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CFRP Tendon Anchorage for Beam-String Structures: Structured Evidence Review, Quantitative Synthesis, and Finite-Element Assessment

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ABSTRACT: Adequate anchorage is essential for the use of CFRP tendons in beam-string structures (BSS). CFRP tendons can develop high longitudinal tensile loads, but may have limited transverse and interlaminar load resistances. This research undertakes a structured review of publicly available evidence, describes and synthesizes anchorage results quantitatively, and develops a one-dimensional finite element model, to study bonded tendon anchorage. Different systems and their failure modes, models, and relevance to "BSS are analyzed. Quantitative synthesis is done on ratios and specimen results, and results are not integrated when they are judged to be different. Bonded tendon anchorage is modeled using the concept of elastic load transfer. In the model, a linear-elastic tendon is represented by an axial element and a shear element. The model is assessed for mesh refinement and length of the bonded element. According to the model, the length of the element beyond the bonded-anchored tendon need not be modeled. Several BSS-related experiments are reviewed, and a model validation strategy is proposed. The model is not validated using these experiments. The study demonstrates that a 5 mm CFRP tendon can be anchored in a BSS, but 7 and 9 mm tendons cannot be anchored using the considered solutions. The study proposes that modeling and design should consider diameters and pressure distributions and contact stresses between the anchor and the BSS. Findings are relative and specific to the models; they are not representative of a comprehensive 3-D wedge damage simulation.

1. INTRODUCTION

A key challenge of long span construction is providing adequate support and reducing the demand for bending in the beams. One system that addresses this is known as Beam-String Structure (BSS) systems. These systems are generally composed of a top beam (or other element which dominates in compression) and a bottom element (the string) in which a major portion of the element is dominated in tension. Systems of this nature rely on a number of factors in order to perform as intended, such as the force introduced by the string, the configuration of the struts and supports, and the natural bending stiffness of the beam and tendons. The ultimate (or limit) state of the system is controlled by the strengths of the connections over which prestressing is introduced and retained. Similar to steel tendons, the strength of the anchorage system is important to the overall system strength, and therefore must be designed as part of the overall system.

CFRP, a composite material, has comparable tendon characteristics to steel, and as such has replaced steel in several cable-stayed and similar systems. The material offers numerous advantages over steel tendons in the areas of weight, corrosion, fatigue, and the tendency to relax less over time. Similar to steel, the strength of the anchorage system is important in the system

strength, and therefore must be designed as part of the overall system. Compared to steel, the tendon characteristics of CFRP are anisotropic, with the predominant strength in the longitudinal direction.

Anchorage of BSS tendons presents unique challenges, as tendons are prestressed and remain a major load path throughout the service life of the structure. Resistance of tendon anchorage connectors also is affected by the release of prestress, environmental effects, and service loads. Designs must consider the potential for minor movements of "tendon anchorage connectors and the possibility of a load path creating excessive friction. A connection that performs adequately in a tensile load test may be unacceptable if significant friction exists during service. For example, consider a tendon anchorage connection that exhibits lower peak tensile load in a pull test than another connection. The connection exhibiting lower peak load may be acceptably designed if it exhibits less brittle failure and tends to evenly dissipate loads within the service load range.

This research uses the development of anchorage connections for large-angle CFRP tendons in BSS to motivate the investigation of alternatives for CFRP tendon systems in BSS. Han et al. (2017) designed, fabricated, and tested a 10-degree wedge-type anchorage for BSS. In their study, a 5-mm tendon was successfully anchored, and a 7-mm and 9-mm tendon failed because of high pressure-related effects. Failure to improve system performance by reducing the slope of the wedge was attributed to limiting the potential movement of the wedge. Their study illustrates design limitations when considering variable tendon diameters, and how, without evaluating the contact and load states of an anchorage connection, design concepts cannot be generally applied.

No new physical experiments were performed for this study. However, as described in Section 6.11, one-dimensional finite element analysis was performed to model elastic shear transfer in a bonded CFRP tendon anchor. Other published models, i.e., ANSYS, cohesive-zone, and contact models, have a level of generality that requires extensive user input. The present study adopts a public source review (PSR) and research synthesis method. It describes the reviewed studies and performs a preliminary analysis of the published data, using a simplified version of numerical analysis to illustrate the principles of the BSS wedge-anchor model. However, the published models and experiments were not misrepresented to provide point-by-point validation of the analysis performed in this study.

There are four main goals. The first is to outline the main mechanisms for the transfer of loads in wedge-type, bonded, and clamping anchorages. The second goal is to analyze the main mechanisms of failure and to consider the limitations of numerical models. The third goal is to identify the design parameters that control the transfer of loads in wedge-type anchorages and to determine the location of the outer limit of loading that causes failure of the tensile elements in the anchorage. The fourth and last goal is to describe how a component may be evaluated and to define acceptance criteria to evaluate CFRP anchorage systems in BSS. The following questions have been asked: (1) what are the key mechanisms for transfer of loads in the main anchorage families; (2) what is the role of limitations and assumptions in numerical models; (3) what conclusions can be drawn from the existing body of evidence for BSS; and (4) what additional evidence is necessary to assess a component as reliable for the purpose of BSS?

2. MECHANICAL CONTEXT: CFRP TENDONS AND BEAM-STRING STRUCTURES

A BSS transfers loads through a system of interacting components. In this case, components include a flexed beam and a string; local forces (e.g. forces at strut connections); axial forces (string carries tension); and components of force transferred between the beam and string (struts). A BSS is presumed to be in equilibrium and the component of the tendon force acted upon by gravity of the loaded part of the beam is balanced by a component of force in the strut. Prestressing of the tendons creates camber and internal loads; the camber and internal loads are reduced as the tendon shortens and defines service limits. Anchorage can lose tendon force-in-relation (effective force) due to slip which adversely affects the tendon system. In other components of the tendon system, the loss of force can effect the equilibrium of the entire system (Wang et al., 2018; Zhang et al., 2021; Han et al., 2017).

Prestressing effects vary, and the anchorage does not always transfer a given design force to the tendon. Jacking force, effects due to creep of the tendon, friction, changes in tendon force due to temperature and deformation of the structure, and time all affect prestressing. The system and loading history depend on the construction method and the BSS. This study does not presume a given prestressing force for tendons. Instead, the focus is on the effect of loss of force due to tendon seating for anchorage and the demand-to-capacity relationship for the tendon system (Wang et al., 2018; Zhao et al., 2020).

CFCP rods and cables, with their longitudinal and lateral elements continuous with each other, exhibit longitudinal response dominated by fibers and lateral response governed by the matrix. Tensile strength in the longitudinal direction of tendons does not determine allowable contact pressures in the lateral direction. Compaction of the matrix can occur in the radial direction before fibers attain their strength in the longitudinal direction. Anchorage design requires consideration of the actual material and not the comparative CFRP material in other forms.

Distinction of cables and rods is important. Load sharing between the component strands of a cable tends to decrease with increasing cable diameter. Anchorage of a rod or cable may be dependent on the material and tendon design, the nature of the contact, and the distance over which the tendon is anchored. A tendon with a transversely enhanced surface or cross-section, when compared with a conventional pultruded tendon, may respond differently to contact. It may, however, still be necessary to determine the local material response. The anchorage of all types of tendons has been studied. Comparisons of anchorage designs should include all dimensions of the tendon and distance over which anchorage is provided.

BSS design requires consideration of numerous factors during anchorage. These include the ability to assemble and dismantle the anchor, stress, and inspect it, as well as the potential to replace it. Anchorage systems may also be protected against environmental exposure. From a design perspective, a system may be mechanically simple, allowing for easy inspection and adjustment. Other anchorage systems may not be as simple, but may allow for smoother stress transfer. When integrating multiple systems into a composite anchorage, the various materials may interact in different ways, affecting contact laws and the overall behavior of the system. From an engineering perspective, selection of an anchorage system depends on multiple factors, including strength, ease of use, and the overall efficiency of the system. Constructability, repeatability, and analysis, collectively, determine the overall utility of the anchorage system. (Wang et al., 2018; Schmidt et al., 2012).

3. METHODOLOGY: LITERATURE-GROUNDED COMPARATIVE ASSESSMENT

A systematic, evidence-based review and comparative synthesis of the literature has been conducted in the present study and coupled with the recently introduced 1D FE model for the elastic shear transfer in bonded CFRP tendon anchorage. Eligibility and search concepts were defined in advance. The search strategy was designed to be transparent and repoducible. While it was not explicitly represented as an authoretized search in Scopus/Web of Science, it was designed to represent an exhaustive search. Preference was given to studies describing anchorage systems in cable and beam-string systems, especially studies describing contact and failure mechanisms. The anchorages described in Han et al. (2017) and other studies by the same authors represent cable and beam-string systems; CFRP cable and mechanical anchorage systems are described in studies by Wang et al. (2018) and Schmidt et al. (2012).

The review is structured around an extraction matrix consisting of the following elements: (1) form and dimensions of the tendons; (2) family and geometry of anchorage systems; (3) load transfer mechanisms; (4) assumptions on contact, friction and/or bond; (5) methods and/or analyses, and experimental procedures; (6) failures or load limits; (7) measurement and/or assessment criteria; and (8)BSS application. Other elements of the matrix will represent limits and/or shortcomings of the state-of-the-art in anchorage systems and not the lack of information reported in the referenced articles. Only if numerical values for loads or other pertinent factors are given in the referred articles will these be presented in the text.

Three major categories of evidence are defined. Evidence in Category A refers to BSS anchorage systems and is primarily based on the large-angle wedge system described in Han et al. (2017). Evidence in Category B is based primarily on the use of CFRP in cable structures. Evidence in Category C is based on experimental and/or analytical studies of tendon anchorages for pretensioned and/or post-tensioned elements. Evidence in Category D is based on general tendon anchorages. The BSS objective of this investigation was to evaluate the design potential based on the combination of all of the evidence defined in the preceding paragraphs and not the design potential for an individual tendon anchorage system.

The methods used in the various studies differ in terms of tendon geometry, material, length of the anchorage, sleeve stiffness, degree of friction, adhesive system, type and sequence of loading, and pre-stressing, and definition of efficiency. Due to these differences, a comparison of the peak values of the different studies would be misleading. Therefore, this paper presents a structured descriptive quantitative synthesis of the studies, and where possible, reports ratios and summarizes data using applicable statistics. A pooled random-effects meta-analysis is not reported, since the studies do not unambiguously report common effect measures and standard deviations.

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An interpretation of the effects of variables on the response of the systems under study is presented based on principles of mechanical sciences. The effect of friction in the system depends on the contact force and the friction in the contact surface. The contact force is affected by the stiffness of the system and the degree of interference in the assembly. A design equation in mechanics is expressed as $F_f \leq \mu N$, where F_f is the friction resistance, μ is the effective friction coefficient, and N is the contact force. Loads are transferred across a bonded interface by means of adhesion. The equilibrium of forces in the tendon allows the determination of the bond shear, but, in general, the distribution of bond shear is controlled by several factors including, the constitutive behavior of the adhesive, thickness of the bond line, and local failure. (Han et al., 2017; Wang et al., 2024).

This study describes the first implementation of a 1D finite element analysis to represent elastic shear transfer in a bonded anchorage. Assumptions and results of the analysis are provided in Section 6.11. The study does not generate any of the published models referenced in this report, including the ANSYS composite-anchor model, the cohesive-zone model of Puigvert et al., or the contact model of Züst et al. These models are referenced as external evidence. This model is a limited mechanics model and is not a three-dimensional wedge-contact or failure model.

The evidence register contains records showing that cited references are fully described in bibliographic metadata. Records are also provided to show that exported records from publishers and scholarly repositories, and DOIs, where available, all align with expectations. Candidates are shown to align with expectations for full-text availability. Because Scopus and Web of Science exports through the institution were not available, the manuscript does not state that verification of database-specific searches was performed. Scopus coverage is assumed for all references.

4. CONCEPTUAL FRAMEWORK

The framework comprises four domains: Anchorage design variables, Mechanisms of force transfer, Local damage response, and Behavior of the Structural System (BSS). The mechanisms responsible for the behaviors described in the framework have not been quantitatively defined. The framework enables comparison and evaluation of different designs and suggests areas for further work.

The following describes the causal relationships defined in the framework. Understand, however, that the relationships illustrated in this example may not necessarily represent all of the causal relationships described in the framework. Design variables (Wedge geometry and thickness, confinement, Adhesive thickness and stiffness, interface friction, and bond length; interference and prestressing) affect force transfer mechanisms (Friction, pressure, and interlock; and shear.) which, in turn, determine the local response (Matrix cracking, damage, Debonding, Rupture, Fragmentation, and slip.) and anchorage performance. The response also influences BSS behavior (Camber, Gap, Deflection, and prestress retention; and distribution.)

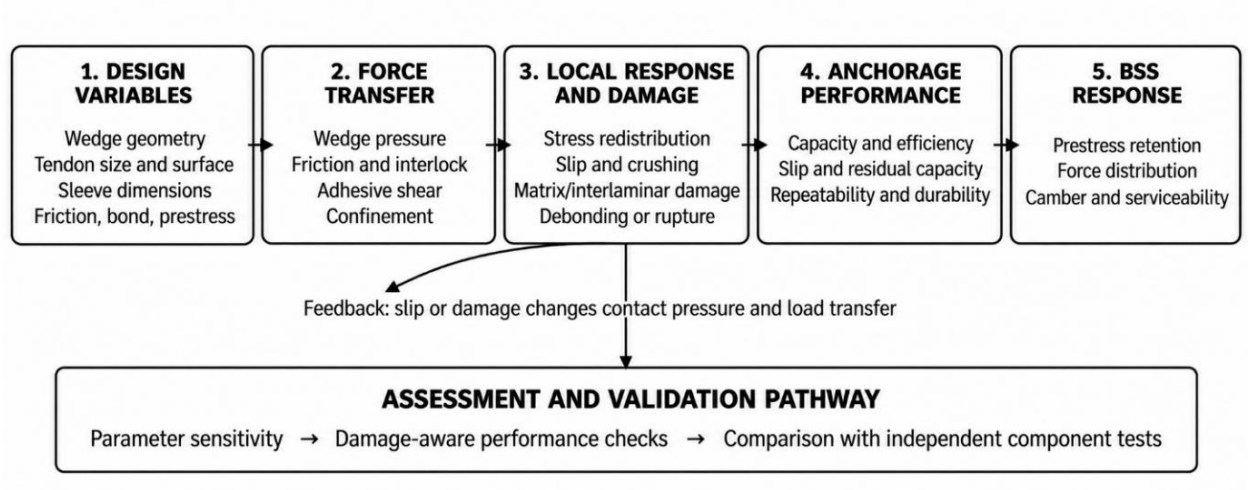


Figure 1. Conceptual framework linking anchorage design variables, force transfer, local damage, anchorage performance, and beam-string structural response.

Source: Developed by the authors from the reviewed literature.

Domain 1 (design variables) encompasses the effects of wedge angle and profile, diameter and surface of tendon(s), sleeve thickness and length, surface roughness, contact friction, interference (or preset) force, length of bond, thickness of adhesive, confinement, and the amount and mode of prestress (magnitude and sequence of stressing). These variables are not independent. For example, the effect of increased interference on wedges may be increased radial pressure and resisting friction; on the other hand, it may also result in increased transverse compressive stress. The effect of increased length of bond may be a decrease of average bond stress, and may also shift the location of the bond stress failure to the anchor. Geometry of an anchoring system should be interpreted in conjunction with the behavior of the materials involved and the interfaces (Han et al., 2017; Han et al., 2023; Wang et al., 2024).

Domain 2 (mechanisms of load transfer) encompasses friction and normal pressure, adhesion, mechanical interlock, and confinement. The behavior of load-transfer mechanisms is integrated. The anchorage body should provide a stable path for the transfer of the tendon force to the structure. Anchoring mechanisms can be of different types and can also be of a combined nature (i.e. a composite anchor). Treating a real anchorage as a single idealized mechanism may explain the reason for local failure (Puigvert et al., 2014; Cai et al., 2016; Züst et al., 2022).

Domain 3: Local Response and Local Failure describes the various failure mechanisms that occur at the tendon/adhesive/hardener/bar/interface, the tendon/matrix interface, the matrix, and the matrix/fiber interface. These include: axial stress redistribution; radial and transverse stresses; interface slip; matrix and fiber/matrix/interlaminar failure; local failure of the matrix; wedge movement; adhesive debonding; and failure by tensile rupture. These failure mechanisms are interrelated and may occur in any order. It is possible for a model to predict that interface slip will be the first failure mode, whereas in a test, local damage or tendon rupture may occur. For the purposes of failure classification, the initiating failure mechanism and the last (terminal) failure mode need to be captured, if this information is provided (Han et al., 2023; Wang et al., 2024; Puigvert et al., 2014).

Domain 4 encompasses the effectiveness of the system to carry loads, and the limits of the behavior of anchorage systems for PSs, including durability, serviceability, and the potential for damage of structures, as well as prestress dissipation. The framework recognizes that the anchorage system may consist of multiple components, each of which is permissible to fail, and the limits of load-carrying capacity of the anchorage systems may be dependent on several factors, including material variability, and the conditions of service of the structure (Wang et al., 2018; Li et al., 2024; Züst et al., 2022).

The framework involves several components, including design variables, contact/bond stress-transfer state, damage, anchorage, and the effect of BSS prestress on structural behavior. Actions may be reverse. In a contact/bond stress state, damage or slip may cause a change in contact pressure or force transfer, and thus may affect the state of the stress field. From a design perspective, the components of the framework may be evaluated by examining their sensitivity. The response of the framework should be verified using independent tests. The implication of the framework is that optimization of the geometry of a structure should be done accounting for potential damage rather than being based on assessments such as limiting friction or peak capacity (Han et al., 2017; Puigvert et al., 2014; Züst et al., 2022).

5. ANCHORAGE FAMILIES AND THEIR FORCE-TRANSFER MECHANISMS

5.1 Wedge-type mechanical anchorage

Wedge anchors are loaded and move axially with respect to each other. The normal force developed by the loading system creates a normal pressure at the contacting surfaces of the wedges and sleeve, if any. The resistance of the contact surfaces to slippage governs the normal pressure, and, thus, the system's grip on the tendon. Wedge anchors have the following desirable characteristics: compactness, positive and near immediate engagement, and the capacity to introduce controlled stress to the tendon. Potentially damaging the tendon is a concern, as is the case with all anchors that use normal (compression) loading. The level of normal pressure and tendon crushing is affected by the wedge angle, contact length, stiffness of the wedge and sleeve, if any, and presetting force, among others. Crushing can occur locally, or the tendon can fail in a split condition (Han et al., 2017; Wang et al., 2024).

The work by Han et al. (2017) is the most relevant to this study, because it examines an anchorage using transverse-enhanced CFRP tendons for a large-angle wedge. These authors stated that successful anchorage of a 5-mm tendon and the inability to anchor tendons of 7- and 9-mm diameters in the same configuration showed that the tendency to scale geometries by tendon diameter is not always valid. It is reasonable to assume that the larger the tendon diameters, the greater the changes to the state

of stress and deformation, thereby influencing the tendon anchorage. Han et al. (2017) noted that factors such as wedge slope, wall thickness of the insert, and the width of the cut along its length must be considered. These authors stated that, for their case, reducing the wedge slope was of no use. Restraining wedge deformation is critical, and, as shown in other studies, slope adjustment of the contacting faces should be considered (Al-Kaysi & Zhou, 2016).

Anchorage of CFRP tendons can lead to pull-out, excessiveness of the wedge and/or tendon movement, transverse crushing of the tendon, and/or interlaminar failure and rupture of the tendon. For a tendon anchorage design, it is critical to ascertain that a sufficient balance is achieved whereby a force is exerted on the tendon so that it does not exceed the tendon's transverse or interlaminar limit. Local failures (e.g., rupture) of tendons can occur despite an overall satisfactory performance of the tendon (Han et al., 2017; Wang et al., 2018).

5.2 Bonded anchorage

In a bonded anchor, tendons are housed in adhesive-filled sleeves or sockets. In this case, load is carried by interfacial shear between tendon and adhesive, as well as adhesive and body of anchorage. Compared to wedge systems, in a bonded anchor, the load may be transferred over a longer length. However, shear stress in such systems is essentially non-uniform and load-transfer gradients may give rise to stress concentrations. Response of such systems depends on various parameters, such as adhesive stiffness and strength, thickness, length of the bond, quality of the cure, adhesive surface preparation, and evolution of damage. If the adhesive is stiff, a small bond length may result in stress concentrations, while a long bond may cause excessive slip.

Puigvert et al. (2014) performed a series of static tests on systems consisting of CFRP tendons and adhesive bonded anchorages. In addition, they analyzed and simulated the systems with various constitutive models of adhesive. The failure of the systems was attributed to cohesive failure of adhesive. The authors discussed the use of elastic-plastic adhesive bonds, and pointed out that a constitutive model of the adhesive, along with a failure function, would allow the development of a bond model for prediction of load. However, such models would have a restricted domain of applicability against systems for which they were developed and tested.

BSS anchors are based on the reliability of adhesive bonds, which can be affected over the long term by temperature, moisture, chemical, and other environmental conditions. Of particular relevance to BSS anchors is the potential of long-term environmental conditions to affect the anchors after they are installed and become inaccessible. In the case of bonded anchors, long-term durability (i.e., beyond the short-term strength of the FRP tendon) is considered an independent issue, and it is assumed that long-term reliability of the anchors cannot be ensured (Zhao et al., 2020). Therefore, the long-term performance of bonded anchors should be assessed considering all elements of the bonded system, e.g., environmental conditions affecting the adhesive, and the long-term behavior of the bonded interface (Zhao et al., 2020; Feng et al., 2021).

5.3 Composite anchorage

The response of a composite anchor relies on the interface of multiple materials, such as friction of the tendon in the matrix, adhesive or resin matrix, the steel sleeve, and the interface of the sleeve and matrix. All of the above-mentioned interfaces can potentially cause failure. The tendon matrix and the adhesive or resin matrix can have varying friction and adhesion. Developing a model to account for all potential interfaces can be challenging. A model that utilizes an equivalent bond may be more suitable (Cai et al., 2016; Mei et al., 2020; Li et al., 2024).

The 2016 study on composite anchors used ANSYS to simulate load transfer within the system. The study examined how different variables affect internal radial stress. The 2016 study demonstrated the utility of numerical simulations to study variables of interest in a composite anchoring system. Nonetheless, the simulations are only as good as the assumptions made about the adhesion and interfacial behavior. Therefore, it is a misrepresentation to claim, based on the results of the 2016 study, that for BSS applications, specific combinations of composite anchoring system parameters should be held constant. The effects of varying other system parameters should be explored. The 2016 study should be evaluated within the context of the experimental basis, the material system, and the range of validity of the simulations.

Advancements in the field have resulted in the consideration of other design variables that govern composite anchoring systems. For example, Li et al. (2024) identified mechanical, bonded, and composite anchoring systems as major classification systems. A recent finite element study (2024) conducted experiments on multi-CFRP tendon anchoring systems to study the effects of

bond length, sleeve restraint ratio and epoxy, among other variables. The study considered design as a coupled and integrated system. BSS implementation may benefit from this line of work to study the effects of tendon grouping, cable formation, and long-term loading.

5.4 Clamping and temporary pretensioning anchors

Clamping systems rely on pressure and interface characteristics to capture the tendon. They can be used for temporary stressing or as permanent anchors. Anchors used for temporary pretensioning are removed after stressing, and as such do not form part of the load path during service. A BSS anchor, on the other hand, is part of the load path during service. The type of pressure and characteristics of the interface used for a temporary stressing anchorage system cannot be used for permanent cable anchorage. Many factors, such as the material used for the wedge (if any), its coating, and the sequence in which the wedges are inserted, affect the permanent anchorage system.

Temporary pretensioning anchors have been modeled and validated by Züst et al. (2022) for use with sand-coated CFRP tendons. A novel aspect of their work was modeling the behavior of the anchorage during temporary pretensioning. They were able to validate their model by comparing predicted tendon strains to strains measured by distributed fiber-optic sensors. Züst et al. (2022) demonstrated that in order to validate a model of an anchorage system, it is sufficient to check the strain field of the anchorage, and not necessarily the ultimate load that the anchorage is designed to resist. Their work, however, sets a limit to the general case; the parameters of the model are only applicable to the modeled case of a temporary anchor.

5.5 Comparative interpretation

Wedge anchors provide fast load bearing capability. However, they are sensitive to friction and lateral loading. Bonded anchors transfer load through shear and depend on the interfacial and adhesive conditions. In comparison to the other classes of anchors, composite anchors incorporate more load transfer mechanisms, and provide load confinement, but increase the number of material interfaces. Clamping systems can be used to transfer and distribute the tendon load, and are effective when the tendon surfaces are compatible. The main limitation of all classes of tendon anchoring systems is the uncertainty in the tendon loads, architecture, and geometry. Other considerations include the loading conditions, environment, service time, and the ability to inspect the tendon anchors. (Wang et al., 2018; Li et al., 2024).

6. NUMERICAL MODELLING EVIDENCE: ASSUMPTIONS, STRENGTHS, AND LIMITS

Nonlinear analysis enables a more realistic model of the tendon anchorage system. Due to the complexity of the tendon anchoring configurations, it may be inconvenient to gain insight on the response of a tendon anchorage system through physical testing. A well calibrated, and validated, numerical model enables comparison of a multitude of tendon anchoring configurations. Numerical models are only as good as the assumptions made, material models incorporated, contact conditions defined, and limitations in the computational domain. (Cai et al., 2016; Puigvert et al., 2014; Han et al., 2023).

6.1 Geometry and dimensionality

Axisymmetric models may be suitable for the preliminary analysis of concentric rod-sleeve configurations. Two-dimensional models of anchorage systems are limited to conditions of plane stress, and symmetric loading. Adequate simplifying assumptions should be stated for each case. Models can become three-dimensional in nature when the anchorage includes segmented wedges, nonuniform contact, cut-outs, asymmetric constraints, local geometrical details, and when tendon arrangements are complex. A three-dimensional model does not guarantee an adequate representation of the system; such a model must account for pertinent physical effects (Cai et al., 2016; Han et al., 2023).

6.2 Material behaviour

The linear variation of CFRP in tension over some useful range of stress does not justify its representation as CFRP as isotropic steel. Axis of elasticity and plasticity of unidirectional tendon materials are in the same direction as that of the tendon. Failure in the transverse and interlaminar directions should be modeled as high strain (damage) behavior with gradual loss of stiffness. Deterministic analysis of unidirectional CFRP tendons should incorporate failure criteria and gradual failure of the tendons. Generally, the initial assumption in modeling tendon systems is that the tendons are linearly elastic. A given set of properties may be used to estimate the ultimate capacity of the tendon system, but such an estimate should be validated against tendon arrangements and failure criteria consistent with the physically realizable tendon systems (Han et al., 2023; Wang et al., 2024).

6.3 Contact and friction

For wedge and clamping anchors, models need to represent normal contact, friction, and sliding. Different contact models (e.g. contact with preset interference) can be employed, but the treatment of wedges in contact models should be consistent. A friction coefficient, in general, controls the load-transfer capacity and the pressure field of the system, and its calibration against a peak load does not ensure that the internal stress field of the system is also correctly predicted. In such cases, an independent measurement of either slip or internal stress field should be used for validation. The pressure-overclosure approach of Züst et al. (2022) provides an example of an experimental characterization of a contact interface, as opposed to treating it as an unrepresented parameter (Han et al., 2023; Wang et al. 2024).

6.4 Bond and cohesive-zone models

Models representing bonded systems require behavior of shear transfer and debonding. Linear elastic bond models, at best, represent the initial response of a system; damage and failure, however, require a nonlinear model, and a cohesive-zone model can represent failure through separation and can incorporate fracture energy. Parameters in a cohesive-zone model can be based on measurements or estimates. In general, for the model validation, it is preferred that failure load is not used for model calibration (Puigvert et al., 2014).

6.5 Mesh and convergence

Wedge edges and anchorage exit stress concentrations can be sensitive to mesh. An adequately fine mesh for global stiffness determination may be overly coarse for representation of pressure and damage location. Numerical computations should represent physical stress concentrations and not singularities. Of interest for mesh convergence is location and contact pressure outside of singularities, average damage, and other quantities that inform the conclusions. A high value for a stress concentration at a corner should not be interpreted in the absence of convergence (Cai et al., 2016; Han et al., 2023).

6.6 Loading sequence and prestressing

The sequence of contact and tendon prestressing may significantly alter the computational results. Wedges inserted and prestressed prior to other loading may create contact pressure that remains upon application of tensile load. A model representing the sequence of service loading, including stressing and lock-off, should be created to the extent required for addressing the research questions. However, for initial screening of component performance, a model representing only monotonic loading may be adequate (Züst et al., 2022; Wang et al., 2024).

6.7 Validation hierarchy

Validation should be assessed according to the intended purpose of the model. As an example, a global force-displacement curve would be used to validate overall stiffness and peak load of the model. Use of a global force-displacement curve to validate the stress field of a model would be inadequate. Measurement of strain along the tendon, displacement of the wedge, contact pressures, if measurable, and the observed failure location would provide better evidence. Local-field validation of the stress field may be accomplished through physical testing. This is demonstrated in a study by Züst et al. (2022). Local field damage prediction in the absence of a model, or in the presence of a model with an unverified failure mode, should be avoided.

6.8 Reproducibility and reporting

A credible numerical anchorage study should be documented to illustrate the basis for the study. This documentation should include the model geometry, material properties, contact conditions, mesh, the type of loading, failure criterion, convergence, and the evidence used to validate the model. A sensitivity analysis should be performed to illustrate the effect of uncertain parameters on the outcome of the study. The study should include a numerical example to demonstrate the assumption of the model. Further, this example should illustrate the model's limitations. Assumptions and the limitations of the model should be clearly expressed. This should be done in all studies where a design change is justified on the basis of a model (Page et al., 2021; Li et al., 2024).

6.9 Structured search and evidence selection

The search was structured with the concepts of CFRP tendon/cable, anchorage, wedge/clamping/bonded/composite, finite-element/numerical modeling, beam-string structure, and CFRP. Search filters were applied to publicly accessible scholarly and scholarly publisher-related resources. Examples of search queries include: (CFRP or "carbon fiber reinforced polymer" or

"carbon fiber" reinforced polymer") and (tendon/cable) and (anchorage/anchor); (CFRP tendon/cable) and (wedge/clamping) and (bonded/composite) and (finite element/element/numerical/modeling/or experimental); (beam-string structure) and CFRP and (anchorage). In order to confirm the presence of relevant literature, backward references were utilized to locate primary and review literature. In order to identify the most relevant literature, forward references were examined. Search restrictions were limited to literature written in English. The focus of the search was to locate literature that supported the anchorage of CFRP tendons. Literature that primarily dealt with the anchorage of fiber reinforced polymers, duplicates, and publications that did not contain identifiable references were excluded.

Although the authors adopted a number of best-practice recommendations for effective literature searches and reviews, such as the PRISMA statement, their search was limited because of the unavailability of a number of essentials, including the exports of databases, a complete record screening form, and double blind review of selected literature. Hence, the actual searches on which their review is based are reported. A number of the search terms, and the concepts for which the searches were designed are reported, in order that the searches may be extended.

Records were considered if they documented experimental data on the performance of CFRP tendon anchorage; performed a numerical analysis on contact, bond, stress transfer, or damage in CFRP tendon anchorage; or was a review focusing on CFRP/FRP tendon anchorage. Records were also considered if they described an application of CFRP tendons and anchorage within the framework of the BSS. Each of the considered records was classified according to its primary anchorage family and type of evidence (numerical, experimental, combined, review, or BSS application). Data were extracted only if the evidence explicitly described the data. For outcomes that were expressed in numbers, but were not explicitly reported, these outcomes were extracted for data synthesis.

6.10 Descriptive quantitative evidence synthesis

There are three main types of outcomes: the first is the absolute tensile capacity of an anchorage in (kN); the second is anchorage strength expressed as a ratio with respect to a given tendon reference strength; and the last type of outcome is continuate outcomes, e.g. strain or slip. In order to compute a pooled estimate, evidence was required to represent outcomes in a clear and unambiguous manner, provide adequate sample size and variance, and be comparable to the other evidence. In evidence of tendon anchorage, the family of anchors, the procedure and loading condition, the reference strength in the denominator, and the dispersion of the outcome express variation. Since the variability is significant, it was determined that a pooled estimate of outcomes was not appropriate. In cases where the evidence supports a clear and explicit expression of ratios, the source of the ratio, and the support is sufficiently clear, the ratio is expressed, along with other descriptive statistics.

An average tensile strength of 2565 MPa has been reported for the 2024 integrated wedge anchorage. This is to be compared to the guaranteed tensile strength of 2513 MPa. The ratio of the average to guaranteed tensile strengths is 1.0207. This represents an over-limit situation, where the anchorage is greater than the guaranteed tensile strength. This situation does not indicate that the tendons in the anchorage have been overloaded. In a worst-case scenario, the actual tensile strength of the tendons may be less than the guaranteed strength. Züst et al. (2022) reported five tensile strength tests of resin-bonded anchor specimens to be 116.58, 107.92, 117.19, 110.76, and 110.78 kN. The mean of the tests was 112.65 kN, and the standard deviation of the mean was 4.05, representing a variation of approximately 3.6%. Züst et al. (2022) also reported a case in which two bonded anchors were loaded to a tensile strength of 80 kN. This loading situation is to be differentiated from the tensile strength tests performed on the anchors. Wang et al. (2024), in the paper referenced by Züst et al. (2022), reports other strength tests performed on the same anchors.

6.11 Finite-element model: bonded-anchor shear transfer

In order to study the elastic transfer of axial force within a CFRP tendon into a rigid bonded anchorage, a one-dimensional displacement-based finite-element (FE) model was developed. Here, the tendon is represented as a linear-elastic axial element, of cross-sectional area A, and of longitudinal modulus E. The surrounding sleeve is considered rigid. The adhesive/interfacial-bond (if any) is represented by a distributed linear-shear foundation of a stiffness, k_s, per unit embedded length, within the sleeve, and relative slip. The model is restricted to the elastic transfer of the load; it does not account for (i) matrix cracking, (ii) cohesive debonding, (iii) transverse crushing of the adhesive, (iv) wedge contact (including micro/macro-separation), or (v) post-peak failure, in general. The scope of the model is to study the load transfer mechanisms, and to demonstrate that, beyond

a certain length of embedding, further embedding of the tendon into the sleeve does not increase the load transfer capacity of the anchorage. The model is not adequate to evaluate the ultimate capacity of such an anchorage.

For a two-node tendon element of length l_e, the tendon axial stiffness matrix is k_ax = (EA/l_e)[[1, -1], [-1, 1]], and the consistent foundation matrix is k_f = (k_s l_e/6)[[2, 1], [1, 2]]. The tendon element matrix is the sum of the two matrices, k_e = k_ax + k_f. The global stiffness matrix is developed over the length of the tendon element which is fixed at the unloaded end and has a prescribed axial displacement at the loaded end. The far end is constrained from axial displacement, and the sleeve remains fixed. Nodal displacements are determined for all constrained degrees of freedom, as well as the axial strains and forces in the tendon element. The model computes the distributed reaction of the foundation. Because the foundation is linear, the response is proportional to the displacement that is prescribed. The length over which the foundation effect is felt is approximately proportion to the square root of the tendon element stiffness and the interface stiffness, k_s.

The stated modeling assumptions for the parametric study were an elastic modulus of E = 150 GPa, cross-sectional area A = 28 mm^2, bond length L = 180 mm, a foundation stiffness of ks = 1.0 × 10^{11} N/m^2, and a slip of δ = 0.1 mm. These represent modeling assumptions and not measured values for any tendons in the experimental studies. Convergence of the reaction load was achieved at 64.83 kN with a mesh comprising 320 linear elements. The reaction load for the mesh comprising 160 elements was 73.12 kN. The mesh comprising 10 elements yielded a reaction load of 83.07 kN. The change between the 160 and 320 elements mesh demonstrated mesh convergence. The 10 element mesh may have failed to represent, or converge to, the actual load. It may be concluded from the analysis of the concentrated load case, that an overly coarse mesh may yield inaccurate load transfer through the anchorage.

The model was run with bond lengths of 90, 120, 180, 240 and 300 mm, using the previously defined baseline parameters. The model predicted that the ultimate end reaction for the shorter bond lengths was 64.86, 64.90, 65.02, 65.18 and 65.38 kN for bond lengths of 90, 120, 180, 240 and 300 mm respectively. The solution shows that the response is diminishing after it surpassed the transfer length. The slight non-monotonic behavior shown in the results for local axial force is due to a coarse discretization. The response shown in the solution for the axial force is used for interpretation. The results shown do not reflect the design limit. The model does not account for failure of the bond and therefore it is not certain that the interface would sustain the loads calculated by the model.

In a parameter sweep, it would also be beneficial to increase the interface stiffness (ks) to see the effects on transfer length. Increasing ks would concentrate the transfer closer to the loaded end. Increasing the length of the transfer would increase the local demand on the interface. Accounting for the demands on the system and behavior of the interface and adhesive in a complete and accurate manner would give a true representation of the limit state of the system. The current model is a first step in that direction. It is suggested that the model be changed to account for a cohesive nonlinear interface to complete the model for limit state design.

6.12 Validation against published experiments

Results are compared to published experimental evidence and not to experimental evidence gathered from tests performed for this study. The contact-based model for a temporary pretensioning anchorage for sand-coated CFRP tendons by Züst et al. (2022) was experimentally validated using a five specimen series. Tensile tests were performed on the resin-cast specimens and the mean strength of the specimens was reported as 112.65 kN (with a standard deviation of 4.05 kN). This published work was used to validate their model using local strains. The specimens and test configuration of this study however, are different from what is published, and therefore the published work does not substantiate the model of this study.

Puigvert et al. (2014) performed tests on CFRP rods potted within a steel tube, and reported that a cohesive-zone model representing an interfacial bond failure was in agreement with experimental evidence of failure of the system. The elastic foundation model of this study is not to represent the failure load of the system. A configuration-matched model and experimental validation of this study would require the extraction of the elastic properties, bond-line dimensions, and a coupling of a test of the system with failure and load-line displacement data. This would be followed by an equivalent model representing the system.

6.13 Numerical interpretation and reproducibility

The model relies on established numerical and physical methods: standard finite-element techniques, linear elastic tendons, distributed interface foundation, imposed end displacement, and free distal boundary. Replicating the model is straightforward. Primary outputs of the model are mesh-convergence and embedment-lengths. These demonstrate an expected behavior of the model, however, for complete representation of the system, i.e. orthotropic CFRP damage, frictional contact, adhesive failure and others, a physical model is essential. The next level of model should address friction and pressure contact, adhesive cohesive failure, and related local decohesion.

6.14 Evidence limitations and future validation

A complete three-dimensional validation model for a large-angle BSS wedge anchor should include complete data on the tendon, anchor, geometry, contact friction and pressure, boundary conditions, and mesh. Additional data should include digitized response curves and load-deflection diagrams from Han et al. (2017). The current model explains a different load transfer mechanism and should not be compared or correlated to Han et al.'s model. Hidden or obfuscated data should not be used in model validation. Future model validations should be completed using the same tendon, wedge and sleeve profiles, load cases, and boundary conditions used in the reference case, and information should be made publicly available.

7. DESIGN VARIABLES AND FAILURE MECHANISMS

7.1 Wedge angle and profile

The effect of wedge angle is poorly understood due to the dependence on friction, travel, geometry of the sleeve, and the behavior of the various components of the construct. It is a common impression that smaller angles result in better grip and larger angles result in greater damage, but this is not always the case. The evidence described by Han et al. (2017) indicates a slope angle and does not provide evidence to suggest a smaller slope angle is better. Thus, the design question is whether the slope angle provides a sufficient contact state with pressure distribution and appropriate reduction of migration of the wedge for the targeted tendon.

7.2 Tendon diameter and surface architecture

There is a common misconception that tendon diameter, or design variables in general, affects the load carrying capacity of tendons in a simple, linear fashion. In the case of BSS, Han et al. (2017) reported the larger diameter tendons were unable to be anchored in a large angle wedge design. Thus, geometric scale up should be avoided. Surface features on tendon designs can increase the frictional state, but may also create design flaws and wear on the surface of the tendon. Other design changes, e.g. transverse features, should be evaluated for their effects on the entire tendon-anchor system. (Han et al. 2017, 2023).

7.3 Sleeve thickness, length, and restraint

The sleeve determines how contact pressure is shaped and where it is directed. The minimum thickness of the sleeve limits its deformation, and too little wall thickness can alter the pressure field and wedge movement. Too much restraint can increase transverse compression. The length of the sleeve and the width of the cutting tool determine the contact area and how stiffly the contact area is constrained, as well as the extent of the load path. Sleeve length, cutting width, and wall thickness have been shown to be critical in design. It is supportive of designing with multiple variables instead of varying a single parameter (Wang et al., 2024; Cai et al., 2016).

7.4 Friction and contact condition

An effective friction coefficient greater than one will increase the resisting axial load of a wedge. However, the value of the friction coefficient is influenced by many variables such as the contact pressure, material, surface condition, and the presence of a coating. The friction coefficient can change during the service life of the component. A component that depends on friction must be designed so the surface condition that governs the desired friction can be reproduced during the manufacturing process of the component. Furthermore, the design must ensure that the friction required to prevent slip of the interfaces is sufficient to prevent contact fatigue (Han et al., 2023; Wang et al., 2024).

7.5 Prestressing and presetting force

Presetting, or a 'preload,' has been used to help initiate anchor engagement; however, the application of a large presetting force can result in transverse stresses that create damage prior to the application of the service load. It is the sequencing of contact, friction, and load transfer that is critical. If a model of a system does not show the sequencing, it may not show the critical state that can cause damage. It is important to document and standardize the procedures for the installation of anchors and find the jacking, lock-off, and seating forces as well as the tension in the tendons (Wang et al., 2024; Züst et al., 2022).

7.6 Adhesive length and thickness

For bonded anchors, longer bond lengths decrease the average transfer stress, but loading may concentrate near the loaded end, and the remaining length may be unwound. The thickness of the adhesive affects the load transfer, and the optimum thickness depends on the stiffness and strength of the adhesive. At service and extreme environmental conditions, the adhesive may not fully wet the bond, and a void may exist. Debonding may occur along the adhesive, and before the loaded component fails, the adhesive may fail cohesively. Cohesive zone models may be used to represent debonding; however, the behavior of the adhesive, and the interfacial behavior should be measured and evaluated before using models to represent failure (Puigvert et al., 2014; Mei et al. 2020).

7.7 Failure classification

Literature describes recurring patterns of anchorage failures including slippage or pull out; wedge migration; local transverse crushing; matrix cracking or splitting; interlaminar failure; adhesive debonding; failure of sleeve or other elements; and rupture of tendon. Each of these failures is defined within the context of anchorage design. Pull out indicates a lack of secure force transmission. Local transverse crushing or splitting indicates that tendon resistance has been exceeded. Adhesive failure indicates that the bond or transfers stress beyond the tendon. Rupture of a tendon or other element of anchorage system indicates that the system concentrates stress on a very small area of the tendon. It is important to classify the observed mode of failure, the primary mechanism of failure and the test conditions. Reporting load at which failure occurs (i.e., failure load) provides very little information. Test conditions, load and environmental conditions should be described in detail to better understand the test or assessment. (Puigvert et al., 2014; Han et al., 2023; Wang et al., 2024).

7.8 Performance indicators

Peer reviewed research has recommended the following as criteria for assessing the performance of tendon anchorage systems: peak anchorage force; load-slip response; slip displacement and residual slip; slip/strain distribution; damage/failure loads; failure mode; and variability. Performance after fatigue, cyclic and sustained loading should be included, as should the edge-to-edge spacing of load introduction on specimens tested. The criteria noted above may vary among specimens and should be reported with a definition of the denominator. The reference values for the wedge system reported to achieve an anchorage efficiency of 118% relative to the manufacturer's specified strength should not be taken to indicate the system and/or related materials achieve an ultimate strength in excess of the wedge material; rather, they reflect the reference values established for the specimens tested and the study. It is important to report the definition of the denominator (Wang et al., 2018; Li et al., 2024).

7.9 Uncertainty and repeatability

Performance may vary as the result of a number of factors including the tolerance in tendon diameter, surface imperfections, misalignment of wedges, machining of sleeves, and inconsistencies in the mixture and curing of the adhesive. The variability of the system precludes the identification of a design magnitude. A tendency has been observed to give a deterministic estimate based on the model. Numerical models, however, should be used to describe and/or capture the range of uncertainty within the system. It is also recommended that models for systems that may be used in safety critical BSS be validated to define the range of uncertainty (Feng et al., 2021; Züst et al., 2022).

8. TRANSLATING COMPONENT EVIDENCE TO BEAM-STRING STRUCTURES

An anchorage is a system component, and it can satisfy the requirements of the system at several levels. From the point of view of beam-string structures (BSS), it is essential to provide and keep tendon forces in anchorage at the required positions. A component test can indicate whether the anchorage resists a monotonic pull. It does not help evaluate if the anchorage can be

installed within the restraints of space, if the losses in prestress are acceptable, or if the structure satisfies the service state requirements. It is required to integrate consideration of the aforementioned service state requirements.

First, consideration should be given to the service force. It is not correct to base the design of the anchorage with respect to the CFRP tendon solely on the strength of the tendon. The limits of the tendon may be govern to the transverse and inter-laminar limits of the tendon. The anchorage should be designed for the tendon of the specified dimensions. The 5-mm and 7- and 9-mm tendons, for example, as studied by Han et al. (2017), may make a significant difference to the design of the anchorage. It should be assumed that a change to the tendon dimensions and/or the number of strands, results in a change to the anchorage.

Second, slip at the tendon anchorages must be accounted for by reducing the effective tendon force. Even if the anchorages do not fail, slip at the anchorages will still occur during seating and will reduce the effective tendon force. In a BSS, a reduction in the effective prestressing force alters the camber, beam bending, strut forces, and service load deflection. The sensitivity of the structure to changes in anchorage slip depends on the geometry of the structure and the distribution of the stiffness in the structure, therefore the conversion from slip in anchorage to structural response will also vary from case to case and cannot be generalized. Therefore, a detailed coupled analysis of the complete BSS will allow prediction of the effect of a measured or assumed anchorage force/slip relationship.

Third, effects of the construction sequence must be examined. The erection of a BSS will usually involve temporary works to support the beam while struts are positioned and stressed. The removal of temporary supports will alter the force in the tendons. The tendons are stressed by a series of mechanical wedges that are typically designed and checked for a single load application. There are many approaches that could be taken to make an anchorage system that will work as designed under the construction sequence. The design approach will depend on the level of risk that is accepted, but could include specification of surface and anchorage preparation and seating tolerances.

Fourth, evidence pertaining to environmental effects and service loadings must be addressed separately. An anchor that has been embedded into the concrete will be subject to various loads and environmental exposure. For example, a reinforcing tendon may experience repeated and varying loads. The anchor itself may experience moisture and/or environments that are corrosive and/or aggressive. Resistance to corrosion of the CFRP anchor does not provide resistance to corrosion of the materials to which it is connected. Fatigue, durability, and corrosion resistance of ancillary components (sleeves, adhesive, and connector wedges) may limit the durability of the anchor system. The anchor may be inaccessible after the construction phase. Designs should incorporate a system that allows the anchors to be checked or assessed.

Fifth, the consequences of system failure and degree of system redundancy should be considered when assessing acceptability of the BSS. System redundancy and geometrical constraints of the structure influence the degree of force redistribution in a structure. The authors do not couple a specific BSS redundancy to their assessment of global structural risk. However, they recommend considering the potential initiation of disproportionate or progressive failure as a result of loss of a tendon and/or tendon anchor.

Anchorage behavior may be evaluated at various structural levels. Behavior of a component or subassembly may be tested and validated to assess interaction of the tendon with the anchor and the connected structure, while a structural analysis may validate behavior of the overall structure. Construction, behavior in service, and expected use of the system may be validated through a full-scale prototype. In the absence of supporting evidence, research conclusions may be limited. In this paper, conclusions identify the scope of validation needed and possible tendon anchorage systems rather than provide design recommendations.

9. COMPARATIVE SYNTHESIS AND RESEARCH AGENDA

The data reviewed in this assessment support five synthesis points. First, in many cases, the local zone of force-transfer is the limiting factor, as opposed to the tendon's nominal longitudinal tensile strength. Second, design solutions can yield trade-offs in performance. For example, a greater contact pressure can reduce slip, but increase the risk of transverse damage. Third, the tendon model's credibility is reliant upon the characterization and validation of the model. Numerical results, therefore, should be interpreted in such a manner. Fourth, mechanisms-based insights are subject to the same considerations discussed in Synthesis Point 3. That is, similar resemblance in the tendon's form, force history, and environmental conditions is required to support the extrapolation of insights from one component to the next. Fifth, a tendon's selection should consider a multi-criteria performance constraint as opposed to relying on the assessment of a single performance metric, e.g. maximum force.

The highest level priority for research should focus on the development of reporting frameworks. Tendon models, by their nature, encompass a wide array of design variables, e.g. transverse and longitudinal material properties of the tendon, tendon's cross-sectional geometry and surface conditions, tendon anchorage, means of force transmission, load control, and displacement measurement, amongst others. Research would substantially benefit from the reporting frameworks described above.

The second highest priority is validation of local response. Researchers should measure the tendon strain distribution, and if accessible, measure the movement of wedges or slippage of interfaces. Evidence beyond the global load line may be provided by distributed fiber optic sensors, strain gauges, digital image correlation, or other techniques. It is good practice to calibrate the model using the set of data used to build the model, and to validate the model using other, independent, sets of data. In this manner, it may be confirmed that the response of the validated model is not identical to that used to create the model.

The third highest priority is damage-aware parametric analysis. In an acceptable parametric study, the wedge angle and contact length should be examined, as well as the thickness of the friction sleeve and surface roughness. The study should consider the tendon diameter, as well as the transverse strength, presetting force, and other types of friction. The analysis may consider the slip potential of the interface, as well as pressure and shear distribution. To assess damage potential and focus on a set of constraints, a multi-discipline approach may be taken.

The fourth priority is coupled anchor-BSS modeling. Local models of anchors can predict slip or force. Global BSS models show the influence of those relations on structure. In some cases, the two models can be developed in separate FEA models, and an interface can be used to couple the two models. Moreover, a BSS modeling approach should account for potential movement at the anchor end(s), e.g., if the anchors are non-perfectly end-fixed.

The fifth priority relates to the durability of the BSS and the effects of repeated loading. It is not always possible to extrapolate the behavior of a structure beyond the results of monotonic static tests. The effective contact or bond behavior may vary due to the environment, loading, and other effects. Research should be undertaken to determine the durability and loading envelopes for the BSS, and the anchors should be tested to represent those conditions. For bonded anchors, the effects of the aging of the adhesive should be considered. For wedge and clamping systems, effects of contact and stability should be considered, as well as potential movement of contact interfaces.

The sixth priority is scale and manufacturing transfer. Changes in specimen size typically affect various aspects of the design, such as the contact area, the stiffness of the sleeve, local stresses, and the manufacturing tolerances relative to the size of the tendon. There is good reason to be concerned with size sensitivity for BSS. As previously mentioned, there is a strong sensitivity to diameter for BSS-style wedge designs. Therefore, it is prudent to require validation specific to each configuration. A design that proposes a scaled version of an existing design should demonstrate which pertinent dimensionless numbers and material properties remain the same.

The seventh priority concerns the development of design heuristics. Currently available literature should enable designers to evaluate which anchorage families are applicable, determine material tests, create and calibrate a simulation model, and establish acceptance criteria. Designers should be able to differentiate between anchors that are used to temporarily stress a structure and anchors that are part of the primary structural system. The emphasis should be on establishing frameworks rather than standards, for example, on the wedge angle or the coefficient of friction. The evidence should be specified to application classes. This would permit BSS to take better advantage of available research.

9.1 Comparative decision matrix

Each family of anchorage has a particular mechanism for transferring a force. This transfer of force is limited by circumstances and evidenced by factors specific to the anchorage. Friction plays a major role in wedge systems, and the normal forces generated by wedges may lead to slippage. Transverse or interlaminar slip is another issue. Shear transfer occurs in bonded systems. The most critical factor in such systems is to maintain the integrity of the bond, and if the bond is too strong or stiff, it may lead to premature failure of the anchorage. Composite systems consist of different interfaces and materials, and the challenge is to determine which interface is the most critical. Tensile and/or frictional systems may be either temporary or permanent, and to make an appropriate comparison, the role or the service condition needs to be defined.

This qualitative matrix provides relative evaluation of evidence within each of the three anchorage systems described, and is not a data-pooled analysis and resulting ranking. For wedge anchors, priority evidence would be tendon transverse behavior, contact pressure distribution, wedge displacement, friction behavior, and failure location. For bonded anchors, priority evidence is the constitutive behavior of the adhesive, the bond-line and bond-length, end-shear concentration, failure location, and the environment. For composite anchors, evidence should delineate the behavior of each interface and the constraint provided by the sleeve. Evidence should consider the procedures followed, environment, and other parameters for clamping anchors. The repeatability and the effect of installation practices on the anchoring system also should be considered for each type of anchoring system.

Efficiency, as used in this context, should be defined and delineated, and should include the denominator(s) against which anchorage efficiency is measured. If efficiency is defined as anchorage tendon strength, comparability requires disclosure of the tendon batch and type, the specimen number, and the method of failure (tendon, interface, body). If other strength characteristics of the tendon are guaranteed, this tendon strength may be less than the tensile strength of a reference specimen, and comparability again requires disclosure of the tendon batch and type, specimen number, and the method of failure. It is important that comparability be addressed to adequately evaluate anchorage systems.

9.2 A defensible numerical assessment pathway

Numerical analysis for the evaluation of BSS cases follows a particular path. It begins with an analysis of the mechanical properties (longitudinal and transverse) of the tendon and anchorage components. It is concerned with the geometrical dimensions, surface conditions, materials and fabrics used in the constituent elements and in the adhesives and wedges, and the tolerances in the manufacturing process. A component model represents the next stage. The interaction of the components should be analyzed prior to the application of an external load if the model represents a case where the wedge is preset. The next stage evaluates the mesh sensitivity and assesses the variation in the input parameters. Of main interest are the load-slip response and contact pressure. It should be noted that the evaluation of the input parameters and output data should be based on the damage or abnormal conditions that may be present in the component. Of primary interest are the maximum loads and the location of the abnormal conditions.

The model should be validated against different global quantities. Of interest are the force-displacement curves, strains in the anchorage, movement of the wedges, and the location of damage. If the model predicts an incorrect failure mode, it should not be considered valid for damage evaluation. A restricted representation of the design space is of interest in the final stage of the study. It is suggested that the input variables of the study be based on the case being analyzed.

Stage six relates component response to BSS. In the structural model, it is assumed that tendon ends are fully fixed. Analysis of sectional components should assess effects of change in prestress on permanent deformation of beams, strut forces and other limiting states of serviceability. These stages of the research plan describe the changes that may occur due to the loss of prestress, and have not been conducted.

9.3 Implications for design and quality assurance

For the BSS, design and acceptance requirements should define the product and diameter of the tendons, allowable anchorage seating movement, inspection or monitoring, and acceptability of loads. Changes from the design, assembly and manufacturing process of the anchorage system should also be assessed. When a manufacturer's anchorage system has a defined qualification, the designer must ensure that the limits of the system encompass the Demand and the Environment of the BSS. Without such a qualification, the designer must perform a literature review. A review of the literature may be used to describe the design of a component, but it cannot be used to replace a component test.

Variables which materially impact load transfer should be the focus of QA activities. For wedge systems, these may include, but are not limited to, the conditions of the mating surfaces, machining tolerances, alignment of the wedges, the condition of the sleeve, and how the wedges were loaded (i.e. measuring loads or seat them in place). For bonded systems, material variation may include the condition of the adhesive, voids in the bond line, temperature during the bonding process, and the bond line. For composite systems, the variation may be found in the interfaces and/or the constituents.

Documenting evidence to support the level of confidence in a final design decision may take many forms. A published test on an anchor of the same geometry, but a different system, or a different type of test on an anchor of the same system may provide

less evidence to support the design decision. An extrapolated numerical model may provide some evidence to support a decision. A published description of an anchor of similar design may, at best, provide rationale for believing that a similar design decision was correctly made. This evidence should be weighed most heavily when the anchor is part of a critical load carrying structure and is difficult to access or inspect.

10. LIMITATIONS AND SCOPE OF THE COMPLETED ANALYSES

This study employed a structured public-source evidence search, outlined eligibility criteria, performed a descriptive quantitative synthesis of identified data, and developed a first-of-its-kind linear finite-element model of bonded-anchor shear transfer. There is significant variability in primary studies with regard to the type of tendons and anchorage, the efficiency denominator, and the loading condition, to name a few. A mechanistically and statistically sound meta-analysis of all anchorage families is not possible with the available data. This study reported outcome ratios and other descriptive data when supported by the evidence and avoided combining disparate outcomes.

The model is based on the assumption of elastic shear transfer within the interfaces. It is, therefore, not a complete three-dimensional model of the BSS wedge anchorage. Results from the model cannot be interprete as an estimate of the ultimate strength of the anchorage and should be considered" as an aid to, but not a substitute for, physical testing. The results from the model are dependent on the modeling assumptions and the numerical values assigned to interface stiffness, tendon stiffness, and boundary conditions. It is recommended that future models account for nonlinear behavior and damage within the interfaces. Such models should also be correlated with experimentally derived load-deflection curves, local strain measurements and other related data.

For the evidence search, the author relied on publically available scholarly and scholarly publisher's resources. An export of search records from Web of Science and Scopus was not available in the search file, thus a full record-level screening log is not available. The author is, therefore, limited in reporting the search strategy and results. The one-dimensional elastic model described and illustrated within the author's manuscript is the model that was validated against experimental data. It is the understanding of the author that validation of a given model against experiment is important and required, however it should not be construed that the experiments in question are the same as, or related to, the model being validated.

11. CONCLUSIONS

The focus of this study was on the analysis of CFRP tendon anchorage in beam-string structures, and on consideration of wedge-type, bonded, composite, and clamping systems. Based on the literature, the main challenge is the presence of transverse loads, contact stresses, and irregularities in the local force transfer zone that may lead to cracking before the tendon reaches its ultimate tensile strength.

The most instructive result of the BSS research on large-angle wedge anchorage are the anchoring of 5 mm tendons, and failure to anchor 7 and 9 mm tendons in the same setup. Anchoring behavior is influenced by the tendon diameter, the roughness of the anchor sleeve, the thickness of the anchor wall, the width of the cutting edge, the depth of the wedge, and the contact pressure. A general rule, e.g. to always reduce the wedge angle, is not of any help.

Bonded systems are challenging to model due to the uncertainty of progressive debonding, and the end effects of the load-bearing interfaces. There exist combined systems of bond and friction that require a good representation of multiple interfaces. Likewise, clamping systems, if loaded in the right direction and with the right surface condition, may also provide sufficient anchorage, but their suitability for prolonged service must be studied separately. Each tendon anchorage system is designed considering the service load, the tendon, and the environment.

Finite-element analysis allows analysis of contact stresses, slip and local failures, and can be used to predict where fatigue cracks may initiate in a system. However, FE analysis should not be relied upon to make the final determination of system integrity unless material properties and interface rules are clearly established and verified, and the simulation has been validated. Reaching the highest peak load in a simulation does not mean that local failures would be correctly captured in that simulation. To have higher assurance that the model correctly reflects the behavior of the system, local measurements of slip and strain, as well as other verification tests and failure modes, should be considered.

The framework demonstrates how design variables are related to mechanistic paths for progression of stress-related damage and anchorage-related failures as well as the loss of material properties due to BSS and prestress. The framework enables

assessment of systems based on a variety of criteria, including capacity and slip, local damage indicators, and assurance and durability. The framework should facilitate comparison of different systems and anchors and provide a means for assessing the merit of previously published work.

Work should be done on standardizing reporting and local-field verification. Other important areas for future research include damage-aware parametric studies and validation, coupled modeling of anchors and BSS, durability assessment, configuration-specific testing, and validation for various sizes of CFRP tendons. Until the points above have been completed for a candidate system, it can be concluded that the available literature identifies several anchorage mechanisms and sensitivities, but does not include design-complete anchorage mechanisms for CFRP tendons for beam-string structures.

The recently presented finite-element analysis incorporated response prediction into evidence synthesis. For the case examined herein, the reaction force attained bond-length-independent convergence, and in relation to the transfer region, the influence of bond length became negligible. This analysis supported the use of a transfer-length approach during preliminary design of bonded anchors. This analysis also substantiated the need for additional" modeling to capture the influence of damage and the strength of the bonded interface. Thus, it can be concluded that evidence synthesis, mechanics-based finite element analysis, and validation should be integrated within a framework of inquiry to advance the design of bonded anchors for CFRP tendons.

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