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# Underdeck Cable-Stayed Tensegrity Footbridge

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## Abstract

This paper investigates the application of Tensegrity principles to underdeck cable-stayed footbridges, a typological combination that has not yet been systematically explored in literature. The concept of Tensegrity, characterized by discontinuous compression members stabilized within a continuous network of tension elements, has long attracted interest for its structural efficiency and aesthetic potential, yet practical applications in civil engineering remain limited. The motivation of the study lies in the possibility of enabling bridge decks that would otherwise be unable to resist external loads to achieve structural viability through the interaction of tension and compression elements arranged according to Tensegrity concepts. Following a review of existing Tensegrity bridge proposals, three conceptual configurations are proposed and evaluated through parametric structural models: floating transverse compression members, variable-length isolated bars and inclined mast planes. The mechanical performance of each configuration is assessed through structural analysis, with attention to midspan deflection, peak cable and strut forces, deck bending moments and self-weight of the whole structure. Results indicate that the proposed configurations achieve meaningful improvements in structural efficiency relative to the baseline underdeck cable-stayed system, and several configurations suggest potential for deployable or partially foldable bridge systems.

**Keywords**: tensegrity structures, underdeck cable-stayed bridges, footbridges, deployable structures, structural efficiency, parametric modeling, cable-supported structures, spatial structures, prestressing.

## 1. Introduction

Tensegrity structures, first conceptualized by Karl Ioganson [1] and later formalized through the work of Kenneth Snelson, Buckminster Fuller and George Emmerich [2], are defined by the coexistence of discontinuous compression members (struts or bars) within a continuous network of tension elements (cables or strings). The resulting systems exhibit self-equilibrium, geometric adaptability, and a visual lightness that has fascinated engineers and architects for decades. Despite these attributes, one of the main drawbacks of Tensegrity has historically been the lack of direct applications in civil engineering and architecture. The limitations that have existed regarding analytical tools, materials, and structural understanding have often relegated Tensegrity structures to the realm of sculptures or conceptual proposals rather than practical engineering solutions [3].

With the progressive development of computational tools, parametric modelling environments, and visual programming platforms, the barriers to designing, analyzing, and optimizing Tensegrity systems have been substantially reduced. This creates an opportunity to revisit Tensegrity principles and explore their integration into well-established structural typologies in bridge engineering. In particular, the

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underdeck cable-stayed bridge, in which cables are anchored below the deck and pass over masts or struts positioned beneath it, represents a structurally efficient and expressive typology whose performance depends critically on the geometry of the cable network and the compression behavior of its masts.

This paper addresses the gap in the literature regarding the integration of Tensegrity principles into underdeck cable-stayed footbridges. The objective is to investigate whether Tensegrity-inspired configurations, in particular, floating or discontinuous compression members embedded within a tensioned cable network, can enhance the structural efficiency, stability, and adaptability of this bridge typology, and whether such configurations can open the possibility of deployable or foldable bridge systems. Three conceptual proposals are developed and evaluated through parametric structural models.

## 2. Background and literature review

### 2.1. Tensegrity principles

The theoretical foundations of Tensegrity were established by Motro [2] and later formalized by Skelton and de Oliveira [4] among others, who developed a comprehensive mechanics framework encompassing stability criteria, prestress design, and form-finding methods. Form-finding, the determination of the equilibrium geometry under a given state of self-stress, has been addressed through dynamic relaxation, force density methods, and genetic algorithms [5, 6, 7]. Key structural characteristics of Tensegrity include deployability, kinematic indeterminacy, high stiffness-to-weight ratios when properly prestressed, and the absence of localized weak points due to the multidirectional tension network [3].

### 2.2. Underdeck cable-stayed bridges

Underdeck cable-stayed bridges constitute a structurally efficient variant of the cable-stayed family in which the stays are arranged below the deck, anchored to the deck itself and deviated through a series of struts. The deviation forces at each strut act as additional elastic supports for the deck, while the prestress of the stays introduces an axial compression that counteracts the bending demand under self-weight and live loads. This enables substantially more slender decks than conventional girder solutions for the same span, with material savings, increased structural transparency and a clean upper profile that has made the typology particularly attractive for footbridges. Their behavior is, however, intrinsically non-linear and highly sensitive to the cable layout, the strut arrangement, the level of prestress, and the relative stiffness between the cable-staying system and the deck, a topic on which several authors have developed extensive analytical, numerical and experimental research aimed at establishing design criteria and a deeper understanding of their stability and post-buckling response [8].



Figure 1: Examples of built underdeck cable-stayed bridges (left [8] and right [18]).

## 2.3. Tensegrity bridge proposals

Although several innovative proposals for Tensegrity bridges have appeared in literature and in practice, not all of them are genuinely Tensegrity systems; some are inspired by Tensegrity principles without strictly adhering to them. The following review distinguishes between structural solutions, aesthetic solutions, and non-Tensegrity solutions that are sometimes incorrectly classified as Tensegrity bridges.

### *2.3.1. Structural Tensegrity solutions*

The Deployable Tensegrity-Hollow-rope Footbridge, developed by Landolf Rhode-Barbarigos as the product of his doctoral research, is a purely Tensegrity deployable footbridge based on the typology of Tensegrity rings that enclose the bridge deck within their interior. Although the compression elements are in contact with each other, the system is deployable from both sides of the span and constitutes one of the most rigorous Tensegrity bridge proposals in the literature [9].

The Simplex Module Footbridge, proposed by Gómez-Jáuregui in his MSc thesis in 2003, explored the juxtaposition of simplex Tensegrity modules to accommodate a pedestrian deck within their interior [10]. This proposal, alongside other building and civil engineering structures, was presented as a basis for further analysis and development.

The Tor Vergata University Footbridge is a modular structure composed of juxtaposed expanded Tensegrity octahedra that house the pedestrian deck in their interior. The bridge features an intentional curved form with a sag reminiscent of tensioned-band footbridges. The deck rests on transverse horizontal bars, while the longitudinal horizontal bars serve as handrails [11].

The Kurilpa Bridge in Brisbane, designed by Cox Rayner and Arup, is the most significant Tensegrity bridge built to date and currently in service. While some vertical compression members are in direct contact with the deck, other transverse bars float freely in the air, meaning the structure broadly adheres to conventional Tensegrity principles. It stands as the most promising executed example of Tensegrity in bridge engineering [12].

### *2.3.2. Aesthetic Tensegrity solutions*

The Tensegrity Footbridge for the National Building Museum in Washington DC, proposed by Wilkinson Eyre Architects, is characterized more by its aesthetic component than by its structural role [13]. The Tensegrity substructure surrounds and suspends the main deck but does not appear to serve any significant load-bearing function.

The Splash Bridge, by Joel Cullum, was a finalist in the DesignByMany Building to Building Bridge Challenge in 2012 [14]. As with the Wilkinson Eyre examples cited above, the main load-bearing structure supports the Tensegrity substructure, which plays a purely architectural and almost sculptural role.

### *2.3.3. Non-Tensegrity solutions*

It is important to clarify that not all structures labelled as Tensegrity bridges genuinely embody these principles. The Forthside Pedestrian Bridge, designed by Wilkinson Eyre and Guilford, resembles the Kurilpa Bridge but is simpler, single-span, and has no isolated compression elements, all posts are in direct contact with the deck. It would more accurately be compared to an inverted Fink truss. Similarly, the Bankside Bridge proposal, whose principal engineer was Mott MacDonald, and the proposal by Zhou, Xie and Huang, featuring two Tensegrity arches with no purpose beyond the imposition of the Tensegrity principle, illustrate the risk of forcing Tensegrity into designs where its application is illogical [15].

The Tensegrity Bridge with Prestressed Deck, proposed by Briseghella, Fenu, Huang and Zordan, represents a more structurally motivated proposal, in which a conventional deck is inserted within a Tensegrity frame to increase its resistance. Scale models have been produced to represent this concept

three-dimensionally [16]. Tensairity systems, while not conventional Tensegrity structures as they use pneumatic elements braced with cables rather than isolated bars, represent an innovative related concept, with temporary bridges having been constructed for seasonal use [17].

### 2.4. Research gap

The review above confirms that, although Tensegrity principles have inspired a range of bridge proposals, none of the approaches developed to date has incorporated Tensegrity concepts into the typology of underdeck cable-stayed bridges. This represents a significant unexplored intersection, given the structural logic of this typology, in which the deck depends on a sub-deck tension-compression system, and the core principle of Tensegrity, which relies on isolated compression members stabilized by continuous cable networks. The present work addresses this gap through a set of three structured conceptual proposals.

## 3. Proposed Tensegrity-inspired configurations

All proposals depart from a baseline underdeck cable-stayed footbridge configuration: a simply supported deck, with V-shaped masts positioned below the deck soffit, connected by a system of inclined stays to anchor points at the deck level. The following proposals progressively introduce Tensegrity principles by incorporating floating or discontinuous compression members into this baseline system.

### 3.1. Proposal 1: Floating transverse compression members

Starting from the baseline configuration, horizontal transverse bars are added between the masts of the structure. In this way, floating compression members are introduced so that do not touch any other compressed component except through tension tendons, satisfying the core Tensegrity condition. As in the case of the Kurilpa Bridge, these isolated horizontal bars are expected to perform two structural functions: they laterally restrain the bottoms of the masts, preventing sideways buckling under loads from the deck suspension as well as lateral and seismic forces; and they act in unison with all masts and cables to resist twisting and lateral forces caused by patch loads, wind, and earthquakes.

The key research questions for this proposal concern the optimal longitudinal position of the floating bars for efficient structural collaboration, the appropriate bar length as a function of their position, and whether there is a dependency between the inclusion of these floating bars and the geometry of the lower tension chord. In the configuration evaluated in this study, the transverse bars are set to a constant length of 4 m.

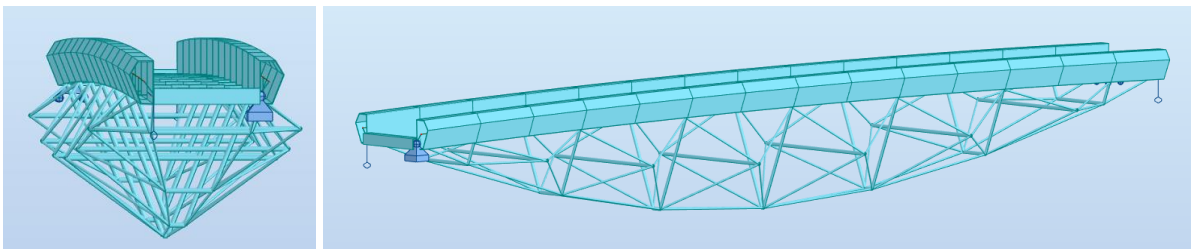


Figure 2: Proposal 1 – Underdeck cable-stayed footbridge with floating transverse compression members.

### 3.2. Proposal 2: Variable-length isolated transverse bars

In this proposal, the lengths of the isolated transverse bars introduced in Proposal 1 are varied parametrically rather than kept constant. Different bar lengths at different longitudinal positions produce an asymmetric compression network that may better match the internal force distribution in the cable system. The central research question is whether this variable-length configuration improves the structural performance of the bridge relative to the constant-length variant. In the configuration

evaluated in this study, the transverse bars vary in length from 4 meters at the ends of the bridge to 3 meters at the center, reflecting the larger stresses that develop toward the supports.

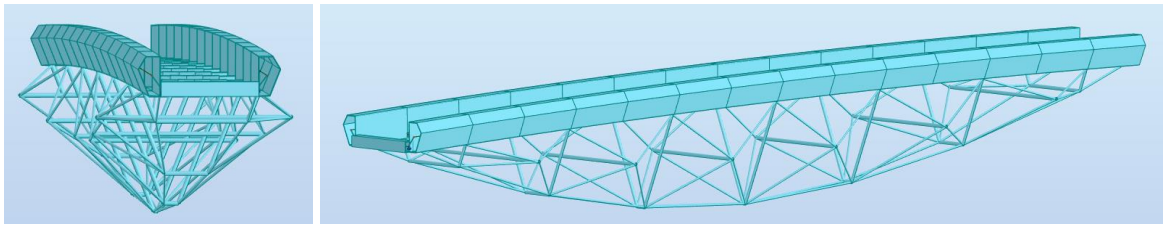


Figure 3: Proposal 2 – Underdeck cable-stayed footbridge with variable-length isolated transverse bars.

### 3.3. Proposal 3: Outward-inclined mast planes

Building on Proposal 1, the plane of the masts is inclined outwards, so that the mast pairs form a trapezoidal shape when viewed in cross-section. This configuration is analogous to the geometry of the Living Bridge at the University of Limerick and introduces a three-dimensional tension-compression interaction characteristic of Tensegrity modules. The angle of inclination is treated as the principal design variable. Research questions include the extent to which inclination of the mast plane improves structural behavior, the optimal inclination angle for a given mast arrangement, and whether the masts could be arranged on a ruled surface rather than a plane.

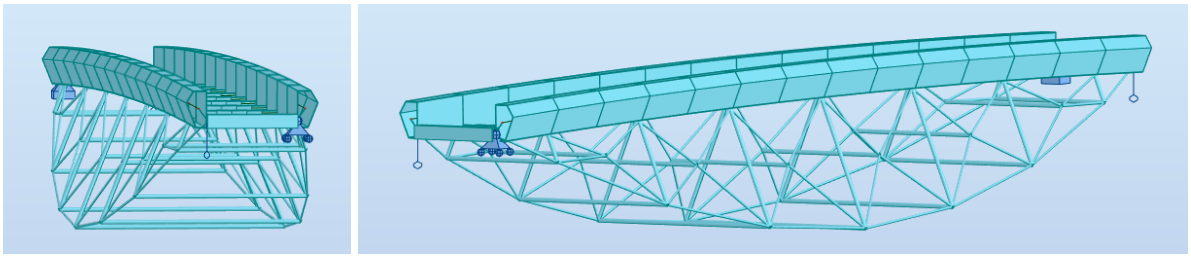


Figure 4: Proposal 3 – Underdeck cable-stayed footbridge with outward-inclined mast planes forming a trapezoidal-shape in cross-section.

## 4. Methodology

The structural performance of the baseline configuration and of the proposed Tensegrity-inspired variants was evaluated through a consistent numerical workflow. For each configuration, the geometry was first defined in a CAD environment, where the deck, masts, transverse bars, and cable layout were laid out in three dimensions according to the parameters described in Section 3. The CAD models were then imported into Autodesk Robot Structural Analysis Professional, which served as the finite element platform for all structural analyses.

Within Robot, each element was assigned its corresponding cross-section. The deck was modelled as a beam element with defined cross-sectional properties. Cables were modelled as truss elements with geometric nonlinearity to account for their catenary behavior under load. Masts, floating struts, and transverse bars were represented as beam-column elements capable of carrying axial and bending actions.

A reference footbridge geometry was established with a main span of 28 m, a deck width of 2.5 m, and mast heights of 2.8 m below the deck soffit. Structural steel properties (E = 210 GPa) were assigned to all bar elements, and high-strength cable steel properties (E = 160 GPa) to all cable elements.

Two load hypotheses were considered. LC1 corresponds to the self-weight of the structure (SW), automatically generated by Robot from the assigned cross-sections and material densities. LC2 corresponds to a uniformly distributed pedestrian live load (LL) of 5 kN/m2 applied over the full deck

area, in accordance with standard footbridge design practice. Both hypotheses are combined with partial safety factors in accordance with Eurocode EN 1990: 1.35×SW+1.5×LL.

Key parameters investigated include the longitudinal position and length of the floating transverse bars (Proposals 1 and 2) and the inclination angle of the mast planes from the vertical, ranging from 0° to 30° (Proposal 3). For each configuration, the analyses returned the deformed shape and the internal force distributions in all members. Performance metrics for comparison include the midspan vertical deflection under full live load, the maximum cable tension force, the maximum strut compression force, and the maximum bending moment in the deck. All metrics are normalized with respect to the baseline underdeck cable-stayed configuration to enable direct comparison across proposals.

## 5. Results and discussion

Prior to evaluating the Tensegrity-inspired proposals, a reference value for the maximum bending moment in the deck is established by treating it as a simply supported beam under the applied live load, without any cable system. For a uniformly distributed load (q) acting over a span (L), the maximum midspan bending moment is given by M=qL^2/8. Taking q=1.35×SW+1.5×LL=1.35×5.36 kN/m+1.5×5 kN/m^2×2 m=22.24 kN/m and L = 28 m, this yields M=22.24×28² / 8=2179.13 kN·m. This value serves as the upper-bound reference against which the improvements provided first by the underdeck cable-stayed system and subsequently by the Tensegrity-inspired configurations can be assessed.

Table 1 summarizes the normalized structural performance metrics for the baseline configuration and the three Tensegrity-inspired proposals under full uniform live load.

| Configuration | Midspan deflection (cm) | Max. cable force (kN) | Max. strut force (kN) | Max. deck bending moment (kN m) | Self-weight (kg) |
|---|---|---|---|---|---|
| Baseline (underdeck cable-stayed) | 1.2 | 238.99 | 29.90 | 112.30 | 17826 |
| P1 - Floating transverse bars | 0.7 | 210.34 | 158.05 | 59.69 | 18120 |
| P2 - Variable-length transverse bars | 0.3 | 210.42 | 155.40 | 59.74 | 18084 |
| P3 - Outward-inclined masts | 0.2 | 217.38 | 158.87 | 61.16 | 18299 |

Table 1: Normalized structural performance metrics for all configurations (P1-P3 correspond to the three proposals described in Section 3).

### 5.1. Results of Proposal 1

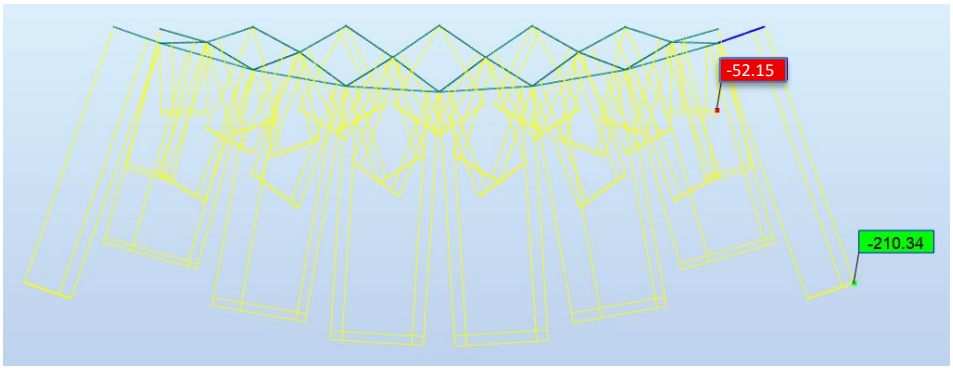



Figure 5: Proposal 1 – Axial force distribution in the cables (highlighted maximum and minimum values).

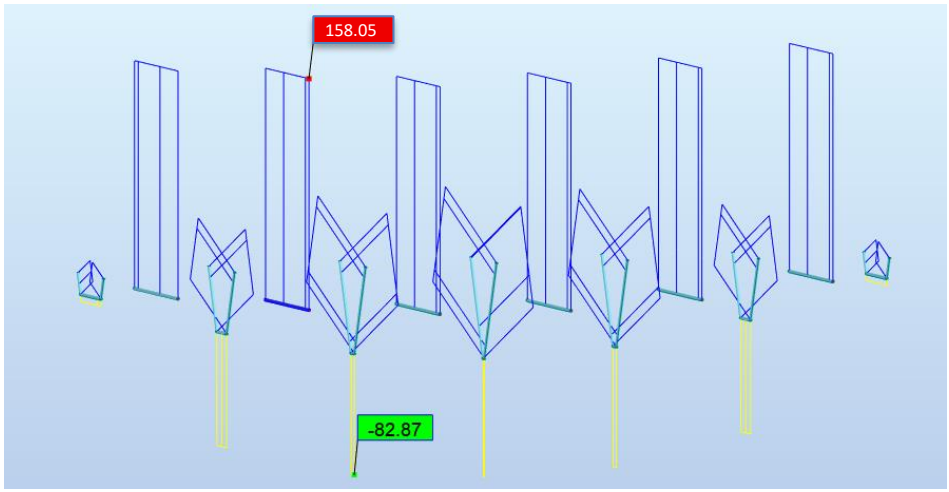



Figure 6: Proposal 1 – Axial force distribution in the struts (highlighted maximum and minimum values).

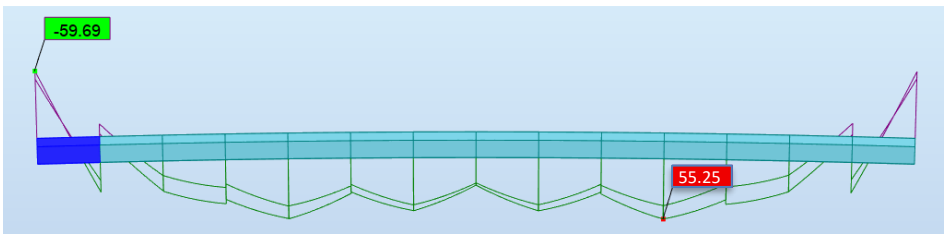



Figure 7: Proposal 1 – Bending moment distribution along the deck (highlighted maximum and minimum values).

The results demonstrate a clear improvement in overall structural performance when floating transverse bars are incorporated. The maximum deflection is reduced by 0.3 cm, while both the peak axial force in the cable and the bending moment in the deck decrease significantly, confirming that the inclusion of transverse bars enhances structural collaboration between elements and validating their role as an effective stiffening mechanism in this typology.

### 5.2. Results of Proposal 2

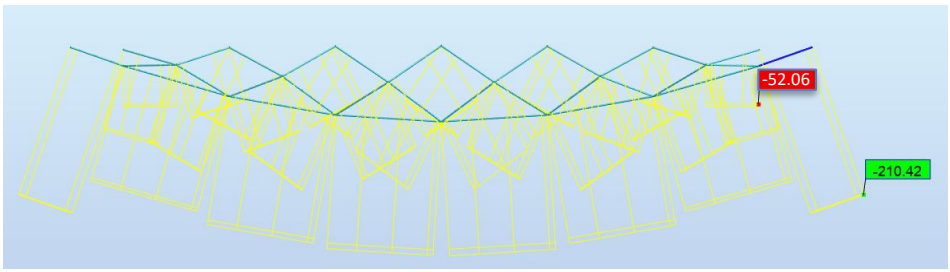



Figure 8: Proposal 2 – Axial force distribution in the cables (highlighted maximum and minimum values).

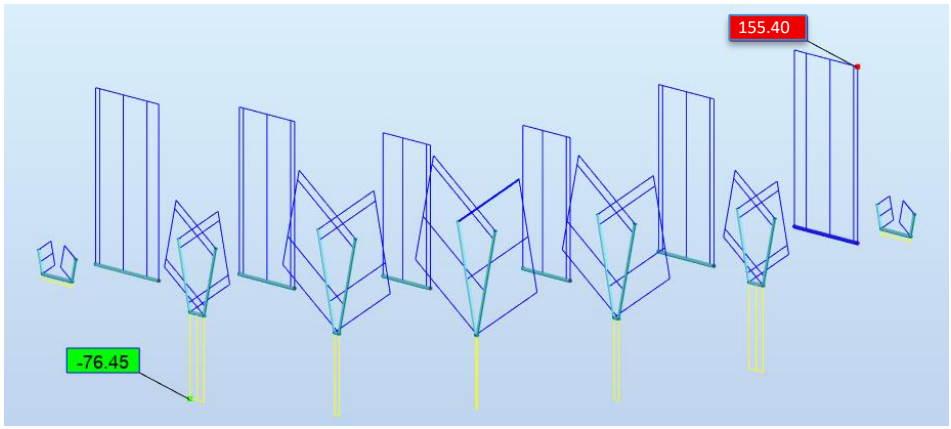



Figure 9: Proposal 2 – Axial force distribution in the struts (highlighted maximum and minimum values).

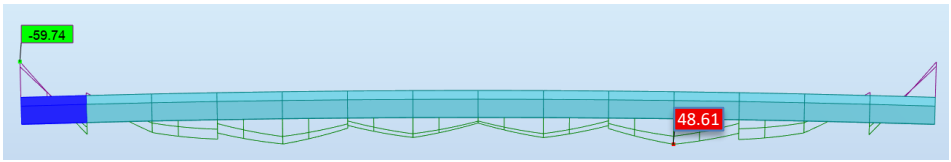



Figure 10: Proposal 2 – Bending moment distribution along the deck (highlighted maximum and minimum values).

The variable-length configuration yields a further improvement in structural performance compared to the constant-length variant. The maximum deflection is reduced by an additional 0.4 cm, while the remaining internal forces (axial force in the cable and bending moment in the deck) remain at comparable levels, demonstrating that the variable-length arrangement achieves greater deformation control without compromising the overall stress distribution.

### 5.3. Results of Proposal 3

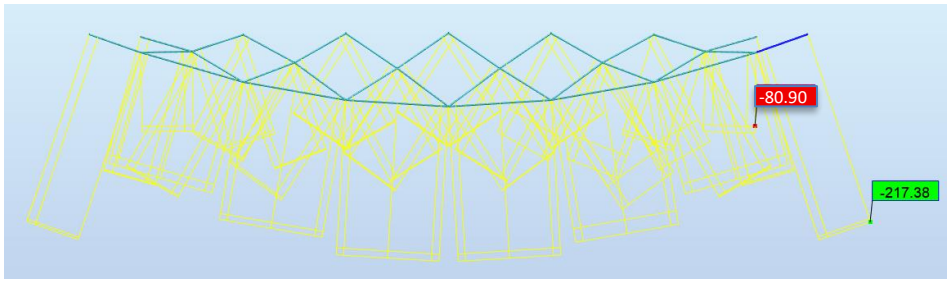



Figure 11: Proposal 3 – Axial force distribution in the cables (highlighted maximum and minimum values).

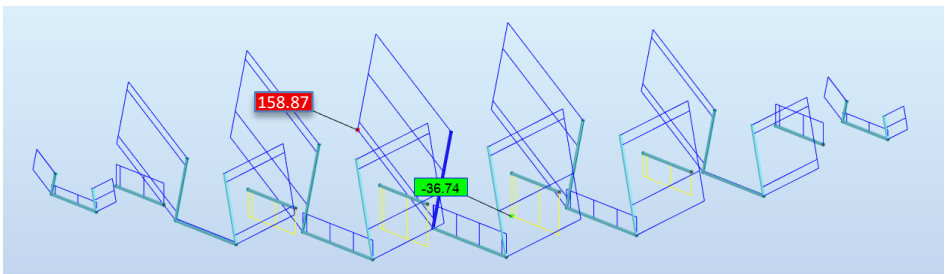


Figure 12: Proposal 3 – Axial force distribution in the struts (highlighted maximum and minimum values).

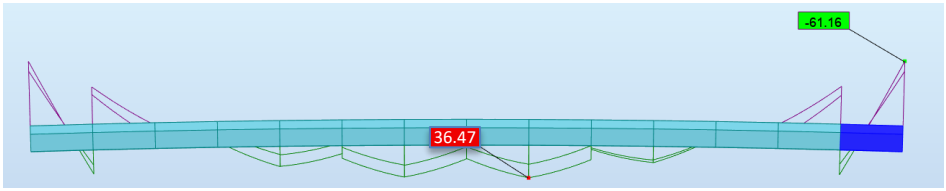



Figure 13: Proposal 3 – Bending moment distribution along the deck (highlighted maximum and minimum values).

The results indicate that inclining the mast plane outward has a negligible effect on the key structural parameters, with no significant improvement in deflection, axial forces, or bending moments. Since no structural benefit is achieved, and the inclined configuration is not considered aesthetically preferable, the V-shaped mast arrangement is retained for this typology.

## 6. Conclusions

The present work has explored the integration of Tensegrity principles into the typology of underdeck cable-stayed footbridges, a combination that had not been systematically addressed in the previous literature. Starting from a conventional underdeck cable-stayed baseline with a 28 m span, three Tensegrity-inspired configurations were developed, modelled in Autodesk Robot Structural Analysis Professional, and evaluated under self-weight and a uniformly distributed pedestrian live load of 5 kN/m².

The comparative results indicate that, in general, the introduction of floating compression members within a continuous tension network improves the structural behavior of the bridge. With respect to the baseline, all three proposals lead to a substantial reduction of the peak axial forces in the cables and of the bending moments along the deck, confirming that part of the load transfer is taken up by the new tension–compression interaction. The increase in axial forces in the floating struts is the expected counterpart of this redistribution and remains within values that are compatible with standard steel sections.

Among the three configurations, Proposal 2, based on variable-length isolated transverse bars, is identified as the most favourable solution. It achieves the largest reduction of peak cable forces and of the maximum deck bending moment of all proposals, while keeping the strut forces lower than in the other Tensegrity-inspired configurations. The variable-length strategy enables the compression network to be better matched to the actual distribution of internal forces along the span, with shorter bars (3 m) in regions of lower demand and longer bars (4 m) where the tension network requires more lateral stabilization. In addition, the use of independent transverse bars of different lengths suggests an interesting potential for deployable or partially foldable bridge systems, which is consistent with the broader motivation of Tensegrity research in civil engineering.

It should be noted, however, that a relevant structural limitation of underdeck cable-stayed systems, including all Tensegrity-inspired variants proposed here, concerns the risk of cable detensioning under certain load configurations. If the cables lose their prestress, the compression arch effect is lost and the deck reverts to a simply supported beam, leading to a dramatic increase in bending moments and potentially to structural failure. This makes proper maintenance of the cable system a critical requirement throughout the service life of the bridge, and underscores the importance of monitoring and periodic pre-stress verification as integral parts of the asset management strategy for this typology.

A more detailed assessment of dynamic behavior, fatigue, and constructability constitutes the natural continuation of this work and a necessary step towards the practical application of Tensegrity principles in underdeck cable-stayed footbridges. Future research should also expand the number of load cases

considered, incorporating wind and other horizontal forces, as well as explore additional structural proposals not covered in this study, such as Fink-type additional cable systems. Furthermore, an analysis of deployability, examining the potential for these structures to be assembled, transported, or deployed in a controlled sequence, represents a promising research direction that could significantly broaden the practical scope of Tensegrity-based footbridge design.

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