displacement remains 2.8345 mm for all discretizations (i.e. 4, 8, 12, 16, 24 and 48 elements). The test mesh-sensitivity checks predict a trend towards a larger maximum bending moment as the mesh becomes coarser. According to the checks, the bending moment increases from 26.692 kN•m for a discretization with 4 elements to 31.274 kN•m for a discretization with 12 elements. The checks state that results from discretizations with 24 and 48 elements agree within three decimal places. The result from a discretization with 16 elements is 31.066 kN•m. The checks provide assurance that the reported displacement is stable, and that the maximum moment in cases with 12, 24 and 48 elements agree to the reported values. The checks do not prove that other responses (e.g. other loads, deformations) approach their limit state. The 12-element mesh is used for comparison to other cases, and because it represents the location of the springs. Ideally, the support and anchor points for the struts should be modeled as compliant; and, the struts, cable and joints should deform to vary their shape, length and position.

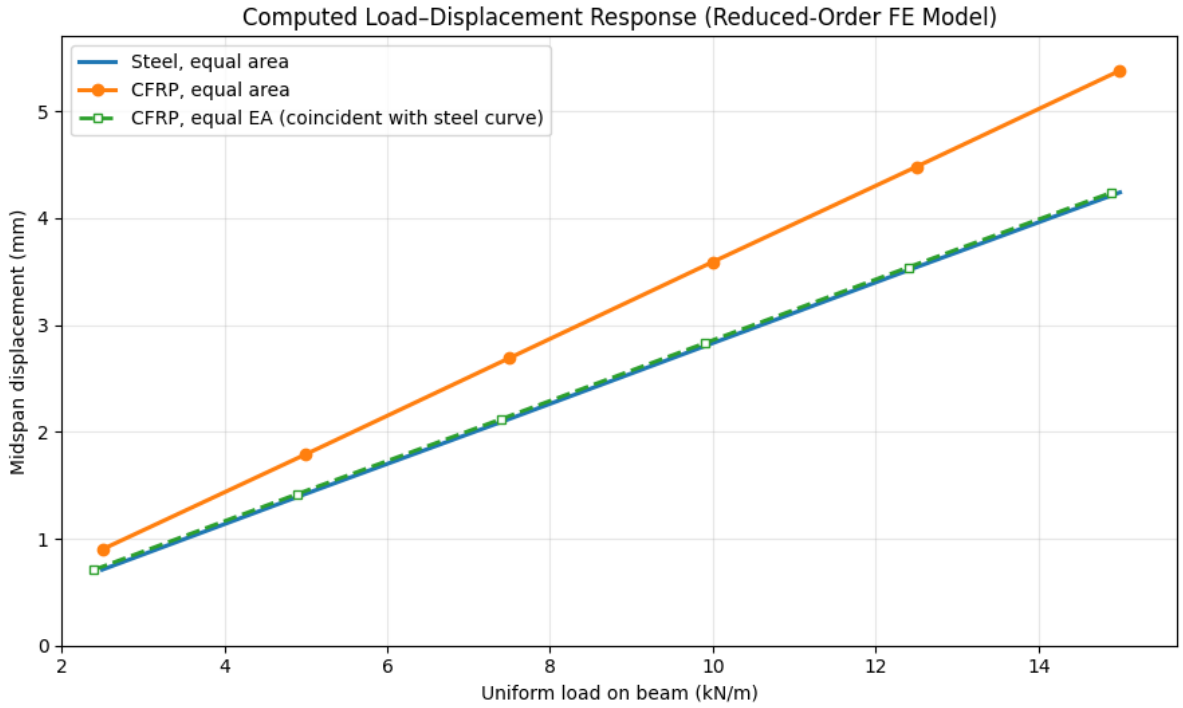

Figure 1. Midspan displacement against applied uniform load.

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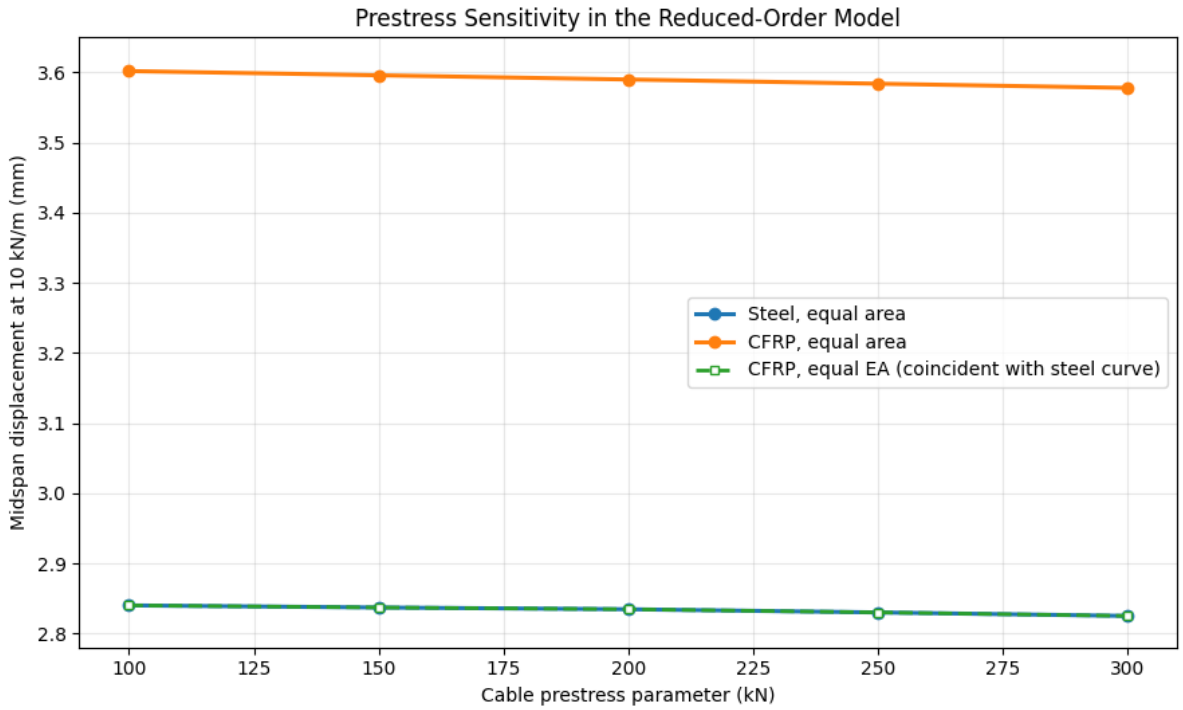

Figure 2. Computed midspan displacement as the prestress parameter varies.

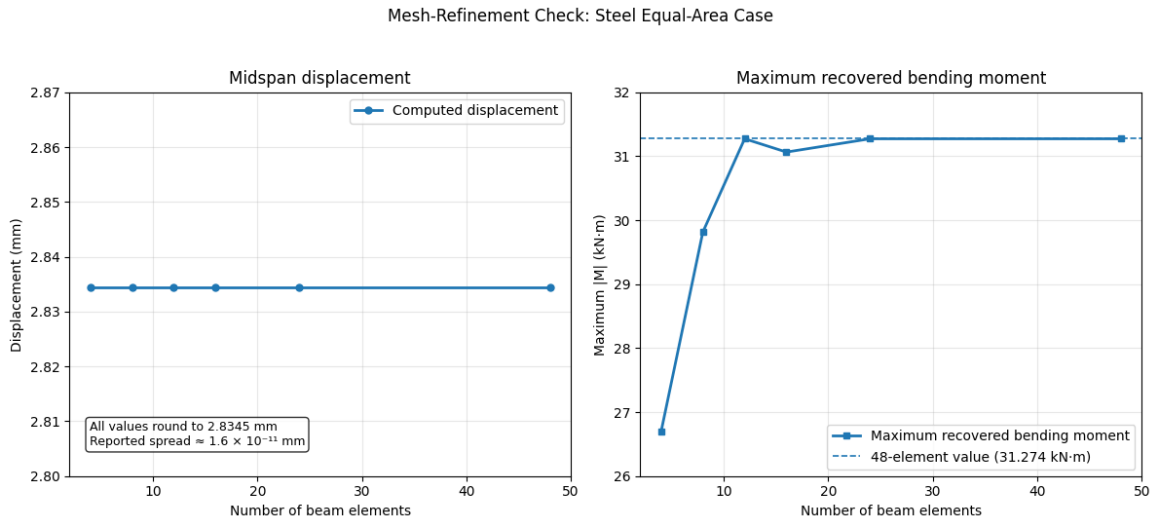

Figure 3. Mesh-refinement check for midspan displacement and maximum recovered bending moment.

6. Discussion

A reliance on numbers alone suggests that conclusions on global behavior cannot be determined from tensile strength and density. Considering equal-area cases, the lower assumed longitudinal modulus of CFRP leads to a higher equivalent cable-system tangent stiffness, which results in greater midspan displacement. Decreasing the assumed longitudinal modulus of CFRP would result in a smaller midspan displacement; however, changing the CFRP to match the EA increases the mass of the cable and increases the size of the

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anchorage. These results are limited to the idealization of the model and do not denote any conclusions on the superiority of the material.

6.1 Interpretation of equal-area results

In this case, the effect of different material properties on a given geometry are considered. The equal-area case involves determining the extension of a steel cable in combination with a cable made from the assumed CFRP product. If the CFRP product has a lower modulus of longitudinal rigidity than the steel cable, then a larger extension is expected. In a case of a balance of satellite supporting struts, the magnitude of the displacement will depend on the shape of the cable, other struts, and the layout of the system as well as the prestressing. It can be expected that equal area substitution will affect the service limit of the cable. However, the magnitude cannot be directly expressed. It is expected that the extension calculated will be less than that of the service limit of the cable. A more detailed study will justify the margin.

6.2 Interpretation of equal-rigidity results

With equal-rigidity comparison, EAs can be matched. However, there are other relevant differences in the structural systems. The cable's product architecture, including the type of anchor interface, can be different. The ultimate strength of the cable can be affected by differences in the cross-sectional area of the cable, which also impact the mass of the cable. If matching the EA requires a larger cross-sectional area of the cable, it may increase the specific weight of the CFRP. A larger cross-section may require a larger anchorage envelope, which also increases the size of the anchorage area. These may affect the detailing and cost of the system. The equal-rigidity case helps to identify differences that are primarily attributed to stiffness.

6.3 Prestress as a design variable

Prestress should not be viewed as an entirely unconstrained variable. In a design case, it affects several elements in the structure, including cable tension, bending stress, strut compression, and anchorage. It can also affect the camber of the structure. The objective of the design case may affect the optimal level of prestress. The effect of prestress should be analyzed and reported, especially the effects on the potential service limit states of the structure. A comprehensive treatment of prestressing and the effects of tradeoffs should be reported in a subsequent publication in the S5 series, which is focused on the design of reinforced concrete structures.

6.4 Anchorage and local load transfer

Anchorage is a subsystem of structural cracks and joints. The longitudinal tensile capacity of CFRP can be insufficient due to the introduction of transverse cracking, fiber splitting, local shear, and bond and slip failures. Wang et al. (2018) mentioned mechanical and bonded anchors as well as composite anchors and indicated that dependable anchoring is one of the main limitations of use of CFRP cables in cable structures. In a global BSS model, an anchor may initially be considered as an ideal bond. However, for the scope of this study, the simplification of an anchor as ideal bonding is not necessary and may be replaced with an algebraic spring. Local anchor stresses must be studied by separate analyses. The static comparison made in this study should not be considered as verifying anchorage. Testing of the anchors and providing a failure model is beyond the scope of this study.

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6.5 Material anisotropy and model adequacy

Treating CFRP as isotropic allows simplifications to the model, however, it assumes the load and displacement response of the CFRP is governed by the longitudinal direction. It is also assumed the model does not provide a means to represent transverse stresses. The proposal states that CFRP will be modeled with anisotropic linear-elastic behavior. It is also assumed that the steel elements will be modeled as isotropic, elastic-perfectly plastic. The solver should allow both of these representations. Cable elements, which provide an axial force-displacement relationship, reduce the required description of the material. This element will also allow the representation of force and displacement transformation along the length of the element. As with line elements, representing the deflection of a structure may require a significant number of these elements, however, local failure may require a representation with solid or detailed composite elements and interface properties.

6.6 Implications for design practice

The aim of this comparison should lead designers to make a reasoned judgement rather than to automatically substitute CFRP cables for steel. The judgement should be structured by the following: Select a CFRP cable with assured axial properties and an appropriate anchorage. Decide if the comparison is dominated by geometric aspects, stiffness or strength. Establish the required prestress and examine its effects on camber and all member forces. Assess if the limits on displacements are satisfied (serviceability). Make a judgment on the adequacy of anchorage and connections. Examine if the system achieves the required levels of durability, serviceability and fitness for purpose over its intended life, taking into account loads, usage and environment. Finally, check the design with tests. Examine if the structures diverge from normal design practice and if so determine the practice required for normal safety and adequacy of the structure (anchorage and connection, material, fatigue, serviceability, durability, etc).

6.7 Limits of transferring evidence from bridges

Evidence from built bridges sheds light on the behavior of CFRP stays including fatigue and anchorage. Evidence from bridges also shows the type and extent of the system response. However, built bridges and Boundary-Aided Strip Suspension (BSS) systems differ in geometry and load path. In a cable stayed bridge, loads on the deck are transferred to the pylon by stays that are inclined with respect to the vertical. In a BSS, loads on the beam are transferred to the string by prestressed members, and the loads on the string are transferred to the embedded anchors by struts that are usually horizontal. The role of geometric stiffness and the stiffness of a beam in relation to a cable is also different. Evidence from bridges is often used to construct plausible models of CFRP strands; this evidence is, however, usually insufficient to construct a case for the displacement capacity of a BSS. In cases where evidence from bridges is used to support a case for a BSS, the authors of the manuscript should acknowledge and explain these limitations.

6.8 Uncertainty and robustness

In cases where results from a test and a simulation are compared, the uncertainties of the measured test results and predicted simulation results should be determined. Measurement uncertainties of test results are due to factors including sensor alignment and calibration, zero drift, and load cell accuracy. The uncertainties of simulation results are due to insufficient element and mesh counts, and roundoff errors of the solver. These factors should not be lumped together to give an overall uncertainty of the simulation. Measuring the uncertainties of a simulation and of a test helps evaluate the main reason for a discordant result. A close agreement of a predicted and a measured result should not be the only evidence that a model is validated.

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The engineering decision should drive the uncertainty analysis. This means the analysis should not be reported in an ad hoc, purely statistical manner. Evidence of the difference in expected displacement between the two cable systems should not alone justify the choice of material based on serviceability. On the other hand, evidence of a stable difference in expected displacement between the two cable systems should be interpreted to justify the use of the more stable system to satisfy design requirements based on the checks for the strength and anchorage of the system.

Several parameters may be uncertain due to variation in the material, initial geometry of the cable, measurement of the prestress, compliance of the supports, and measurement of the displacements. Variation may also arise in the final geometry of the cable due to installation. A design should be based on uncertainty and sensitivity of the result, rather than a strict comparison. Epistemic uncertainty should also be considered when drawing conclusions. It is not always possible to quantify all sources of uncertainty. In these cases, variability should not be ignored, and design choices based on uncertainty should be validated by additional tests. Aleatory uncertainty should always be differentiated from epistemic uncertainty.

A small difference in expected behavior between two systems may be entirely due to variability in the systems and inputs. It may also be entirely due to an epistemic uncertainty, such as unknown properties of the anchorage. These variabilities should be analyzed in conjunction with expected behavior of systems to provide a complete picture of uncertainty.

7. Limitations

Conclusions are based on the assumptions of the models, as well as the constraints of the available structural data. Reliable numerical analysis of a prototype requires a set of geometry and material data for the cable and sheaths, a definition of loading and initial prestress, and a convergence of the finite element solution. A BSS with CFRP cables is tested against a given loading case by measuring the response of the system. Until such measurements and comparisons are made, the applicability of the framework to other designs remains to be established.

7.1 Model limitations

Line-element models of cable components tend to idealize cable elements as straight, fully-tensioned members. Joints in such models may likewise idealize connections as smooth and (relative) frictionless. Progressive failure and ultimate break-up of the CFRP cable, if modeled, requires implementation of and reliance on a proper and validated failure criterion. Steel-element models of cable components are likewise bound by the limitations of the defining constraints and assumptions. As stated earlier, geometric non-linearity of models do not justify consideration of time-variant and/or environmental effects on the system. Such behaviors are outside the scope of the model, and it would be improper to deduce information about such behaviors from the model.

7.2 Experimental limitations

Because a steel BSS test is not the same as a CFRP BSS test, the results of the former cannot be used to justify the global structural model of the latter. The substitution is not valid. During testing, multiple factors such as limitations of the testing equipment, manufacturing tolerances, cable bending, and support deflections may come into play, and may not be directly proportional to the geometric scale. It is important to consider the nature of the validation data. Certainty and measurement should be adequately established. Without explicit

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proof, the statement “excellent agreement” should not be made. Claims should be supported by the data. Raw test data should be presented to establish a claim. If test data are not presented, the author should support statements about the test with evidence from the literature. The author should not extrapolate beyond the evidence presented.

7.3 Generalizability

The behavior of one BSS configuration cannot be generalized to all other BSS structures. The effects of cable modulus and area are dependent on the geometry of the BSS and the type of loads, supports, and prestress. A symmetric two-dimensional BSS may not be representative of a three-dimensional BSS. This is particularly true for CFRP products. It is good practice to limit statements to the load cases for which the behavior has been validated. Other design statements should be supported by logic and relevant mechanics.

8. Conclusions and recommendations

A comparative analysis of CFRP and steel cable representations in BSSs under static loads has been computationally studied. Using a reduced order model, the implications of load and displacement as well as initial prestress in the system have been explored. Future work is recommended to model the entire BSS using ANSYS; it was not the solver used in this research. The scope of this research is limited to the computational modeling of cable systems. It does not represent a complete physical prototype and has not been validated or calibrated using the Xue and Lui (2009) experimental data. The literature supports the use of CFRP in cable systems and has identified constraints such as, anchorage and brittle failure (Wang et al., 2015, 2018; Yang et al., 2020; Rafieizonooz et al., 2024).

8.1 Conclusions supported by the available evidence

Equal Area Comparisons differ depending on the constraint. If constraints are geometric, an equal area comparison is more appropriate. If the constraint is serviceability, equal rigidity comparisons can be made. Equal Strength Comparisons are appropriately made if the constraint is on the strength of the system. In all cases, design factors and other assumptions must be made.

First, answers to questions relating to Equal Area Comparisons, Equal Rigidity Comparisons and Equal Strength Comparisons are to be reported separately. Second, Cable Modulus and area play a role in the extension of the cable, but the overall response of the system to loads and the force transfer path is dictated by a number of parameters, including geometric constraints, prestress, arrangement of struts, stiffness of the elements, and the nature of the connections. Third, a system must be prestressed; the state of initial prestress must be reported and the state must be verified. Fourth, a full system model in ANSYS is an appropriate next modelling step; however, as noted in the paper, results are from a reduced order system modelled in Python. Fifth, validating models against experimentation is not the same as directly comparing a model to experimentation. In the authors' defense, the prestressing steel is to be considered with the same importance as the CFRP, as conclusions on system safety ultimately rely on anchorage and material properties of the CFRP.

8.2 Interpretation and validation requirements

The comparison of mechanisms shows that in a BSS, the combination of prestressing and geometry controls the tensile and compressive force distributions and the force-carrying capacity, and the stiffness of the system;

the interaction of the BSS with the surrounding supports and surrounding soil controls the force-carrying capacity; and the integration of the BSS with the passive soil controls the deformation. Ultimate capacity cannot be determined through an elastic analysis, and there are a number of failure modes (e.g. rupture of the steel cables, anchor failures, etc.) that must be incorporated to define the limit state of interest. The implications must therefore be defined with respect to the anchor and load connections, as well as the cable type and model assumptions that have been validated.

8.3 Design implications

In case of a prototype, a model would need to represent verified member geometry and be developed using product-specific parameters, demonstrate equilibrium and mesh convergence, represent the prestressing sequence, and compare equal-rigidity and equal-geometry cases. The steel elements of the BSS can be validated against a benchmark, and the CFRP system elements would require measurement of cable forces, displacements and anchorage movements.

8.4 Final statement

Based on the results of the analyses and predictions of the Python-based model of the BSS, CFRP cables offer a potential low-mass high-corrosion-resistant alternative to steel cables in a beam-string system, but this requires a system level analysis. The model predicted that the difference in displacements between two support conditions was dependent on the assumed axial rigidity of the cables and the comparison basis. Thus, the findings from the analyses allow us to draw some relative comparisons, but not to make prototype recommendations. In general, measurements should be compared with the predictions and models should be developed using the parameters and products for which the comparisons and conclusions are drawn, to allow a system level analysis to be performed.

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