

## Advances in Stress Ribbon Bridge Design and Analysis: A Review

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# Advances in Stress Ribbon Bridge Design and Analysis: A Review

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**Abstract**— This paper comprehensively reviews the changes in the structures and the technical innovations in Stress Ribbon Bridges (SRB) over time to pinpoint the major deficiencies in the existing modeling and optimization techniques. A thorough content analysis was carried out by accessing various academic databases and covering the time span 1900-2025. The findings were categorized into structural systems, high-fidelity non-linear numerical modeling, aerodynamic stability modifications, and patented construction methods. The study discloses a significant advancement in the technology from simple equivalent modulus approximations to sophisticated non-linear Finite Element Method (FEM) utilizing isogeometric elements for better convergence in flexible systems. The aerodynamic properties are enhanced by using semi-circular fairings and variable-depth 'Fish Belly' girders with the help of which tension-bearing and traffic-bearing functions are successfully separated. However, the present design optimization is still heavily dependent on computationally very expensive and non-transparent heuristic black-box algorithms. Due to the inherent lateral and torsional instabilities of SRB, their applications today are mostly limited to the light-traffic pedestrian walkways. Hence, there is an urgent need to carry out the physical validation of the bridges under extreme non-linear seismic events, which is the big gap in research pointed out in this paper. Advancing the field of research is contingent upon the use of Physics-Informed Neural Networks (PINNs) and Explainable AI (XAI) in combination.

**Keywords**—Bridge Advancement, Bridge Engineering, Literature Review, Structural Engineering, Stress Ribbon Bridge.

## I. INTRODUCTION

Stress Ribbon Bridges (SRB) are lightweight and relatively inexpensive to build. These structures are often valued for a straightforward assembly process. Historically, designers have used them mostly for pedestrian and bicycle paths. The design of the SRB is unlike any other type of bridge because it is basically a cable system without "suspenders," and as such, it has a very unique profile. The unique aspect of an SRB is that the concrete deck can be installed directly on top of the tension cables that run along the length of the bridge. The main cable system, usually made of steel cables or plates is rigidly connected to the concrete deck [1], creating a solid composite structure. Furthermore, multi-span stress ribbon structures are used for longer distances across, which require flexible hinges at the connection joints to help manage stress concentrations while accommodating the forces exerted on the structure [2]. An SRB is illustrated in Figure 1 and its main components in Figure 2. While the advantages of using

stress ribbons are apparent, the structural analysis of stress ribbon systems presents considerable challenges, because of the interaction of forces caused by lateral displacement of intermediate supports under dynamic loading conditions. In many cases, the analytical predictability of stress ribbon systems comes from the theoretical assumption of a structurally flexible ribbon element [3].



Figure 1: Leonel Viera Bridge, Uruguay



Figure 2: SRB Components

Currently, there is a clear gap in understanding the complete structural behaviour of steel stress ribbons due to limited experimental and analytical studies [4]. Furthermore, traditional structural analysis relies heavily on either oversimplified equivalent stiffness methods or computationally prohibitive iterative heuristic algorithms. These conventional approaches struggle to accurately capture extreme geometric nonlinearities and often act as computational black boxes, obscuring the underlying structural logic necessary for safe, dynamic optimization. Hence, a rigorous assessment of a stress ribbon's flexural stiffness is required to determine the actual stress distribution; this aspect is often ignored or over-simplified during preliminary load analysis [5].

The development of Physics-Informed Machine Learning and Explainable AI (XAI) has paved the way for solving the nonlinear complexities of flexible structures without breaching fundamental equilibrium laws, thus providing enormous possibilities. However, the literature that combines these technologies with the mechanics of SRB is still very scattered. A review of the current situation in the field is,

therefore, necessary to integrate the independent analytical studies, evaluate the boundaries of the present heuristic optimizations, and set a unified baseline that will facilitate the gradual shift toward the AI-based, transparent, and resilient SRB design.

The target of this paper is to address the above-mentioned gaps in knowledge by outlining specific tasks as follows:

- Thoroughly inspect the state-of-the-art analytical and structural modeling methodologies for SRBs from the point of view of the comparison between the simplified equivalent modulus methods and the high-fidelity non-linear finite element formulations.
- Evaluate the latest progress in aerodynamic stability and structural geometry, thereby figuring out how changes in the deck-edge and the application of new profiles can help in coping with the dynamic excitation.
- Carry out a comprehensive study of the inadequacies of traditional heuristic design optimization algorithms and present a brief outline of the necessary changes in the engineering of flexible bridges that entail a move toward the use of Physics-Informed Neural Networks and Explainable AI frameworks.

## II. REVIEW METHOD

This review paper is carried out with systematic content analysis methodology to refine the structural and

technological development of SRBs. By implementing a multi-step review method that includes identification, screening, and technical categorization, the research ensures that inferences drawn are valid engineering interpretations.

- 1) **Data Sources and Search Strategy:** Literature were gathered from the leading engineering databases such as Scopus, Science Direct, Wiley Online Library, DOAJ, and Sage. The search window covers a period from 1900 to 2025 to include both the foundational mechanics of the structures and current AI technologies usage.
- 2) **Literature Selection Criteria:** The choice was exclusively for the academically peer-reviewed articles, technical books, and conference proceedings on SRBs, suspension systems, non-linear cable behavior, or advancements in bridge engineering. The research keywords involved the following phrases: 'Stress Ribbon', 'Stressed Ribbon', 'Cable Supported Bridge', 'Ribbon Bridge', 'AI in Bridge Engineering', and 'Cable behaviour'.
- 3) **Analysis Framework:** Both qualitative and quantitative methods were utilized to assess the construction techniques and structural performances. The technical soundness of the work was ensured by the authors thus the identified works were integrated into two different matrices - Table 1 (Structural Analysis and Dynamics) and Table 2 (Optimization and Aerodynamics).

Table 1: Literature Summary - Structural Analysis, Form-Finding, and Dynamics

Author / Year	Focus Area	Key Technical Findings	Limitations / Gaps Identified
Lorenzi & Moser (2022) [1]	SRB Design in extreme environments.	Feasibility of a 118m SRB in the Italian Alps. Demonstrated complex non-linear design and low-impact construction.	Execution relies entirely on the presence of highly competent designers and specialized contractors.
Koláček et al. (2024) [2]	Dynamic parameters of slender SRBs.	Quantified the effect of temperature, prestressing force, and discontinuous mass overlays on bridge natural frequencies.	Acknowledged that particular dynamic parameter monitoring methods for SRBs are still to a large extent unknown.
Ziaja et al. (2025) [3]	Numerical modeling of degraded footbridges.	Cable pre-tension heavily impacts mode shapes. Successfully modeled cable elongation due to 30 years of rheology.	Severe challenges exist in modeling and validating aged bridges when original technical documentation is lost.
Sandovic (2017) [6]	Deformation of steel bands in SRBs.	Replacing highly flexible bands with flexural-stiff profiles suppresses undesirable kinematic displacements under asymmetrical loads.	The introduction of stiffer profiles complicates the initial erection phase compared to perfectly flexible cables.
Karoumi (1999) [7]	Nonlinear Finite Element Method (FEM) of moving vehicles.	Utilized a combined Newton-Newmark algorithm for analysis and exact elastic catenary elements to model dynamic tire forces.	High computational cost for time-history analysis of long-span bridges under continuous, heavy traffic flow.
Goldack & Schlaich (2016) [8]	Saddle mechanics and contact stress.	Saddle curvature effectively reduces bending moments. Barlow's formula accurately predicts contact stress up to the detachment point.	2D FEM provides safe baselines but entirely misses 3D Poisson's ratio effects and localized edge stress spikes.
Abdel-Ghaffar & Khalifa (1991) [9]	Cable vibration in seismic response.	Proved that Multi-Element Cable Systems (MECS) are strictly required to capture coupled deck-cable lateral and torsional motions.	One-Element Cable Systems (OECS) completely fail to predict localized cable swinging and its massive energy-absorbing effects.
Camara & Eftymiou (2016) [10]	Deck-tower transverse seismic interaction.	"Stiff" towers (inverted Y/A shapes) possess much higher frequencies. Coinciding deck/tower frequencies trigger catastrophic resonance.	Analytical expressions provided are highly theoretical and require extensive, site-specific soil condition calibrations.
Alic & Persson (2016) [11]	Dynamic Relaxation (DR) and Isogeometric Analysis.	PHT-splines combined with DR effectively analyze large-deformation membrane and complex bending-active structures.	The initial non-uniform rational B-splines (NURBS) geometry requires strict continuous boundaries over knots, limiting immediate integration with standard CAD tools.
Wallin & Ristinmaa (2015) [12]	Topology optimization via inverse motion.	Algorithm determines the optimal undeformed manufacturing shape by rigidly prescribing the boundaries of the deformed operating state.	Complex non-linearities in thermos hyper elastic structures can cause numerical instabilities in localized low-stiffness regions.
Malerba et al. (2012) [13]	Extended Force Density Method (EFDm).	Overcame standard FDM limits by introducing fixed nodal reactions, allowing the form-finding of mixed rigid-strut and flexible-cable networks.	Requires the starting configuration guess to be sufficiently close to the final solution to guarantee fast numerical convergence.

Table 2: Literature Summary - Optimization, Aerodynamics, and Advanced Monitoring

Author / Year	Focus Area	Key Technical Findings	Limitations / Gaps Identified
Huang et al. (2023) [4]	Dynamic assessment via SHM and non-destructive evaluation (NDE). Use of Steel - ultra-high-performance concrete (UHPC) Truss Pedestrian Bridges.	Integrated Operational Modal Analysis with ultrasonic NDE to identify concrete core debonding in concrete-filled steel tube (CFST) arches.	Global modal parameters reflect broad system changes but strictly require NDE for precise local defect identification.
Zhang et al. (2025) [5]	Use of Steel - ultra-high-performance concrete (UHPC) Truss Pedestrian Bridges.	They demonstrated that using UHPC as a cover greatly improves the ability of steel truss/arch bridges to carry loads and their structural resistance.	UHPC has been extensively integrated in the construction of continuous girder bridges; Its application in intricate truss systems is still very rare and remains an area of limited research.
Xu et al. (2025) [14]	Use of rail-damper systems to reduce vibrations.	Flexure of the deck causes the handrail to rotate which in turn effectively powers viscous dampers, thus providing essential additional damping.	This method depends heavily on very precise adjustments; the non-dimensional rail stiffness should be very high, whereas the natural damper stiffness should be kept low.
Dong et al. (2023) [15]	Seismic control using Tuned Mass Dampers (TMD).	A 5% mass ratio TMD decreases vertical displacement by 36%. Torsional TMDs drastically reduce pier forces and directional seismic sensitivity.	Numerical focus is limited to linear assumptions; extreme nonlinear seismic events with large plasticity require further physical validation.
Li et al. (2024) [16]	3D printed concrete cable (3DPC) structures.	The 'FloatArch' occurred successful integration of topology optimization and prefabricated, pre-tensioned 3DPC segments.	Interlayer adhesive strength and optimal reinforcement strategies within the 3DPC matrix are still the main structural limitations.
Louhibi et al. (2025) [17]	Computational Fluid Dynamics (CFD) for aeroelastic stability.	Accurately extracted drag and lift coefficients for bluff decks. Identified critical flow separation zones and vortex shedding vulnerabilities.	Simulations were entirely steady-state; failed to capture unsteady phenomena like structural buffeting or transient gust effects.
Song et al. (2023) [18]	Surrogate models for cable force optimization.	Combined B-Splines with Differential Evolution and surrogate predictors to reduce raw material consumption drastically reduced.	The surrogate predictor's accuracy heavily depends on the quality and volume of the initial training sample set.
Atmaca et al. (2023) [19]	Jaya algorithm for force optimization.	Optimized cable sizes as well as post-tensioning forces very effectively, and no special tuning parameters of the algorithm were needed in the process.	The selection of the final optimal design from the set of solutions generated by the Pareto front is greatly dependent on the engineer's judgment.
Pirner & Fischer (1998) [20]	Wind-induced vibrations of SRBs.	Empirically confirmed high sensitivity to dynamic wind loads due to the structure's ultra-low bending rigidity and low inherent damping.	Required highly specific aeroelastic scaling for wind tunnel tests; extrapolation to full-scale phenomena carries inherent uncertainty.
Yoshimura et al. (1997) [21]	Aerodynamic edge modifications.	Proved that half-circular and half-elliptical edge fairings suppress vortex excitation and drastically increase the critical flutter speed.	Specific to elongated rectangular cross-sections; aerodynamic benefits may vary widely if applied to deeper or highly asymmetrical girders.
Hasani et al. (2025) [22]	AI-driven Automated SHM.	Using Discrete Wavelet Transforms and long short-term memory (LSTM) autoencoders, they were able to automatically detect and spatially localize stiffness loss zones.	AI models need to be trained with very large amounts of accurate baseline data to avoid false positives coming from harmless environmental noise.
Araya-Santelices (2025) [23]	Bridge management with AI, unmanned aerial vehicles (UAV), and building information modelling (BIM).	Demonstrated the entire process from capturing UAV point clouds to using convolutional neural networks (CNN) for their processing and then finally integrating the results into BIM Digital Twins without any problem.	Three main issues remain - data standardization, cross-platform interoperability, as well as the huge computational power demand of real-time multi-sensor fusion.

III. STRUCTURAL SYSTEM AND MEMBERS

The SRB system primarily consists of a deck and steel cables. In most projects, the deck is constructed from concrete, with prestressing and bearing tendons distributed uniformly throughout its cross-section. Designers typically use structural steel for the tension members, including plates, tubes, pipes, bars, or rolled shapes. Commercial cables come in types like locked coils, spiral strands, parallel wires or ropes. These systems generate large horizontal tensile forces. To work properly, the end abutments have to resist all that force. Still, multiple countries constructed them because, they are slender and aesthetically look great. Analyzing them turns out to be a bit of a headache. Geometric nonlinearity is the main issue, and it pretty much dictates the structural review. It also reacts heavily to creep and shrinkage. Finally, since they are so thin, they are quite prone to dynamic excitation. This flexibility is a core challenge. [14], [15], [24].

The physical form of an SRB depends on having a horizontal force that remains constant along the entire structure. During the design phase, the mid-span sag  $f_{max}$  for the maximum span  $L_{max}$  must be determined. From the equilibrium

conditions in horizontal direction, the mid-span sag  $f_{i,max}$  for the span of the length  $L_i$  is:

$$H = (g L_i^2) / (8 f_i) = (g L_{max}^2) / (8 f_{max}) \quad (1)$$

$$f_i = (L_i^2) / (L_{max}^2) f_{max} \quad (2)$$

In the span  $i$  we have

$$f_i(x) = 4 f_i (x(L_i - x)) / (L_i^2) \quad (3)$$

And,

$$p_i(x) = 4 f_i ((L_i - 2x)) / (L_i^2) \quad (4)$$

For a two-span structure as presented in Figure 3.

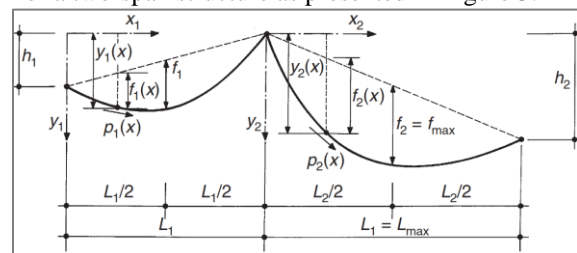


Figure 3: Structural system of cable - Figure illustrates the geometric parameters of a two-span SRB cable system under static equilibrium. It shows the coordinate systems (x,y) used to derive the local mid-span sags ( $f_1, f_2$ ) relative to span

lengths ( $L_1, L_2$ ) and support elevations ( $h_1, h_2$ ). These variables are mathematically required for determining the constant horizontal tensile force required across the entire structure during initial form-finding. [24]

For Span 1:

$$y_1(x) = \frac{h_1 - h_1/L_1 x + f_1(x) = h_1 - h_1/L_1 x + 4f_1(x)(L_1 - x)/(L_1^2)}{(5)}$$

$$p_i(x) = -h_1/L_1 + p_1^0 = -h_1/L_1 + 4f_1((L_1 - 2x)/(L_1^2)) \quad (6)$$

And for Span 2:

$$y_2(x) = \frac{h_2 - h_2/L_2 x + f_2(x) = h_2 - h_2/L_2 x + 4f_2(x)(L_2 - x)/(L_2^2)}{(7)}$$

$$p_i(x) = -h_2/L_2 + p_2^0 = -h_2/L_2 + 4f_2((L_2 - 2x)/(L_2^2)) \quad (8)$$

The load transfer in an SRB is a highly sophisticated operation because it depends on the use of very large horizontal tension for equilibrium. The dead weight of the precast concrete deck panels and the main tendons, together with transient traffic loads, are the vertical loads which the main cable system takes directly. These vertical forces are converted into huge horizontal tensile forces due to the shallow kinematic profile of the catenary curve. Thus, this very large horizontal load has to be transferred through the huge anchorage blocks and the foundations to the surrounding soil for complete dissipation as shown in Figure 4.

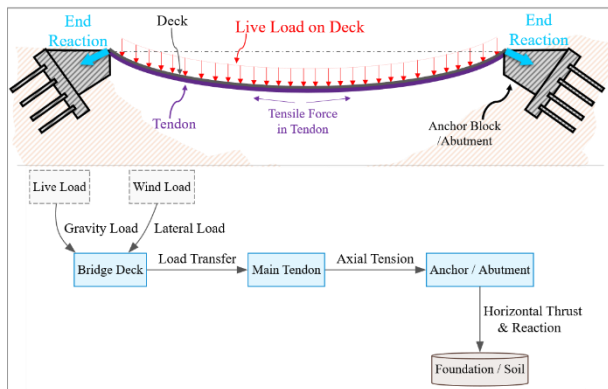


Figure 4: Load transfer mechanism

Intermediate load transfer in multi-span layouts is achieved using saddles. Here, the changing vertical reactions and the applied dynamic loads cause the friction forces to resist the longitudinal movement of the tendons. These saddles are very important structurally because they add their own curvature to the ribbon which in turn lessens the bending moment concentration and reduces the stress spikes at the points of detachment.

#### IV. CONSTRUCTION PROCESS

The build process for a SRB typically begins by anchoring bearing cables between the abutments. Once these cables are secure, precast concrete segments are positioned along the lines, followed by the pouring of concrete joints. To achieve monolithic behavior, engineers use prestressing. This method introduces compression throughout the deck, essentially turning the system into an inverted arch. It is also possible to prestress the bridge by preloading before the joints are finalized [25]. In practice, the assembly of an SRB is usually

independent of the specific terrain features below. These precast units are suspended from the main tendons and moved into their design locations (Figure 5). Overall stability for the finished deck is achieved through prestressing, which is applied after the casting of the joints or the full continuous band.

The bridge undergoes a fundamental change in behaviour over time. During the construction stage, the system acts like a perfectly flexible cable, yet it functions as a prestressed tendon once in service. Ultimately, the geometry and stress levels set during the erection phase are defined by the loads expected during the lifespan of the bridge.

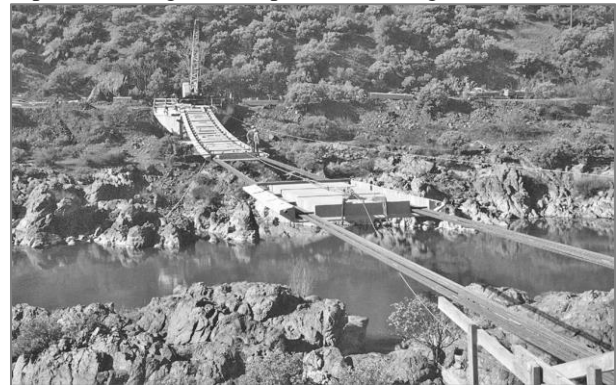


Figure 5: Placing of deck over SRB main cables [24]

#### V. MAIN TENDON

The performance of an SRB is mostly dictated by its high degree of geometric nonlinearity, which thus necessitates a thorough structural analysis of the bridge. In contrast to standard girder bridges, an SRB experiences a unique set of motions and changing structural characteristics throughout its lifetime; it is essentially a highly flexible cable at the time of initial erection, but it behaves as a highly prestressed, monolithic composite tendon after the concrete joints are cast and the bridge is in service. Table 1 comparative study explains that mitigating the difficulty of performing such a thorough analysis of an SRB structural performance calls for a trade-off between the excessive computational cost of a detailed finite element model and the need for accurate dynamic response predictions. The main tendons, which are in the form of a shallow catenary, dictate that the structural behavior of these elements comprise large displacements and include highly non-linear stress-strain dependences [6], [7], [25]. Considering the sag under different tension conditions, the behavior of the main tendons is accurately accounted for by the mathematical model given in [26], [27] where the equivalent tangent modulus of elasticity  $E_{eq}^*$  is conventionally derived. The corresponding equation is:

$$E_{eq}^* = \frac{E^{cable}}{(1 + \frac{(\rho g L_x)^2}{12 \sigma^3})} \quad (9)$$

where  $E_{cable}$  is the elastic modulus,  $\rho$  is the material density,  $g$  is gravitational acceleration,  $L_x$  is the horizontally projected length, and  $\sigma$  is the tensile stress. Furthermore, because the deck profile is exceptionally thin, the flexural stiffness of the system is highly sensitive to time-dependent material deformations, particularly concrete creep and shrinkage.

The second method involves partitioning each tendon into multiple straight segments as illustrated by [28] to

approximate the cable's catenary arch shape. Such models usually lead to a significant rise in degrees of freedom. Therefore, there is a high demand for both computer memory and processing time. Probable calculation instability or incorrect results might happen, if the equilibrium at those specific nodes is not perfectly satisfied. A third strategy for tendon representation makes use of isoperimetric elements as seen in [16]. Basically, these specialized elements incorporate the natural curvature of the catenary arch into their mathematical formulation. By adopting this technique, one can represent the curved cable path using far fewer elements than the straight element method requires. As evidenced by the limitations identified in Table 1, particularly regarding Karoumi (1999) [7] and Goldack & Schlaich (2016) [8], the primary bottleneck in current numerical modeling is not the lack of precision, but the inability of standard 2D and 3D FEM to account for Poisson's ratio effects and localized edge stress spikes without reaching a state of computational instability. This yields high-quality outcomes while keeping the model size manageable by normal computer systems.

Research by Arndt Goldack and Mike Schlaich[8] performed research on how this system behaves upon contact with a saddle. One of their main goals was to look into the points of detachment. They also worked out the distribution of shear forces and bending moments. Additionally, they aimed to determine the specific stress distribution through the use of Finite Element Method (FEM) modeling. To establish an analytical solution, the researchers used a simple span under uniform loading conditions. In this analysis, the behavior of the main tendon was treated as equivalent to cables or ropes, following the logic established by Gribniak [29] and Ma et al. [30]. Barlow's formula clarifies how the contact stress of surface is distributed from the saddle peak toward the point where the bridge ribbon detaches. It is worth noting that a similar pressure pattern is seen in elevator wires moving over pulleys and sheaves [31].

Results from the FEM suggest that a saddle provides a very effective support system for an SRB. By forcing the saddle's own curvature onto the ribbon, this setup lowers bending stresses more effectively than fixed supports. The bending moment at the end support stays limited. Importantly, it does not seem to depend on how the bridge as a whole deforms. Their numerical investigation into pedestrian-scale SRBs supports these analytical findings. Observations show that typical contact stress patterns appear between the ribbon and saddle, characterized by a stress spike at the detachment point. Because of traffic and wind, the main tendon experiences fluctuating tension during its service life. Li G et al. [32] proposed a specific tension test to address this issue. This is a fatigue-based evaluation which, continues until the bridge tendon wire actually breaks. This type of tests is much less common than standard bending tests. Currently, published test results are not formatted in a manner that allows for easy comparison with other data [33].

## VI. ANALYSIS AND OPTIMIZATION

SRB analysis is generally divided into two phases, static and dynamic. The static behavior of an SRB is derived from its underlying structural system and the sequence of construction. Figure 6 indicates a structure in which main

tendons support deck of disconnected precast concrete slab panels. The weight  $g$  is composed of the weight of main tendons  $T_g$  and the weight of the deck panels  $S_g$ . Assuming that main tendon as polygon which follows the catenary curve of equal loads placed at vertices. At every joint  $i$ , the result force  $T_Ri$  in main tendons balances the vertical load  $G_i=glp$ . The anchor block at end are loaded by tension forces  $T_{N0}$  and  $T_{Nm}$  that originate from the bearing tendons. During construction, the initial sag of tendon alone  $f_T$  increases to  $f_g$  when deck segments are placed as shown in Figure 7.

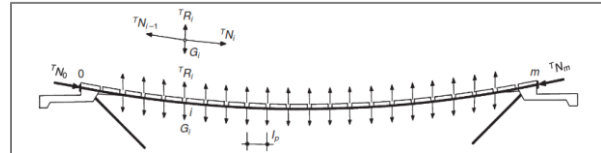


Figure 6 : Free-body diagram illustrating the static equilibrium of main tendons supporting disconnected precast concrete deck panels along a polygonal catenary profile. At each joint  $i$ , the vertical gravitational load  $G_i$  is balanced by the resultant tension  $T_{Ri}$  from adjacent cable segments. These accumulated axial loads transfer longitudinally to the anchor blocks, represented by equilibrium tension forces  $T_{N0}$  and  $T_{Nm}$ .

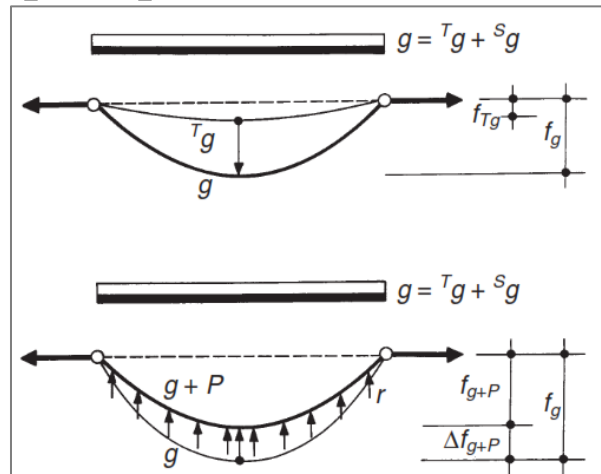


Figure 7: Loading deformation of SRB. Drawing shows geometric nonlinearity of the bridge during progressively loaded. Initially, the tendon's construction sag  $f_{Tg}$  increases to an equilibrium state  $f_g$  under the superimposed dead load  $g$  of precast segments. After application of live load  $P$  induces an additional non-linear kinematic deflection  $\Delta f_{(g+P)}$ , highlighting the system's structural sensitivity to dynamic displacements.

Structurally slender SRB can be considered as a very vulnerable to dynamic excitations from wind, traffic, and even seismic events source, especially if one looks at it solely from a performance perspective. During dynamic loading, the prestressed concrete deck interacting kinematically with the support cables results in a very complicated combination (matrix) of forces that comprise vertical, lateral, and torsional ones. To assess structural stability accurately, analytical models must linearize the dynamic setup near the static prestressed state, resulting in a stiffness matrix that strictly separates elastic contributions from the geometric stiffness provided by the massive cable tension. While the high axial tension provides the necessary global geometric stiffness, the slender deck remains vulnerable to aerodynamic instabilities,

requiring careful evaluation to prevent vortex-induced oscillations and aeroelastic flutter. Ultimately, ensuring long-term structural performance requires a rigorous evaluation of the ribbon's flexural stiffness which is frequently neglected or oversimplified in preliminary designs to prevent lateral displacement of intermediate supports under dynamic loading conditions. Throughout construction, the main tendon is the cable that carries all the loads. Usually, these tendons are not fixed in any way to the saddles, so they can slide freely when forces are applied. The cables for the span  $gL_1$  and  $gL_2$  pass-through the fixed support structures (Figure 8). Changes in applied load can create saddle friction, which depends on the vertical reaction  $R$  and the friction coefficient  $\mu$ . At each support, the frictional force  $\Delta H$  works against the tendon movement, where  $\Delta H = R \mu$ . At last, tendon stress is affected by anchorage block elongation and, potential displacement of the end supports.

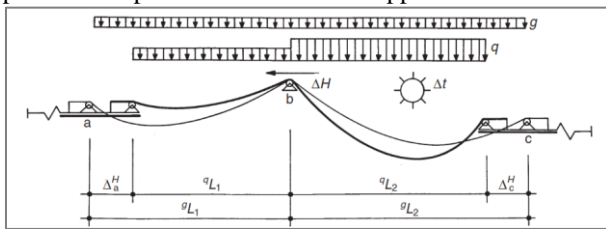


Figure 8: Diagram illustrating the tendon's kinematic behaviour during construction, functioning as a flexible cable across discrete supports. As the tendon slides freely over intermediate saddles, asymmetrical loads  $q$  induce longitudinal movement. This sliding is mechanically resisted by localized saddle friction  $\Delta H$ , derived from the vertical reaction  $R$  and the interface friction coefficient  $\mu$ .

Other researchers suggested using a multi-body mechanical system for structural system analysis. Using this concept, an elastic section model was recently introduced to explain suspension bridge dynamics as an equivalent flexible multi-body system [17]. The author stated that interactions between the cable and the deck of bridge, which can be nonlinear or linear, often involve vertical, lateral, or torsional deck forces. These also include the major transversal forces produced by multiple resonant tendons. To represent these cable bridge dynamics in the cross-section plane, a multi-body model is often adopted. This model is made of a primary subsystem, which is a rectangular rigid body, along with two secondary subsystems consisting of two identical point bodies. From a structural engineering angle, this arrangement is more or less a geometric model of a standard rigid bridge deck section. The deck is suspended by two pliable cables that are connected to the main suspension cables running on top.

Vertical centroid displacement  $V$  and the rotational angle  $\theta$  fully define the dynamic setup of the main subsystem, as seen in Figure 9. Two linear elastic springs link this main subsystem to the ground below in a standard arrangement. This specific configuration effectively represents the dynamic state of the overall bridge model. Eventually, the researchers found that linearizing the dynamic model near the static pre-stressed state results in a standard cable bridge problem. A stiffness matrix governs this problem, where geometric and elastic parts are identified as separate contributions. SRBs typically use a relatively simple deck and main tendon arrangement in most practical designs.

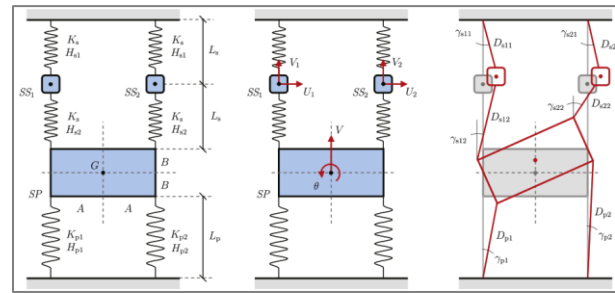


Figure 9: Multi-body section model. This equivalent flexible multi-body section model represents the dynamic interactions of complex beam-cable-beam. A large rectangular primary rigid body representing the stiff deck is connected with secondary point-mass subsystems and linear elastic springs simulating suspension cables. The dynamic state of the system is mathematically described in terms of the vertical centroid displacement  $V$  and the torsional rotational angle  $\theta$  to differentiate modal responses [17].

In their specific work, Xiao Wei Ye et al. discussed the nonlinear dynamics involving beam-cable-beam interactions [34]. They explored the behavior of these systems across several different configurations to ensure a broad understanding. The authors used a planar structural model with two vertical cantilever beams that were fixed at the base. A shallow cable with a specific sag connects these beams at their top ends to form the arranged system. The computed data looked at global, local and hybrid systems using various degrees of freedom as part of the study. It was seen that the geometric nature of quadratic and cubic couplings influences the motion equations and boundary conditions significantly. Natural frequencies and modes were calculated using an exact numerical solution for linear eigen problems which govern small vibrations. To check the nonlinear forced response of the system they created a two-degree-of-freedom (2DOF) model. This involved projecting displacement fields into a smaller space representing global and local modes. Model damping appeared to have only a small impact on the results in this particular case. Furthermore, the study accounted for internal detuning and cubic terms to improve accuracy. Finally, the authors identified a quasiperiodic solution following torus bifurcation at lower amplitudes. These findings were observed within a specific, limited range of the parameters used in the model.

Globally, engineers continue to build bridges supported by cables for various needs. These bridges are often the top choice for long spans and critical transport links. Within an SRB the cable represents the primary structural component. Few authors have suggested ways to improve tendons in order to save costs or improve strength. Most of these solutions focus on the geometry of the tendon profile or the cross-sectional area. For example, Dabrila [35] performed an in-depth study on the dynamic response of such bridges. By using a 3D model that included geometric nonlinearities, the research examined how long spans behave under nature's lateral forces. Both synchronous and nonsynchronous excitations at the supports were used to observe how traveling seismic waves affect the structure. Abdel and Khaliffa [36] looked at dynamic behavior as well. Specifically, they researched for how vibrations in the main cable impact the total bridge response. Hongyou et al. [37] took a different

path by focusing on optimization for safety. The team studied seismic performance to see if passive isolation systems - located between the deck and connecting parts - could provide benefits. Regarding isolated bridges, Yang et al. [38] studied how dynamic soil structure interaction changes behavior during seismic events. At last, Caetano et al. [39] worked on mathematical modeling for dynamic performance. Their 3D FEM model included the transversal motion of the tendons. It was also refined using field data from various vibration tests of labs.

Camara inspected various analysis methods to assess how cable-supported bridges behave dynamically in both linear and nonlinear ranges. This work also looked at how design variations and passive devices inside the towers might help bridges handle seismic forces better than other dissipation system. In a specific study, Camara and Efthymiou [10] examined how the deck and its supports interact during transverse seismic events. These researchers investigated how various vibration modes are affected by factors like main span length or the specific shape of the towers. They also accounted for the cable system layout, deck geometry (width and height), and local ground conditions. Most of this research was informed by various laboratory vibration tests. Multiple other studied about the optimization of cable-stayed bridges under static load which has been published in [18], [19], [40]. The computation tool for generative artificial intelligence technology was studied by Zhang [41]. In this research, they have presented structural concreting modelling and stated proper optimization methodology for bridge as shown in Figure 10. A computational flowchart presented here describes an iterative multi-objective optimization framework for cable-supported bridges. It deeply integrates a structural analysis module considering time-dependent parameters, geometric nonlinearity, and modal frequencies with a sensitivity analysis algorithm. The system, by continuously updating design variables according to stress ( $\sigma$ ), displacement ( $u$ ), and frequency ( $\omega$ ) gradients, eventually converges on an optimal configuration.

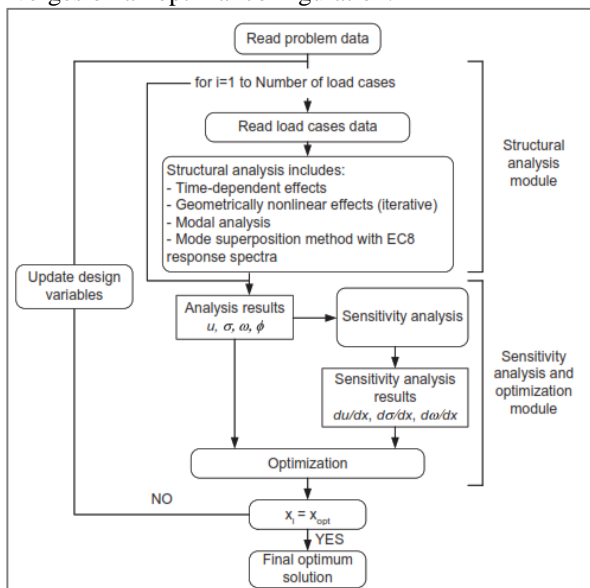


Figure 10: Flowchart for computer program for optimization. [41].

The study found that a multi-objective optimization framework can be used to design concrete cable-supported

bridges under seismic conditions. These mathematical solutions aim to strike a balance between structural efficiency and economic costs during earthquakes. However, the researchers pointed out that certain influencing factors were omitted from this analysis. For instance, the research does not cover active or passive control devices [11]. It also excludes soil-structure interactions and the spatial variability of ground motion, which remain in the future scope. Significant effort has already gone into the design optimization and form-finding of cable-based structures [12]. Common strategies in this field include the force density method (FDM) [42]. Few of the researchers, have also used the dynamic relaxation method or the geometrically nonlinear FEM [43]. These approaches provide the foundation for current cable bridge modeling.

On the account of high geometric nonlinearity, even minor movements in a supporting frame can heavily impact the final shape and force distribution of a cable-based structure. Consequently, researchers argue that the flexibility of the frame and its interaction with the cables must be fully accounted for during form-finding and design stages [44], [45], [46], [47], [48]. These established useful methods have been explored further to handle the form-finding of entire structures that include both tendons and other structural components [49]. One of the recommended strategy for managing cable-strut systems involves replacing compression members with equivalent external forces. With the same focus, P.G. Malerba explored, cable-strut systems using the extended force density method (EFDM). One more research was done by fixing certain point positions while also defining the intensity of the reaction forces on member [13]. A common challenge is that cable and beam elements are often non-compatible. This means that a cable network and its flexible support frame usually cannot be joined directly during the initial form-finding phase.

Further studies by Rui Nie, Biyan He, and their colleagues focused on optimizing cable networks that use flexible frames [50]. The researchers in their study, applied the force density method to complex networks and solved the resulting equations using both mathematical theory and ABAQUS FEM computer software. Their model treated cables as linear elastic components. Meanwhile, they used Euler-Bernoulli beams to account for bending and axial strain within the frame. This specific approach was used to optimize the design of mesh reflector antennas, which require very high surface accuracy. The results were later confirmed through computer-aided verification. In a related field, Zhiwei Cui and Xiaoqiang Tang examined cable tension optimization for cable-driven parallel robots [51]. Their research proposed a new geometric method to handle tension distribution. Unlike traditional iterative optimization, which can be quite time-consuming, this new method does not require a specific starting point to begin calculations. This helps remove problems like unpredictable calculation times or the need for a high number of repetitions. The authors concluded that using a centroid method for cable tension results in better continuity and improved safety levels. Junjun Guo and Wancheng Yuan et al [52] studied on the topic of cable optimization for curved cable bridges with annealing simulation. In this research, they have created a numerical model of a curved cable-stayed bridge for cable force

optimization. This was done in the OpenSees platform as shown in Figure 11. They have proposed a method for determining the optimum cable force which can be used for future designs related to the field. In order to find global optimization in a large search, Simulated Annealing (SA) approach was used. This was done for approximation using the reference problem [53], [54]. As compared in Table 2 alongside other recent algorithmic approaches, these heuristic methods are powerful but often obscure the underlying structural logic. The implementation flow of the SA is shown in Figure 12. It is mentioned that the Python language was used by the researchers for the simulations.

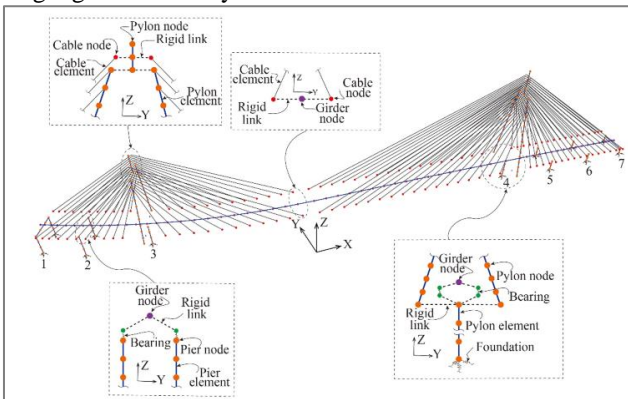


Figure 11 : Three-dimensional finite element model details the spatial discretization of a curved cable-stayed bridge for targeted cable force optimization. Developed within the OpenSees platform, the geometry utilizes dedicated nodes, elastic elements, and rigid links to accurately transfer multidirectional spatial forces between pylons, girders, and discrete cable strands. It captures the coupled torsional-flexural behaviours necessary for optimization algorithms. [52]

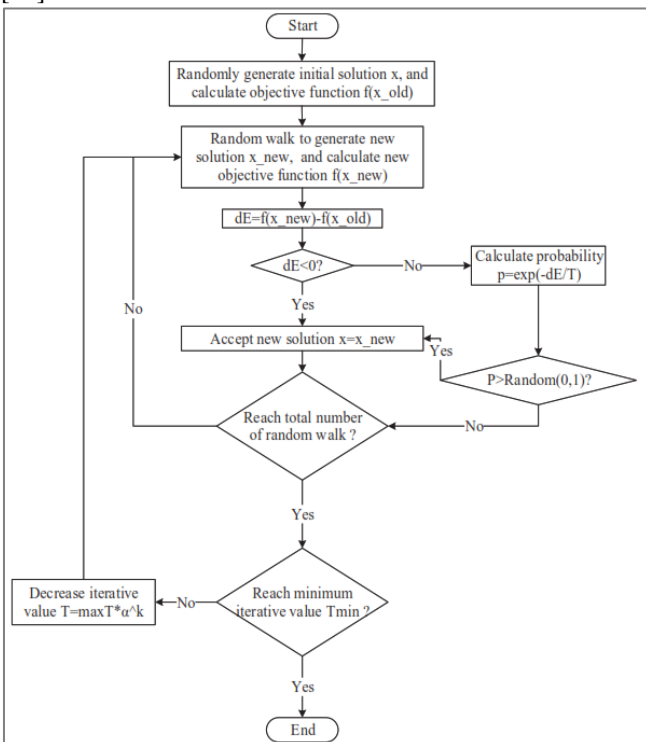


Figure 12: Algorithmic flowchart delineating the SA heuristic methodology applied to achieve global optimization of cable tension forces. It evaluates random probabilistic walks,

calculating the differential energy (dE) between objective functions. To purposefully escape local minima, it strategically accepts suboptimal states using a temperature-dependent probability function  $P = \exp\left[\frac{-dE}{T}\right]$ , gradually decreasing temperature T until reaching the absolute global optimum.

### AERODYNAMICS

It is well established that large-span SRBs are highly sensitive to wind forces. The study on improvisation in the aerodynamic stability was done by T. Tanaka et al. [55]. In the study, they have prepared two categories of hybrid pedestrian SRB. These consisted of a very large full-steel or light weight concrete-steel girder. Experiments were done on two types of edge, types of which include one with normal flat and the other one with circular as shown in Figure 13.

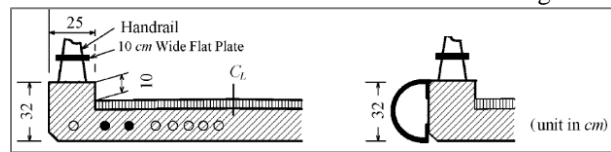


Figure 13 : Flat and round edge of bridge deck - This cross-sectional diagram compares a standard flat-edged concrete-steel girder against an aerodynamically modified semi-circular edge. [55]

A 1:4 2D model was prepared by the researchers in order to find the aerodynamic characteristics of the SRB. The research concluded, The horizontal component of tensile force in the cable can be reduced up to 1/23 of the typical concrete SRB. Also, it was found that the asymmetrical live load can be well controlled by the use of central clamps. It is seen that vortex-induced oscillation in both vertical bending and torsion does not occur in the bridge. Therefore, this type of bridge can be designed for vehicle bridges. Pirner and Fischer [20] have studied on the vibrations occurrence in SRB due to wind force. It is a fact that the ribbon bridge is highly sensitive to the dynamic loads. Due to that, it creates discomfort to the users. A scaled model of the bridge was prepared by the researchers in order to study aerodynamic behaviour. Authors have concluded that, danger of aeroelastic and other wind excited vibrations can be avoided. This can be done by using adequate design procedure and wind tunnel tests.

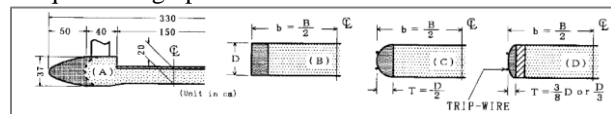


Figure 14: Edge modification profiles for aerodynamic study - The variations include an aerodynamic fairing (A), a standard blunt edge (B), a half-circular edge (C), and a half-elliptical edge (D) equipped with trip-wires.

Yoshimura and Mizuta et al. have carried out research on edge modification of SRB to increase the aerodynamic stability of the bridge (detailed in Table 2). The researchers have tested various models with different edge conditions in the wind tunnel as shown in Figure 14 [21]. The edge is tested with an aero shaped profile, flat rectangular profile, and half circular & half elliptical profile. Authors have also studied for vortex excitation of lighter decks. They concluded that by the deck-edge modifications, the critical flutter speed for elongated rectangular cross-sectional models can be increased. Up to

for thin airfoils, they found the circular cylindrical edge effective for the aerodynamic stability of the bridge.

### VII. PATENTS & NEW TECHNOLOGIES

Younggu Choi et al. [56] have invented a stress ribbon lever structure. This innovation was designed to reduce localized bending moments and streamline the SRB construction method. With five claims to the invention, they have presented a lever structure (10). It is formed integrally with the fixing member (12) and the vertical member (14) forming an obtuse L-shape. The fixing member is around the alternating portion (20) in the ground slope direction as shown in Figure 15. The roller portion (162) reduces the excessive horizontal force and bending moment generated at the local point. Additionally, the inventors have suggested the construction method of the bridge. This consisted of chaplet placing main tendons first and arranging the deck segment over it one by one. At the end, the prestress is applied to the main tendon to make it a global structure.

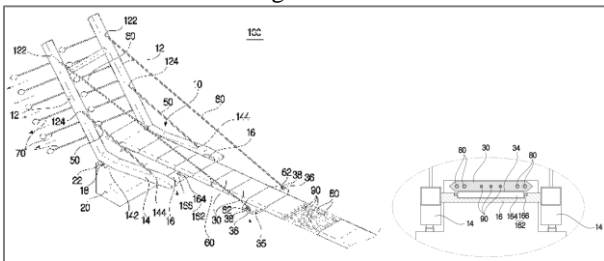


Figure 15: SRB - level structure

Han Kyu-seung et al [57] invented a self-anchor for stress ribbon pedestrian bridge in 2013. The invention was developed in order to solve the critical weakness of the self-supporting ribbon bridge. That is a sidewalk bridge supporting most of the force by the compression of the girder welded at the construction site. It can reduce the overall weight of the superstructure while functioning as a bridge. To reduce the horizontal force in the bridge, the inventors have increased the sag of the main tendon. This is done to reduce horizontal tension in the tendon. This caused a very steep slope on the profile and cannot be used for traffic. To overcome this issue, the inventor introduced the stirrups over the tendon and placed the deck over it to get a flat profile to use as shown in Figure 16.

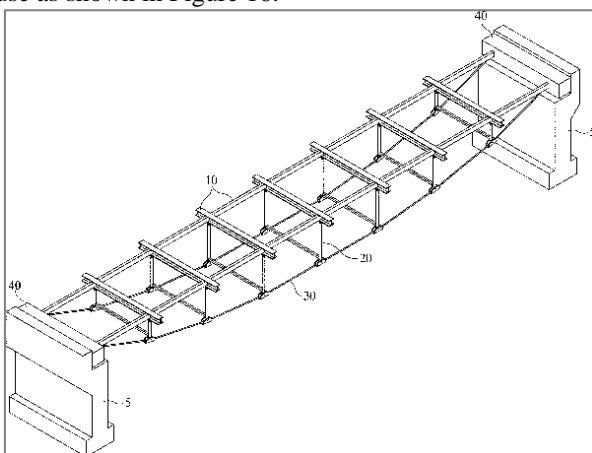


Figure 16: SRB with flat traffic profile

The inventor claimed the arrangement of the bottom fiber, plates, struts, and beam arrangement. This invention is inspired from the fish belly shaped prestressed concrete beam

invented by Lee Seon-gu. [58]. In this research, the inventor has introduced a beam with varying height and the profile looks like a fish boat from the side. The bottom of the beam is supported with a tension member as shown in Figure 17.



Figure 17 : Fish belly beam bridge

Ho-Keun Lee [59] has invented a fixed abutment-based SRB and its construction methodology. In this, he has invented a hinge support for the main tendon over the support which is more effective. It has better performance in stress generation at the support. Park et al [60] have invented a method. In this, they have presented a construction method for the precast segment of the deck member fixing on the main tendon. Additionally, they have proposed the providing of additional vertical members at the joint in order to reduce the frequency of the structure. The same inventor [61] has invented another construction method for the precast segment. In this, the inventor proposed placing the main tendon inside the deck and equally distributed tendon. Another inventor Hyun Ko [62] invented the fiber plate and fibre-reinforced polymer (FRP) deck system including its construction methodology for SRB. The inventor presented a deck system which can take heavy loads and have good structural performance.

Hasani H et al. [22] looked at an Artificial Intelligence (AI) based framework for structural health monitoring in order to automate modal identification and damage localization under different environmental variations. However, as highlighted in

Table 2, the successful deployment of these AI models requires massive amounts of accurate baseline data to prevent false positives. In a separate study regarding bridge assessment. Trach et al. [63] performed a similar study in the field of Structural Evaluation and used AI-based technology to assess the quantitative and qualitative condition of bridge parts/pieces such as reinforced concrete deck areas. In addition, Araya et al. [23] created a comprehensive review of bridge management systems that incorporate a combination of AI, unmanned aerial vehicles, and building information modeling technologies to improve damage detection and improve the ability to visualize data.

### VIII. DISCUSSION & CRITICAL ANALYSIS

This part discusses the modeling strategies and optimization methods recognized, and critically evaluates them. It categorizes the methods according to their fidelity and computational cost to deal with the geometric nonlinearities that are inherent in SRB.

#### 1) Comparative Assessment of Modeling Approaches

The literature review shows that there is a clear division in the modeling strategies in the two approaches: simplified equivalent stiffness methods and high-fidelity numerical integration. In the first stages of the design, the equivalent modulus method is mainly used. This method considers the catenary tendon as a linear bar element with its stiffness modified to account for the sag. Although, this type of

approach is simple and will linearize the problem which is essentially nonlinear. As it is shown with the equations that govern the catenary sag or mid-span (Eq. 1-4), the relationship of the horizontal force to the vertical displacement is very sensitive to the changes in the geometry. Accordingly, the usage of equivalent modulus methods is only right in sizing at the starting point and they cannot fully describe the beam-cable-beam interactions which are brought out in the latest publications.

From the furnished document, in later stages the design will be forced to non-linear FEM. With the isogeometric elements, the difference brought in the element formulation by using the exact catenary curve, is the major step forward from the usual discretization to isogeometric analysis. Consequently, the mesh required for the same level of accuracy compared to the straight-element approach is less. It is very important for SRBs where the material cross-section plays almost no role in stiffness besides the inherent geometry. In return, there will be a significant increase in the demand for computing power especially when evaluating dynamic saddle friction, and the sliding that happens at the supports.

To sum up, while a quick reference for the initial sizing is given by analytical models such as the equivalent tangent modulus [Eq. 9], their level really does not suffice in capturing the limit states of ultra-slender SRBs subjected to non-synchronous seismic excitation. A deep dive into the topic literature points to a solution through combining isogeometric analysis with AI-based surrogate models that makes it possible to retain high-quality results at only a fraction of the computational costs of highly nonlinear FEM-based traditional approaches.

### 2) Synthesis of Aerodynamic and Structural Stability

A synthesis of the aerodynamic research points out that the major lever for controlling the structural stiffness of SRBs is not the amount of material but the shape. For the geometric stiffness and Mass, the traditional heavy decks rely mainly on the stiffness from gravity,  $H = wL^2 \sqrt{8f}$ . However, the hefty decks bring along also an increase in the seismic mass. Studies on the changes to the edge of the deck tell that there is a better way. The idea would be to change the aerodynamic cross-section (e.g. circular or fairing edges) in order to postpone the start of vortex shedding.

In optimization of the cable profile, the concept of the 'Fish Belly' beam explores the catenary shape's fundamental limitation, that is, its bending under asymmetrical live loads. It is akin to a beam with variable depth that has more stiffness at points of high bending moment (supports or one-quarter points), thus the behavior of a cable and a beam has been effectively hybridized. This evidence supports the notion that the best SRB solutions are those that separate the functions of tension-bearing (cables) and traffic-bearing (stiff deck).

### 3) Advanced Design - From Heuristics to AI

The most common optimization techniques for SRB namely heuristic algorithms have been based on successive iterations, SA as well as other evolutionary methods. They are capable of determining the global minima of the cable force distribution effectively, yet they are computationally very inefficient. Traditionally this type of method considers the structural analysis as a 'black box' and thus one has to depend on the FEM iterations. The drawback of such a method is that

the structural logic is concealed. An important issue that these methods fail to address is the incorporation of AI and explainable AI (XAI) in the SRB design which remain unexplored and therefore offer a huge potential for a breakthrough. PINNs embedding the governing differential equations of the catenary (Eq. 5-8) into the learning process as a constraint, producing results in line with physical laws, without paying the astronomical price of numerical integration with standard methodology, should be the focus of future work. Moreover, to support the full automation of Structural Health Monitoring as the development progress, XAI will be a key technology overcoming the black-box nature of automated tools and making it possible for the engineers to distinguish clearly between environmental e.g. creep and structural damage that is critical.

## IX. CONCLUSION

This review paper systematically evaluates of the structural mechanics, aerodynamic stability, and optimization methodologies of SRB. Bridge engineering is, according to the study, moving from a stage where simplified analytical assumptions were used towards high-fidelity computational models. Among the most important observations is the fact that the transition from the linear equivalent modulus methods to the non-linear FEM with isogeometric elements has made it possible to capture extreme geometric non-linearities and complicated beam-cable-beam interactions with great precision. Besides the structural stiffness is better controlled by structuring the cross-section such as in the 'Fish Belly' variable-depth girder, and aerodynamic measures like semi-circular fairings, which effectively reduce vortex-induced oscillations and raise critical flutter speeds. Referring to the cable force optimization, however, it is still mainly dependent on heuristic 'black box' algorithms which, although solving the problem of finding global minima, keep the structural logic, a key component of safety-critical design, hidden.

In spite of these developments, noteworthy research remains in the aspects of dynamic validation and physical stabilization of ultra-slender decks. Extending the focus on issues associated with severe non-linear seismic responses and transverse deck-tower interactions, in particular, the coupled torsional-lateral instability, there is hardly any data available. Moreover, the 3D modeling of saddle mechanics dynamically at a high fidelity level including local edge stress spikes and transient longitudinal sliding is still beyond the reach of the conventional engineering workflows due to excessive computational requirements. The possession of sizable training data continues to be a major challenge for the application of AI in SHM, in which the existing systems less capable of identifying the critical structural degradation separate from the benign environmental noise or the rheological effects of creep and cable relaxation.

The resolution of instabilities in the next-generation bridge, therefore, requires research to concentrate largely on the integration of Physics-Informed Machine Learning and XAI. With the help of PINNs, it is possible to incorporate the governing catenary differential equations into the AI loss functions so that physical equilibrium laws are respected in rapid design optimizations without sacrificing the cost of numerical integration. Besides, the transition to XAI-based

monitoring systems will dismantle the opacity of current automated tools, thereby enabling engineers to clearly isolate the variables responsible for structural damage during the detection process. Lastly, the integration of biomimetic structural features such as self-diagnosis and damage tolerance offers a pathway toward bridges capable of actively responding to lateral vulnerabilities and dynamic excitations in real time.

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#### CONFLICTS OF INTEREST

The authors declare that there are no known competing financial interests or personal connections that could have influenced the findings presented in this manuscript.

#### AUTHOR'S CONTRIBUTION

Vijaykumar Parmar: Conceptualization, methodology, literature search, and drafting the manuscript.  
 Kaushal Parikh: Supervision, formal analysis, and critical review of the final manuscript.

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