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Critical Discussion on the Performance of Underslung Movable Scaffolding Systems Strengthened With an Active Prestressing System

Discusión crítica sobre el desempeño de cimbras autolanzables inferiores reforzadas con un sistema de pretensado activo

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ABSTRACT

Movable Scaffolding Systems (MSSs) are widely used for the in-situ construction of prestressed concrete bridge decks, particularly in span-by-span methods. Underslung MSSs are typically applied to spans up to 60 meters; however, recent developments incorporating active prestressing systems have extended their applicability to longer spans. This paper presents a critical assessment of the performance of underslung MSSs with and without active prestressing, focusing on structural optimization and practical limitations across all construction stages. A case study based on the modular C-60 system is analysed for different span lengths (50 m, 60 m, and 70 m), evaluating both Ultimate and Serviceability Limit States. Finite element modelling and staged loading simulations are employed to assess performance under pouring and launching conditions. Results show that while active systems reduce main girder stresses (yielding up to 19% weight savings in localized modules) their influence is constrained by the construction sequence and inapplicability during launching. Furthermore, the modest overall weight reduction (~10%) may not justify the additional cost and complexity of implementing active control. The study concludes by discussing contexts where such systems may be advantageous and recommends directions for future development, including integrated economic evaluations and systems capable of multi-phase actuation.

KEYWORDS: movable scaffolding systems, external post-tensioning, active prestressing, span-by-span construction, launched structures, steel structures.

RESUMEN

Las cimbras autolanzables (MSS, por sus siglas en inglés) son un método ampliamente utilizado para la construcción in situ de tableros de puentes de hormigón pretensado, especialmente mediante procesos tramo a tramo. En particular, las cimbras de tipo inferior (underslung) son comúnmente utilizadas en vanos de hasta 60 m; sin embargo, la incorporación reciente de sistemas de pretensado exterior activo ha permitido extender su aplicación a vanos de mayores luces. Este artículo presenta una evaluación crítica del desempeño estructural de MSS inferiores, con y sin sistemas de pretensado activo, abordando su optimización estructural y las limitaciones prácticas en todas las etapas constructivas. Se analiza un caso de estudio basado en el sistema modular para vanos de 50 m, 60 m y 70 m. Mediante modelado por elementos finitos y simulaciones de carga por etapas, se determina el comportamiento estructural durante las fases de hormigonado y lanzamiento. Los resultados muestran que, si bien los sistemas activos reducen los esfuerzos en las vigas principales (logrando ahorros de hasta un 19% en módulos localizados) su eficacia está limitada por la secuencia constructiva y su inoperancia durante el lanzamiento. Además, la reducción total de peso (~10%) podría no justificar los costos adicionales asociados. El estudio concluye identificando los contextos en los que estos sistemas resultan más ventajosos, así como los escenarios donde su aplicación podría no ser justificable.

PALABRAS CLAVE: cimbras autolanzables, pretensado exterior, pretensado activo, construcción de vano a vano, estructuras empujadas, estructuras metálicas.

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Figure 1. Construction of a bridge with an underslung MSS.

1. INTRODUCTION

Movable Scaffolding Systems (MSSs) are an in-situ full-span-by-span construction method used for concrete bridge decks. This technique was first implemented in 1961 on the Krahnenberg Bridge in Germany, designed by Hans Wittfoht [1]. The construction process involves external formworks supported by the MSS, whose assembly depends on the structural configuration - typically defined by the main supporting girders or a bowstring scheme with a similar concept [2]. After a span is poured and it obtains the minimum allowable resistance, the MSS removes the formwork from the deck, changes its supports, and then it is launched to build the next span. This process occurs repeatedly until the last span is cast. Therefore, it must be observed that MSSs work under different structural situations. For example, the supporting devices when pouring the deck are not usually the same during the launch process. Furthermore, this latter manoeuvre results in different structure arrangements with specific support situations. More detailed information is included in Section 2. According to different authors [2–6], MSSs are often the preferred choice compared to other bridge construction equipment (BCE) for multi-span bridge construction due to the following advantages:

- Regarding bridge design, there is a reduction in post-tensioning steel minimizing material consumption.
- Regarding bridge construction, the geometry control becomes simpler and improves safety during construction, as it requires less manpower and facilities, resulting also in cost-effective production.
- Regarding the emplacement of the bridge, it is suitable for areas with strict architectural requirements and/or difficult topography.

Although these advantages are significant, it is important to account for the costs associated with shipping, assembly, dismantling, technological demands, and potential modifications to the original bridge design.

MSSs are commonly classified based on their relative position to the deck [7]:

- Overhead MSSs: Positioned on the deck. See example in [5].
- Underslung MSSs: Positioned under the deck. See the example in Figure 1.

In particular, underslung MSSs have been widely and successfully employed in spans ranging from 25 to 60 m. However, spans up to 70 m were reached using active external prestressing systems [8,9]. The latter is named active as the load in the prestressing tendons, or unbonded cables, varies in real-time according to a specific objective. In the case of MSSs, this objective is typically set to limit the deflection on the main span during the pouring stage. As a direct consequence, the structural demand for the MSS structure is also reduced, as more detailed in Section 3.

Although active external prestressing devices directly impact on a reduction of the steel of structural elements, this material save can be significantly constrained by other factors, such as the MSS launching procedure or the construction sequence of the bridge deck. In addition, the optimization with active systems usually considers an MSS that is not initially optimized [10]. Therefore, in this paper, the structural optimization through the use of active prestressing systems is presented and analysed, discussing its limitations. To illustrate this, a case study of an existing MSS is examined and optimized using this strategy alongside a conventional design approach.

2. CONVENTIONAL DESIGN OF MSSs

2.1. Stationary stage

As mentioned in Section 1, one of the main MSS conditions is the stationary stage. In this situation, the MSS is positioned to pour the concrete of the deck that is about to be built. In multi-span bridge construction, it is common practice to build on every sequence a full span length according to a

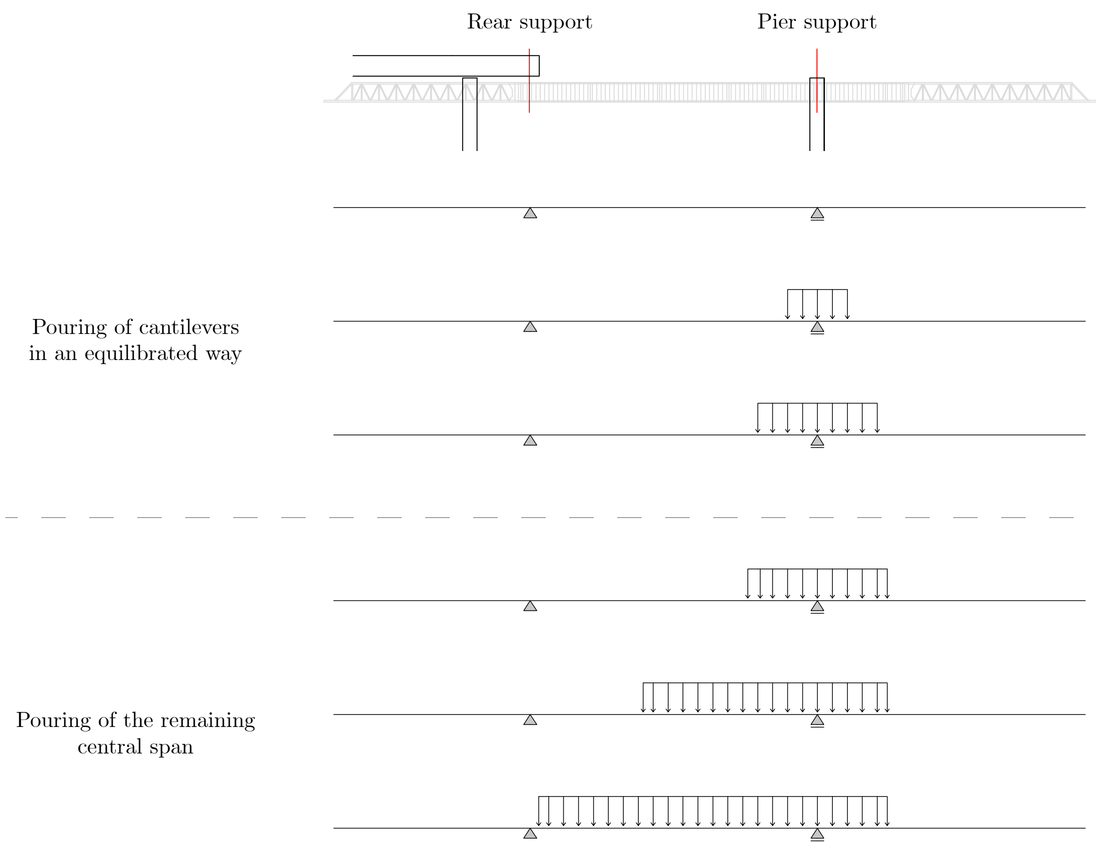

Figure 2. Typical pouring sequence in bridge deck construction with MSSs.

part of the zone between the piers and a cantilever [11,12]. Therefore, if *L* is the span length and *Lcant* is the cantilever length, it is built the remaining length (*L*-*Lcant*) between piers and *Lcant* after the last pier location obtaining the whole span length. The cantilever length usually ranges from *L*/5 to *L*/4 as this is the approximate location of zero or minimum bending moments due to self-weight.

Ideally, the MSS would be in the stationary stage for only the concrete pouring. However, it remains here in all the situations before and after pouring that do not include the launch phase (see Section 2.2). The latter requires meeting specific requirements related mostly to weather conditions to proceed safely. Consequently, during the stationary phase, the MSS may also be subjected to different challenging conditions such as out-of-service wind scenarios, and unexpected snowfall, among others. The pouring stage is detailed in Section 2.1.1, while Section 2.1.2 briefly addresses the additional scenarios.

2.1.1. Pouring stage

The underslung MSSs are usually supported by a rear support on the deck and a pier support. Therefore, the structure is simply supported with two remaining cantilevers at the extremes, (refer to the top row of Figure 2). To properly quantify the structural demand that comes from the weight of the deck, it is important to consider its construction sequence.

Two principal procedures are employed for deck pouring. The most widely adopted sequence, illustrated in Figure 2, begins with a compensated cantilever pour, followed by casting the remaining centre span. In the alternative sequence, the cantilever is also poured first; however, the main span is then cast progressing from the pier toward the rear support location [13].

As it can be seen, the load is first incremented on the cantilevers, and then on the main span. This construction process produces that, first, the bending moments in the cantilevers are increased without modifying the bending moments in the main span, to finally increase them on the central span. An example of this behaviour is illustrated in Figure 3, where the dashed lines represent the bending moments without the influence of fresh concrete (initial condition), and the two situations addressed previously in Figure 2: the balanced pouring of cantilevers (orange line) and the fully cast deck (green line). Additionally, the envelope is shown in grey.

This specific construction process allows better control when pouring the diaphragm at the pier, which is why it marks the beginning of the building sequence in all common scenarios. Additionally, the construction sequence plays a crucial role in evaluating the efficiency of active systems, a topic that will be further discussed in Section 4.2.

2.1.2. Other load situations

Other stages in which the MSS also remains in the same stationary configuration can be the following:

- Out-of-service wind: Both the pouring stage and the launching stage are limited to specific weather conditions to ensure safety in each of these processes. Among them, the most important is the wind speed. Therefore, it is

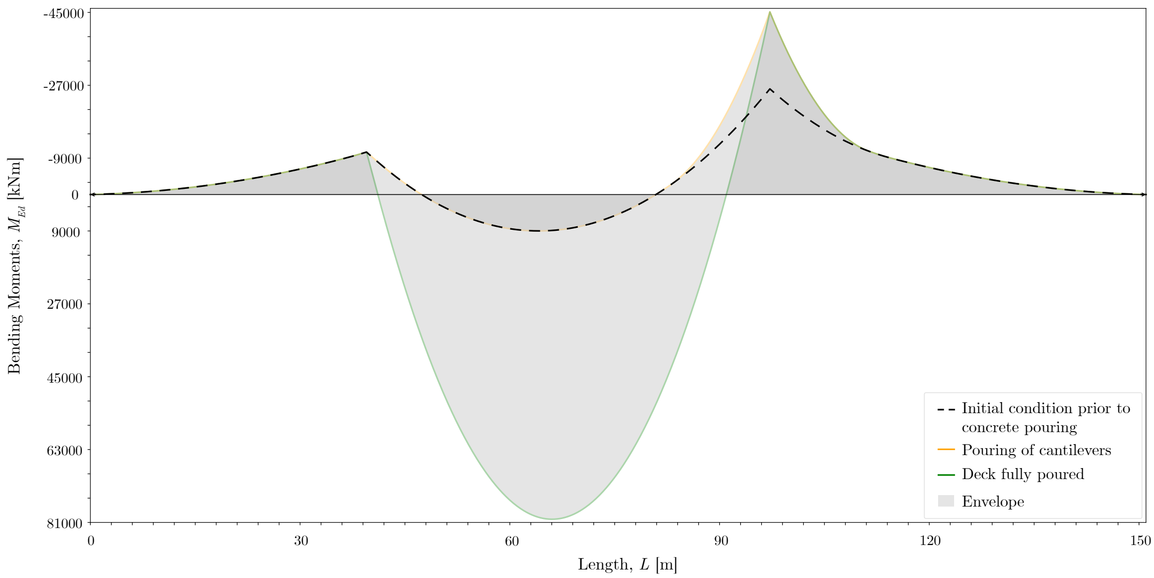

Figure 3. Bending moments during the pouring sequence.

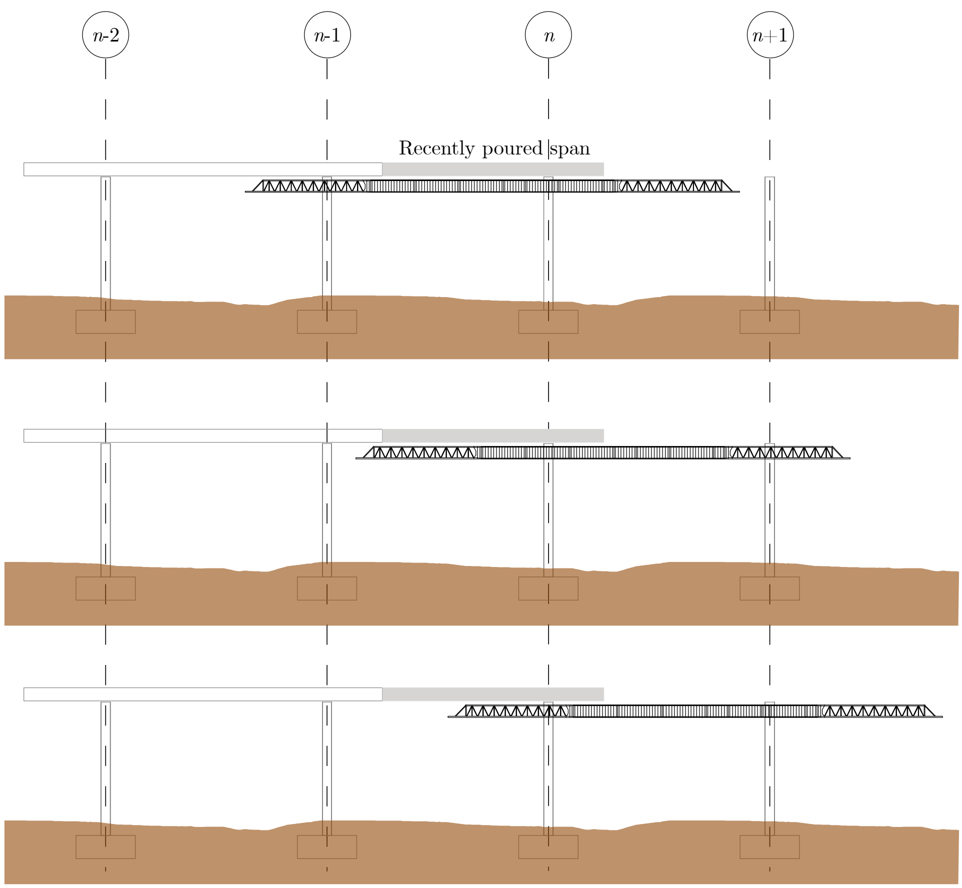

Figure 4. Typical launching sequence of an MSS.

common practice to have an anemometer on site and to continuously review the forecast to plan each of these procedures. The out-of-service wind scenario refers to conditions in which the support configuration remains identical to that of the pouring stage. In this situation, the structure receives primarily the permanent load and the full wind action corresponding to higher wind speeds.

- Earthquake loads: Since they are difficult to predict, seismic actions are usually considered in all situations of the MSS, but with a low return period of occurrence [2]. Nonetheless, when knowing the high probability of occurrence of them is known, there are specific manoeuvres which most of them consist of fixing the MSS on the deck [11].
- Other loads: The MSS might also be exposed to scenarios

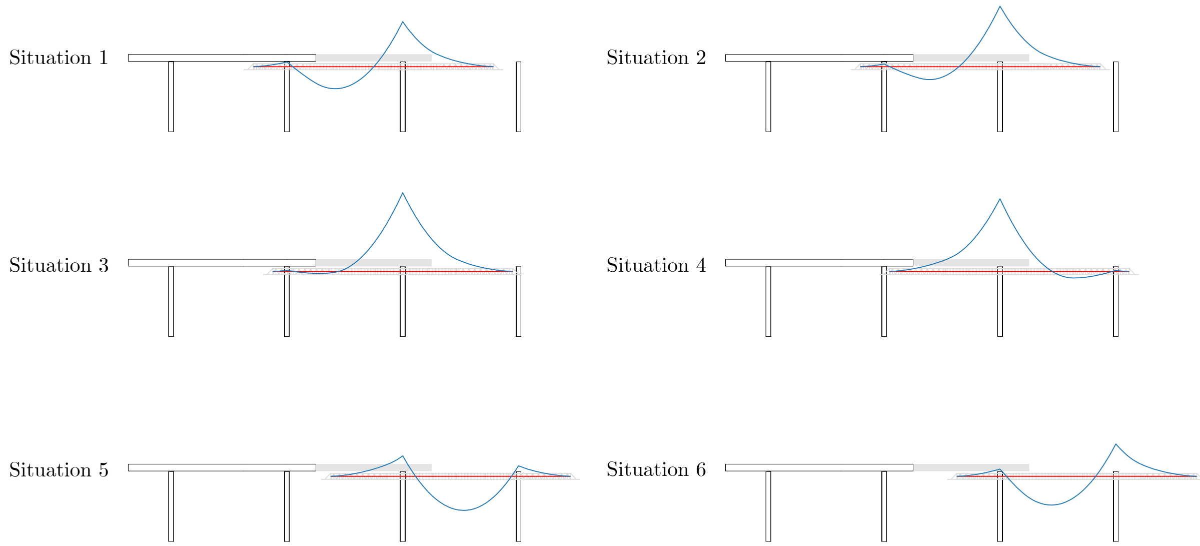

Figure 5. Bending moments during the launching phase.

such as snow occurrence and accidental loads. However, any of these situations can occur in both the stationary and launching stages [2,11,12,14].

2.2. Launching stage

This stage includes all configurations of the MSS from the end of one stationary phase to the beginning of the next. Provided that all necessary conditions for launching are satisfied, the following sequence occurs (see Figure 4).

First, once the recently poured span has obtained the minimum required strength, the formwork is removed from the deck. Subsequently, the rear support, located between axes *n*-1 and *n*, is detached from the structure. Concurrently, a pier support is prepared at axis n-1 to receive the MSS. Another pier support is also installed at the upcoming pier on axis *n*+1, anticipating the forward movement of the MSS. The launching process then begins with the MSS initially supported at axes *n*-1 and *n*. As it advances, it transitions through an intermediate configuration where it is temporarily supported on three axes (n-1, n, and *n*+1) before finally being fully supported between axes *n* and *n*+1. Throughout this process, the MSS undergoes several structural configurations. Once it reaches the designated position for the next span, the pier support at axis *n* is reconfigured into the new rear support, marking the beginning of the subsequent stationary phase.

For example, Figure 5 presents the main representative situations that occur during the launching stage, also illustrating qualitatively the permanent loads' bending moments (in blue) for each specific case:

- Situations 1 and 6: Initial and last situation of the launching process (identical, but with a different MSS location).
- Situation 2: Example of first stages with increasing front leading cantilever.
- Situation 3: Maximum front cantilever.
- Situation 4: Maximum back cantilever.
- Situation 5: Maximum positive bending moment during launch.

As seen, the launching process involves several situations that the MSS goes through, in which the span length of the bridge works as both maximum cantilevers and the main span of the MSS. Therefore, each situation should be considered in the design of such elements. Herein, it is common practice to plot the envelopes of the whole launch for all the structural configurations to analyse specific scenarios. An example of this envelope is shown in Section 4.2.

3. ACTIVE PRESTRESSING SYSTEMS

3.1. Concept and applications

Active structures are systems where part of them can adapt their configuration in response to specific performance criteria. To achieve this, it is necessary to install sensors, actuators, and a control system [15]. The usual functioning of this scheme is as follows. First, given an external stimulation, the sensors perceive the response of the structure. Subsequently, the control scheme receives the information from the sensors and processes it to then send an instruction to the actuators. Finally, the motion is defined to meet the control objective. Here, there are many particularities, since active systems can be used for different purposes and with different types of control units. For instance, it is common practice to use active control for Vibration Serviceability Limit States (VSLS) using Tuned Mass Dampers (TMDs) [16]. Therefore, a convenient way to divide them would be to control static responses such as deflection or to fulfil vibration serviceability responses, v.g., accelerations. The first type is the focus of this study.

A simple application is presented in Figure 6 to consistently understand the advantages of active systems. This example presents an active system that is set to limit the deflection to zero at midspan in a simply supported beam with one strut in the centre of the span and external prestressing tendons. When an

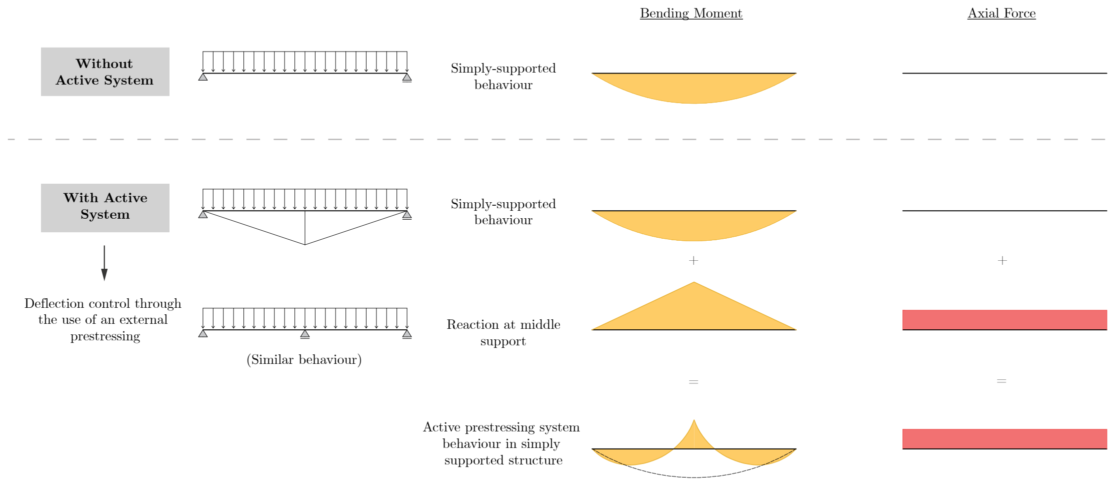

Figure 6. Concept of a responsive prestressing system for deflection control.

external load acts on the beam, the midspan point behaves as another support, since the vertical displacements are 'restricted', making a new system of a beam supported in three points. However, this can also be observed as follows. Since the instruction is to limit the deflection to zero, to accomplish this, the prestressing load increases, and this force is then transmitted to the strut as a compression. This element transmits this force to the beam, resulting in an uplift force and thus a negative bending moment. At the same time, the cables introduce an axial force at the edges. Therefore, the result is the sum of both bending moments, the simply supported one and the negative coming from the vertical force, and the axial force on the beam.

It can be observed for this example that there is a considerable improvement in the positive bending moments plus new, but small, negative ones. Herein, the axial load must not be disregarded, as it could play a restricting role depending on the type of cross-section and the material that is being assessed. For instance, the use of thin-walled steel cross sections could be prone to plate buckling sooner under pure compression stresses than under exclusively bending compression stresses. Further information and examples of active systems can be consulted in [16–18].

In the case of underslung MSSs, the active system is typically incorporated to control the deflection of the main span by using external prestressing tendons or unbounded cables. Herein, the prestressing load is changed by an actuator. As far as the authors know, there is only one full-scale realization for underslung MSSs in [8,9]. Nonetheless, there are other studies on the feasibility of using them in MSSs [10,19]. In Section 3.2, the implementation of active prestressing systems in MSSs is explained further.

3.2. Application on MSSs

3.2.1. Stationary stage

As mentioned in Section 3.1, active prestressing systems in MSSs consist of varying the load on external tendons or cables to control the deflection on the main span. During the stationary stage, it is during the pouring stage that the active system can be more efficient, as it can control the deflection when the fresh concrete is placed over the formwork. Given that in the stationary stage, there is no space over the MSS, the external system only can be either inside the cross section or below the structure. From both, the most efficient is to use an external prestressing under the main girders, resulting in an under-deck cable-stayed structural typology [20,21].

For the whole scheme, there are two possible solutions in terms of actuator location (see Figure 7). Option A varies the load in the prestressing by modifying the length of the strut which is also the actuator. Consequently, the deformation and load on the cable change proportionally to the actuators' opening. When having more than one strut, the actuator could be in one or more of them. Option B modifies the load on the cables by directly jacking the tendons. For that reason, the actuator needs to be in one of the anchorages.

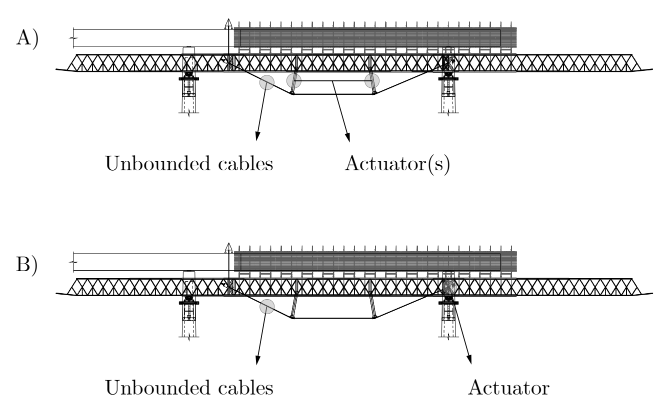

Figure 7. Actuator locations in MSSs with active systems.

There are many possibilities in terms of structural configuration. For instance, in Figure 8, some possible solutions are presented which correspond to the following:

- Option I: One strut with anchorages in the supports.
- Option II: One strut with anchorages in the rear support and at the end of the cantilever.
- Option III: Two struts with anchorages in the rear support and at the end of the cantilever.

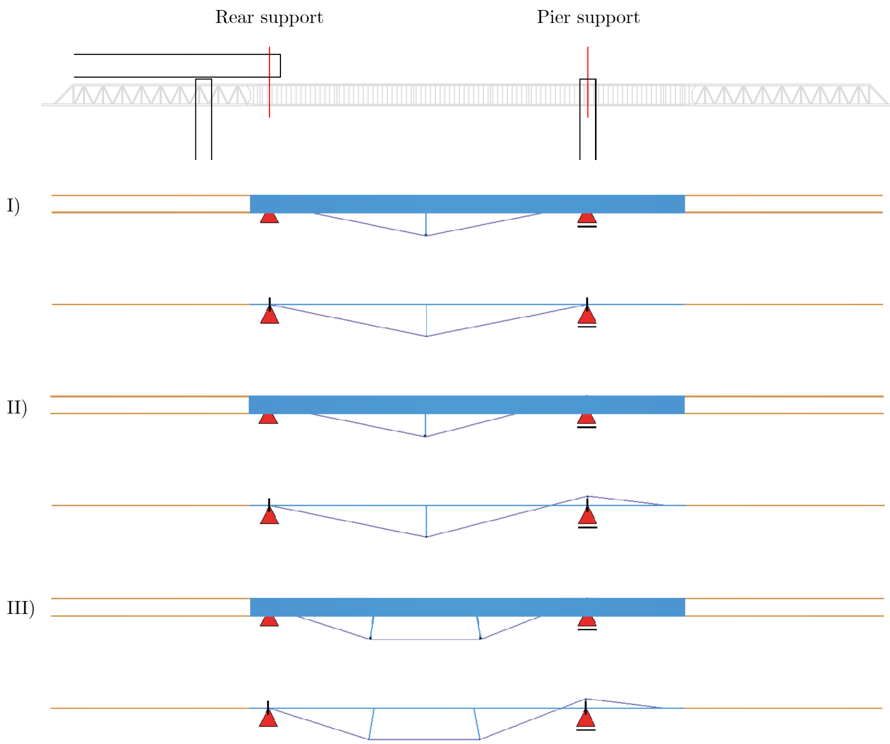

Figure 8. MSSs design solutions with external prestressing.

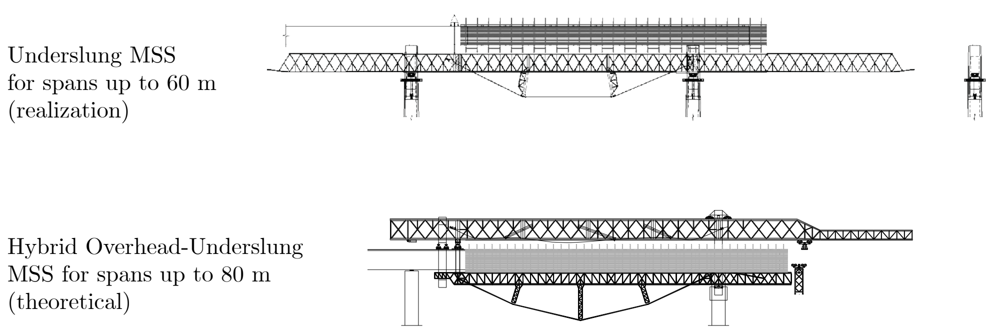

Figure 9. MSS configurations with active systems [19].

The difference between these alternative systems is that option I introduces an exclusively negative bending moment law, while options II and III also introduce a positive bending moment law on the cantilever. Also, the last two differ on the number of struts on the main span, in which option III accommodates better the bending moment introduced by the concrete pouring and requires a lower load on the cables to achieve the control objective.

It was previously pointed out that due to the lack of space, it is not usually possible to add new elements over the main girders of the underslung MSS. Therefore, the efficiency of the prestressing system on the cantilever zone is here conditioned by the space inside the cross-section, which is the height of the element.

Some examples of MSSs with active systems are presented in Figure 9 extracted from [19]. As seen, some of these solutions resemble the conceptual design presented previously.

As the main drawback of this technology, in other situations that differ from the pouring stage in the stationary position, the active system does not improve considerably the behaviour of the MSS since the prestressing system primarily affects the vertical response, and the rest of the situations are mostly affected by transversal actions, e.g., the out-of-service wind. Therefore, their effect in these situations is negligible.

3.2.2. Launching stage

For underslung MSSs, the typical launch procedure is the one presented in Section 2.2. As observed, it is necessary to have free space below the main girders, as they are from which the whole structure is launched. The active system for these situations must be either retired or retracted so it does not represent an obstacle when launching. Therefore, during this stage, the active prestressing system does not work, making the MSS work as a conventional MSS plus the load of the struts and cables, which might or may not be neglectable.

3.2.3. *Active prestressing and permanent loads*

In the design of stay-cable systems, e.g. cable-stayed and extradosed bridges, there are no specific criteria on how to apply favourable or unfavourable coefficients, but it is mentioned to decide according to the situation of each structure [22]. In this sub-section, this matter is discussed focusing on the European context, and using the concepts of 'active load' and 'passive load' on cables as the following [23]:

- Passive load (*Ppas*): The load increment on the cables due to their deformation caused by an external load on the deck. For instance, in a cable-stayed bridge with a composite concrete-steel cross section, during the placement of concrete of the top slab, the cables deform and, at the same time, the load on the cables rises.
- Active load (*Pact*): The one coming from jacking one of the anchorages, in any construction phase, to compensate part of the permanent load of the bridge. This is usually done during construction or after the installation of dead load. For example, in the case of a ballasted deck for railway traffic, this would be after the installation of the ballast and rails. In the context of MSSs -as further discussed at the end of this subsection- this load category most accurately represents the increase in active cable force in response to the pouring of fresh concrete.

In the European guidelines, prestressing loads and tension elements are treated differently. Eurocodes 2 and 3 [24–26] in the case of stay-cable systems recommend using EN-1993-1-11 [27] which indicates to use favourable and unfavourable coefficients for both permanent loads (G) and load on tension elements (*P*, being the total load, i.e., $P = Pact + Ppas$). Notably, this approach does not differentiate between active and passive components. This treatment is primarily based on the behaviour of cable-stayed bridges with highly flexible decks, where deformations directly influence cable forces. However, this assumption does not consistently hold for extradosed bridges or other stay-cable configurations, where the relationship between deck deformation and cable force can be significantly different [28,29]. On the other hand, for prestressing loads, Eurocode 2 [24] considers the action P to be fully independent of permanent loads using specific safety factors.

Virlogeux [30], Menn [31], Ruiz Terán [23], Mermigas [29], and Carrillo [32] agree on a different treatment of forces distinguishing them in an active and passive part. Specifically, they recommend treating the passive part together with the permanent loads as a group, and the active part differently with other safety factors. Then, Ploch [28] supported this procedure by studying the definition of security in external prestressing inside and outside the cross-section and demonstrated that the treatment of permanent actions and prestress together as a group does not lead to safe designs. Therefore, the latter also proposes the independent use of this force, indicating specific safety factors for each case.

For active systems applied to MSSs, the load increases proportionally with the fresh concrete load on the main span, closely resembling a purely active prestressing load (*Pact*). Therefore, it is recommended to use specific partial safety factors for this load. On the safe side, it is suggested to use the characteristics value of them and set some disequilibrium between the active load and the part of the permanent load that it compensates. For instance, Pacheco [33] considers the active system independent of permanent loads and applies the same safety factors as in the case of prestressed structures [26].

4. DESIGN OF A LARGE-SPAN MSS WITH AND WITHOUT AN ACTIVE PRESTRESSING SYSTEM

4.1. Definition of case study

To accurately evaluate the effectiveness of active systems, the same MSS is optimized in two configurations: with and without an active prestressing system. In both cases, the structural steel weight of the main girders is reduced by using lighter sections per module. The selected case study and its characteristics are described in the following sub-sections as well as the design basis and modeling.

4.1.1. Geometry

The C-60 model from Mecanotubo, previously employed in the literature [10], is selected as the reference MSS. The system is composed of different modules of different lengths, ranging from 3 to 12 m, and different cross sections, divided mainly into truss modules and box modules. The first ones are 3D-spatial trusses, and the second ones are steel plate box cross-section girders (see bottom of Figure 10). optimize the load-bearing capacity of the deck prior to self-resistance, box modules are employed in the central region. Then, at the extremes, lightweight truss configurations are employed to minimize weight. These truss ends function as launching noses during span transitions and as cantilevers during the stationary phase.

The C-60 system was initially conceived to build spans of up to 60 m. Its modular nature allows flexible assembly configurations to accommodate different span lengths. Consequently, it is also possible to use this structure with the rear support located at both *L*/4 and *L*/5. Cantilever lengths between these values are also possible. These two main assemblies are shown in Figure 10 for span lengths of 60 m.

In these configurations, the box cross sections are identical except to the ones located at supports during the stationary stage. These modules are distinguished due to the type of connection they have to their corresponding support. Thereby, their name starts with a C and A, respectively, for the cases of the rear support and pier support. In terms of stiffness of the cross-section, the only one stiffer than the rest is the one located in the pier support, which weighs 6% more than the rest of the modules.

For other lengths of pouring span, it is maintained the ratio of the total length of the MSS to the bridge span length, and the length proportions of each typology of modules to the total length of the MSS. Here, it is important to establish an appropriate length for the box modules since they must be at least in the span length to be poured, as they are the most resistant sections compared to the truss ones.

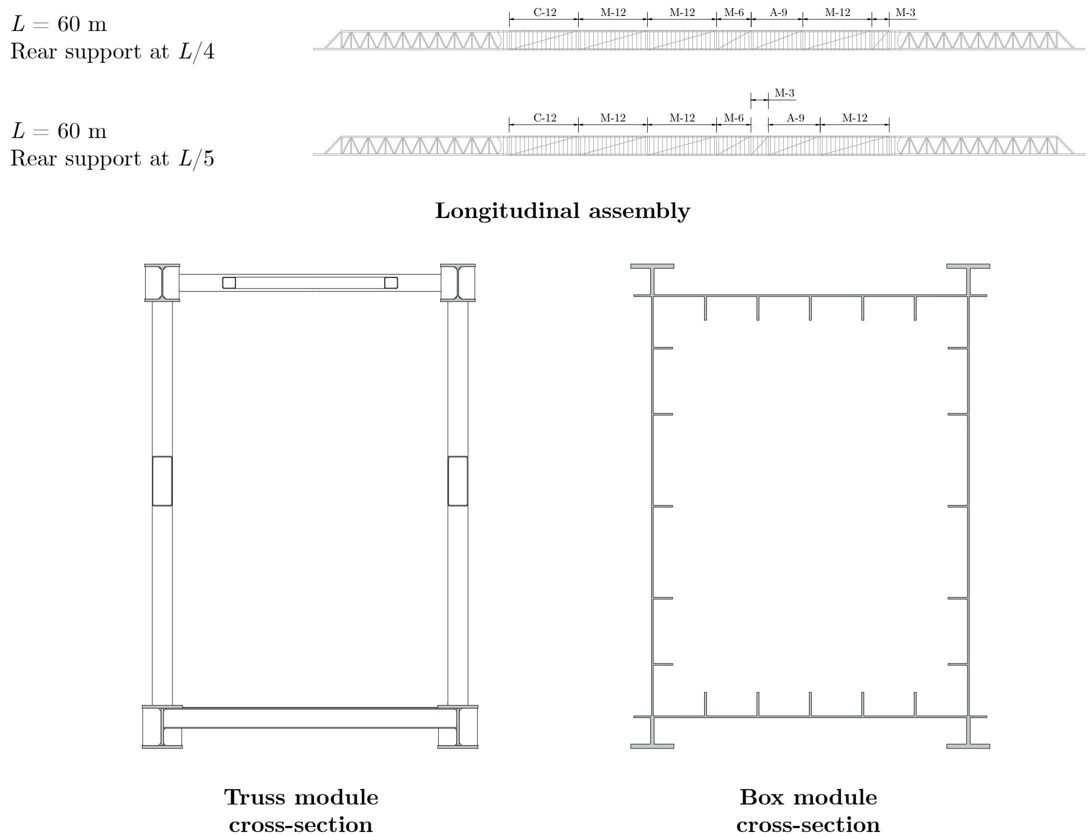

Figure 10. C-60 system by Mecanotubo as reference MSS.

4.1.2. Design basis

The design basis follows the methodology outlined in [2], which agrees with both American and European code provisions for Ultimate Limit States (ULS) and Serviceability Limit States (SLS) in terms of actions and load combinations. Nonetheless, the safety factors are according to Eurocode 0 [22] and Eurocode 3 for steel structures [34,35].

Regarding the treatment of active system loads, these are considered independent from permanent loads and are assigned favourable and unfavourable partial factors of 1.00. Additionally, a load imbalance of ±5% between the prestressing force and the compensated portion of the permanent load is verified, as recommended by the Spanish National Annex to Eurocode 1990 [22] and the Spanish National Guidelines [36,37].

For the calculation of fresh concrete weight, existing full-scale bridges are used as a reference. Specifically, the Asteasu Bridge (Figure 11) and the Molvizar Bridge (Figure 12) are used, respectively, to represent railway and highway bridges. The first one is a viaduct part of the Basque Country railway line located in the Hernialde – Zizurkil Section. Also, this bridge has a maximum span length of 51.86 m resulting in a height-to-span length ratio of 1/19. The second one is part of the Mediterranean Highway, specifically in the Amuñecar (Taramay) – Salobreña (Lobres) Section. Furthermore, this structure has a height-to-span ratio of 1/16. Thus, these bridges represent typical applications of MSSs for the construction of multi-span bridges for different traffic services ranging in deck heights from $L/15$ to $L/20$, with L being the maximum span length between piers.

4.1.3. Optimization goal and modeling

In terms of the loading condition problem for optimization of the MSS, the decks of Figures 11 and 12 are used and adjusted by extending the web to obtain the appropriate height for pouring spans of 50 m, 60 m, and 70 m. Here, it was decided to use $L/15$ and $L/20$ deck heights to span-length ratios for railway and highway bridges, respectively. Therefore, the goal is to obtain efficient modules for each span-length application. By that, it is considered that some modules are optimizable and that some reinforcements in specific points are also needed depending on the optimization strategy.

Verifications on the structure consider global resistance, stability, as well as local checks such as joints and patch loading for launching stages. As mentioned previously in Section 3.2.2, the MSS operates under identical conditions during launching, regardless of the presence of an active prestressing system. Therefore, the optimization results for both MSS configurations must satisfy the same performance criteria during launching manoeuvres.

The FE modelling has been performed in SOFiSTiK [38] using beam elements for the whole MSS. Two different model approaches were adopted for different verifications. For the box-section modules, one single beam element was

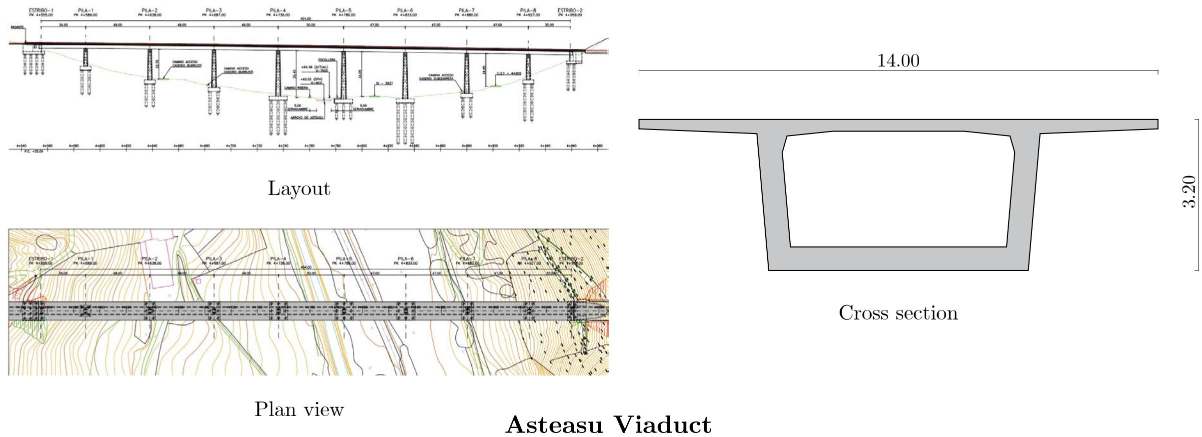

Figure 11. Deck case study for a railway bridge.

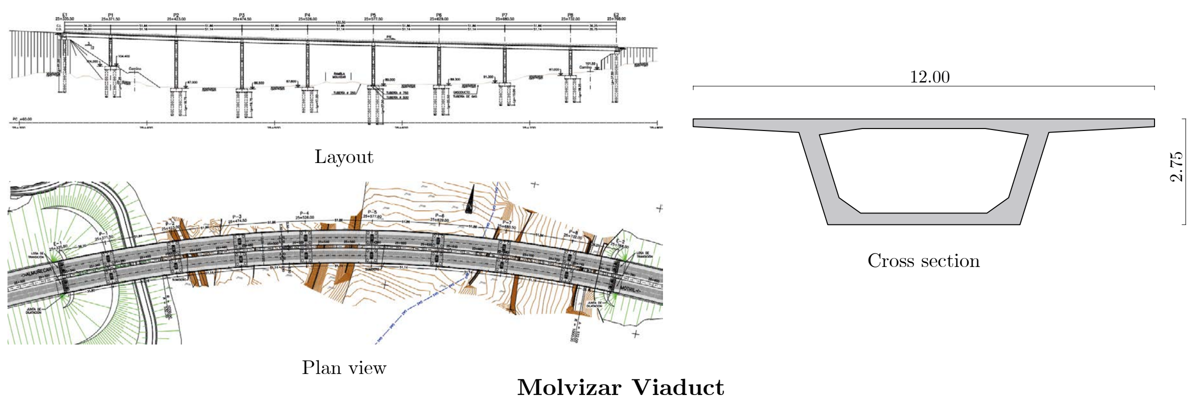

Figure 12. Deck case study for a highway bridge.

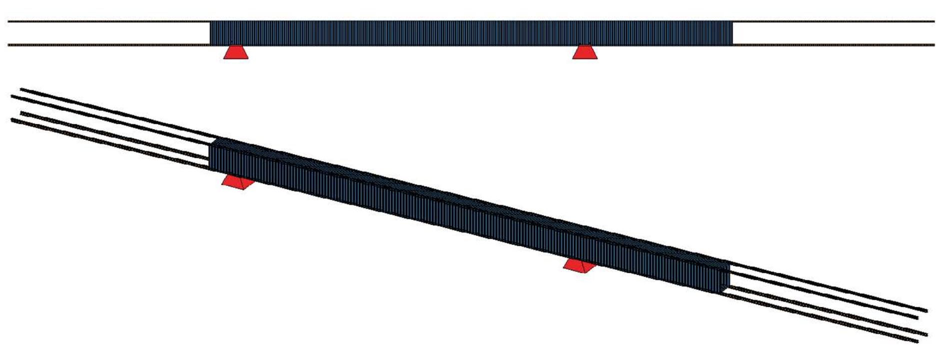

Figure 13. Modeling approach 1: Longitudinal beam elements representing the cross-section of each module.

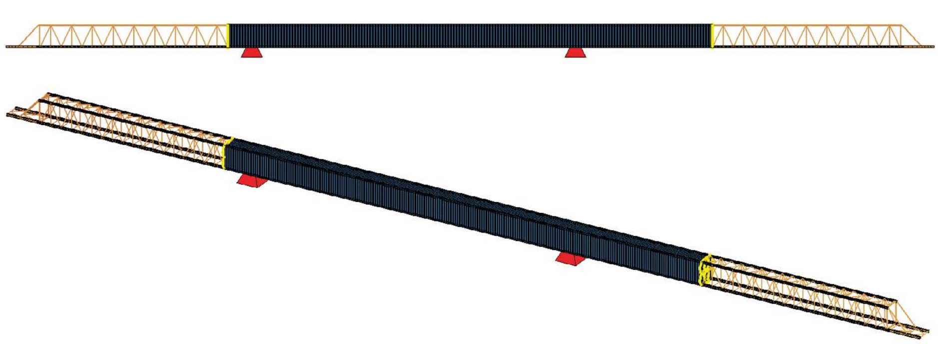

Figure 14. Modeling approach 2: Beam elements for the cross-section of each box module and truss components.

used to represent the cross-section of each module. For the truss-type modules, two approaches were applied: the first employed only longitudinal beam elements with equivalent cross-sectional stiffness to represent the truss behaviour (Figure 13), while the second modelled all the individual truss components (Figure 14). Both models were cross-compared to ensure that the simplified longitudinal-only model accurately captured the overall stiffness of the truss. The simplified one is used for most global analyses, whereas the more detailed one is applied for local analysis. Additionally, in specific launching cases, it was also modelled the behaviour of the launch devices in contact with the bottom chord.

4.2. MSS design optimization with an active prestressing system.

For the design optimization of MSSs with an active prestressing system, the cases previously presented in Figure 8 were studied. For these, the strut height was selected as the tenth of the main span length to not interfere with the vertical clearances that can be present below the bridge. It must be pointed out that the MSS is already of important dimensions below the deck which sometimes can be conditioning. Also, it is particularly used the options with the anchorage on the cantilever zone after the pier support.

The ULS and SLS verifications studied herein are the following.

- ULS: Interaction of normal stresses (bending moments and axial force) considering global buckling and plate buckling reductions, shear resistance and its interaction with normal stresses, patch loading (pure and interaction with concomitant bending moments), and connections.
- SLS: Displacement of the MSS to allow the correct pouring shape of the bridge deck, and connections.

The influence of the number of struts and the effectiveness of the active system during the pouring stage can be seen in Figure 15. Herein, it represents the envelope of the pouring stage of each case, varying the number of struts. Additionally, it is included in grey the envelope area of the case without using active prestressing. From this plot, the following can be observed:

- The effectiveness of having the cable system in the cantilever zone is almost negligible (see the zoom of the plot in the upper right of Figure 15). This is exclusively due to the construction process. In the initial stages when there is a balanced pouring of the cantilever zone (see Figure 2), there is no increase in bending moments in the central zone and, therefore no additional deformation in the main span; consequently, the active system does not work. In this situation, the maximum negative moment is reached without the contribution of the active system. The differences observed in the plot are due to the cables working as a passive element with a minor contribution.
- The grey area highlights the degree of minimization of the positive bending moments when the control system is working. This reduction is at least 85% for this specific case. Nevertheless, it must not be disregarded the axial force contribution which is not evident in this plot. To see the contribution of the axial load and the acting transverse forces, the maximum normal stresses in the box cross sections are presented in Figure 16. This plot includes the launching stage envelope (in yellow) apart from the cases of the active system during the stationary stage of Figure 15.
- Having one or two struts impacts the degree of compensation of the bending moments and their shape since with two struts it is possible to reproduce a better fit of the positive bending moments distribution. Also, when having two struts, a lower force is needed to reduce the deflection on the main span compared to the solution with one. This directly impacts the number of prestressing tendons.

As seen in Figure 16, the axial force component plays an important role that cannot be seen by observing only the bending moments. While there is a significant reduction according to Figure 15, when considering the rest of the concomitant acting forces, it results in a less impactful reduction. Then, the launching stage also introduces specific peaks on this plot that correspond to maximum cantilevers, back and front. The stress level of these zones shows that the launching procedure is more restricting than the pouring case in the central zone, while in the rest of the zones, it is the stationary stage. In the extreme zones where the active system is not as efficient, the stationary stage becomes the restricting situation.

To simultaneously observe the launching and stationary stages in a single plot, Figure 17 illustrates the envelope of this manoeuvre plus the pouring stage of the two studied options of Figures 15 and 16. The plot indicates that the configurations incorporating active systems during the pouring stage generally remain within the loading envelope of the launching stage, with the exception of the pier support zone.

However, when evaluated in terms of stress distribution (see Figure 16), their demand is comparable, with the stationary stage remaining critical in the extreme regions of the structure. Based on the observed behaviour of the active system during fresh concrete pouring, the configuration employing two struts is selected for structural optimization, as it offers the most effective reduction of stress in the main girders.

The optimization procedure for this case follows a systematic approach. First, the case of a pouring span length of 70 m with an adjusted configuration of the MSS for this scenario is studied. Then, after all the conditioning situations are identified, a search for more optimized modules for all these scenarios is performed. If a studied configuration allows for further optimization, the selected modules are reduced and reassessed one more time. This iterative process continues until a fully optimized MSS meeting both ULS and SLS criteria is achieved.

Table 1 presents the assessment of the initial configuration of the C-60 MSS (without any cross-sectional modifications) for a 70 m span using an active prestressing system. When ULS or SLS requirements are not satisfied, the table specifies the maximum required percentage of additional

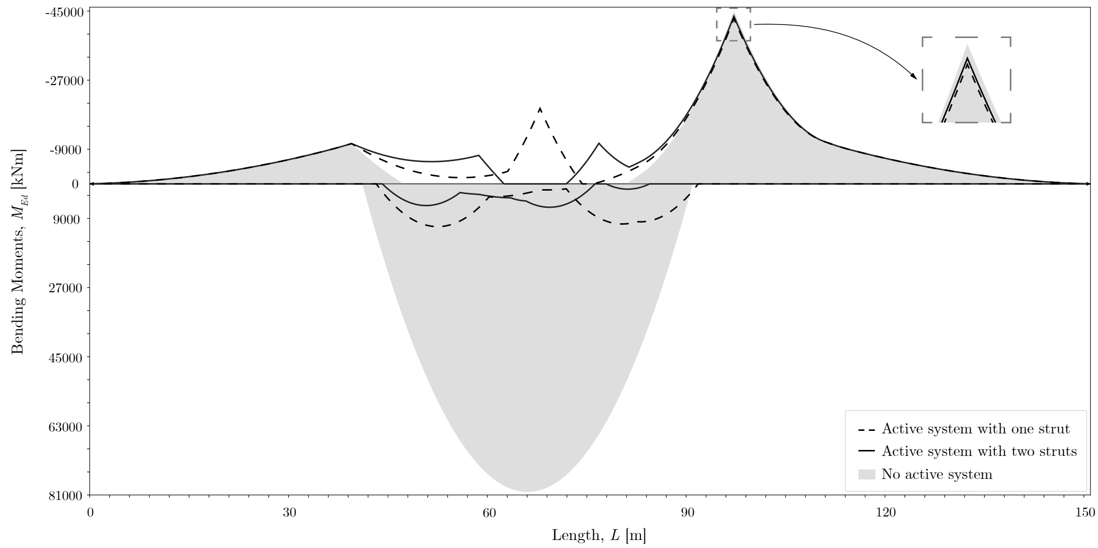

Figure 15. Influence of the struts number on active prestressing during stationary stage for a span length of 70 m.

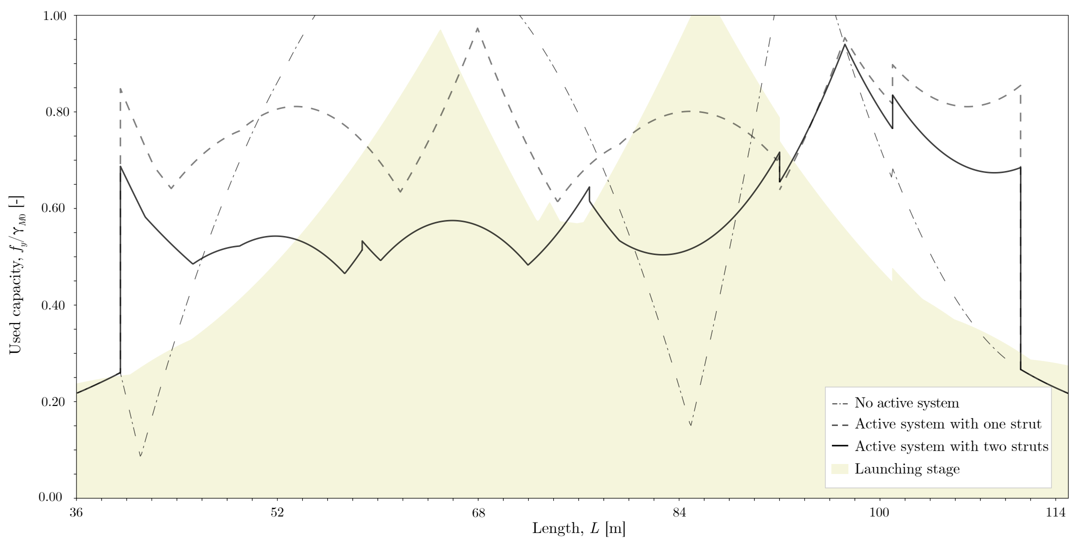

Figure 16. Maximum normal stresses for MSSs during stationary and launching stage for a span length of 70 m.

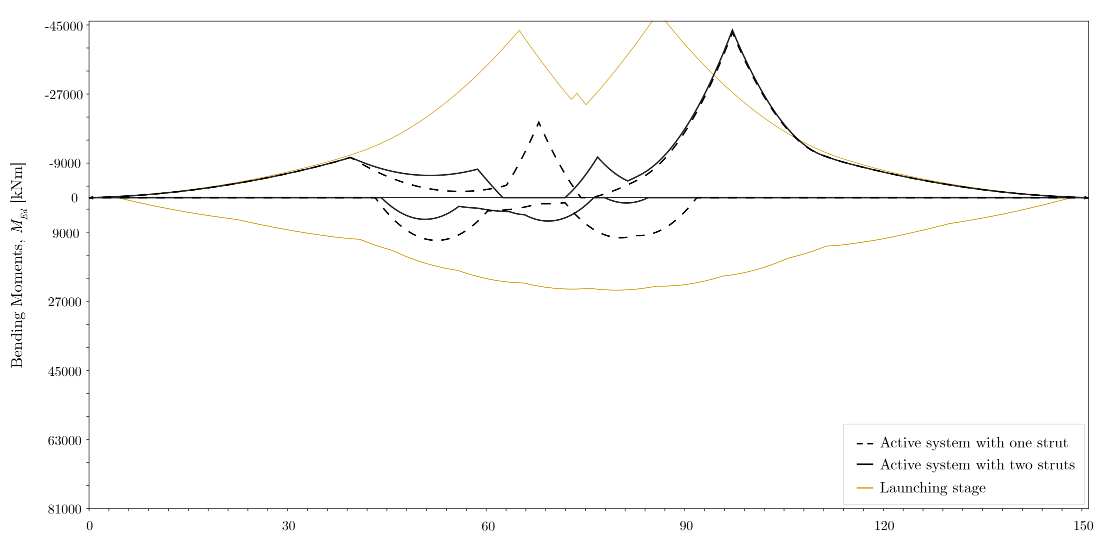

Figure 17. Launching and stationary stages for a span length of 70 m.

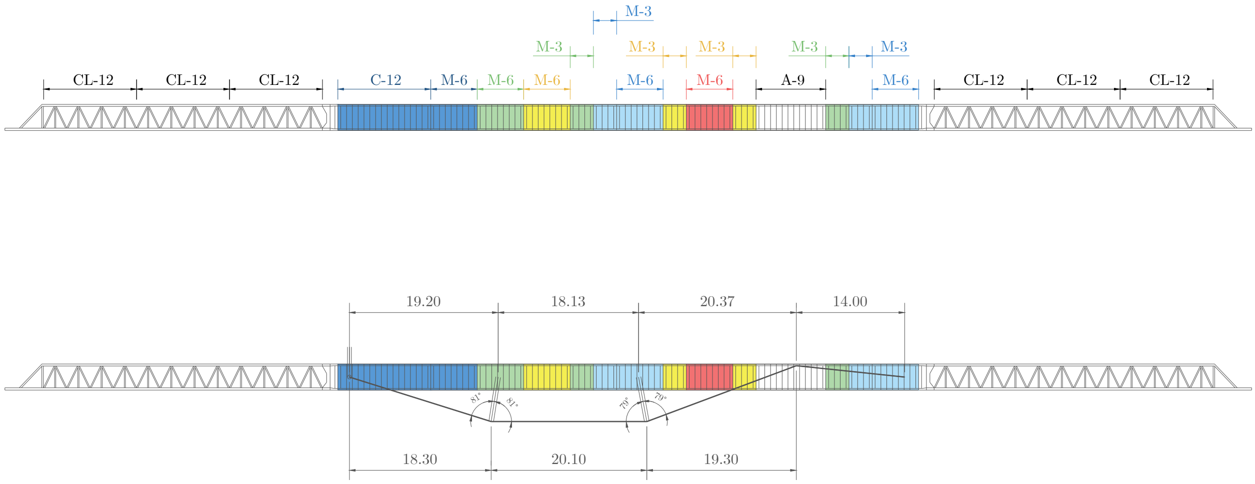

Figure 18. Optimized solution for a pouring span of 70 m using an external active system.

reinforcement. In this case, the governing constraint was the bending capacity, primarily limited by the plate buckling resistance under normal and tangent stresses during the launching stage. As shown previously in Figure 16, the modules satisfy ULS requirements during the stationary stage, with a similar response in SLS. Therefore, the optimization process is initiated from this baseline configuration. It is important to note that in MSSs incorporating active prestressing, the SLS criteria are inherently satisfied due to the prestressing effect, which reduces the margin for further optimization.

TABLE 1.
Limit States (SLS and ULS) the fulfilment for initial condition of MSS with an active system

Length [m]	Traffic service	ULS				SLS
		Stationary stage	%	Launching stage	%	
50	Highway Railway	✓ ✓		✓		✓ ✓
60	Highway Railway	✓ ✓		✓ ✓		✓ ✓
70	Highway Railway	✓ ✓		X X	106%	✓ ✓

Once obtained the optimized module configuration for the 70 m span, the case of the next smaller span length is studied using the same type of modules with a configuration that minimizes the MSS weight. Then, this process is repeated for the subsequent case. The final optimized configuration for a span length of 70 m is presented in Figure 18.

The modules shown in this figure correspond to the ones listed in Table 2. The number and percentage represent the reduction in terms of weight of each module. For instance, module 55%T means a weight reduction of 45% of the initial starting box section module.

TABLE 2.
Optimized modules for MSSs with an active prestressing system

Module	Length
55%T	12m 6m
75%T	6m 3m
85%T	6m 3m
100%T	6m 3m
106%T	6m

To ensure the best optimization for each case, the cantilever length is restricted to L/5 when using active systems, where *L* represents the pouring span length. This approach maximizes the benefits of the active prestressing by minimizing the cantilever and, consequently, reducing the maximum negative bending moment. This optimized solution can be now compared to a conventional one, which is defined in the next section.

4.3. MSS design optimization without an active prestressing system

For the design optimization of a conventional MSS (without any active prestressing system), a cantilever of *L*/4 is used, *L* being the pouring span length. This choice is primarily due to the magnitude of the maximum positive bending moment, which is strongly influenced by the main span length during the stationary stage. In contrast, the negative bending moment is directly related to the cantilever length, which does not increase as significantly. In the first scenario, the bending moments grow quadratically with the span length, while in the second case, they increase linearly with the cantilever length.

The ULS and SLS verifications are the same ones mentioned in Section 4.2. The main difference is that in these

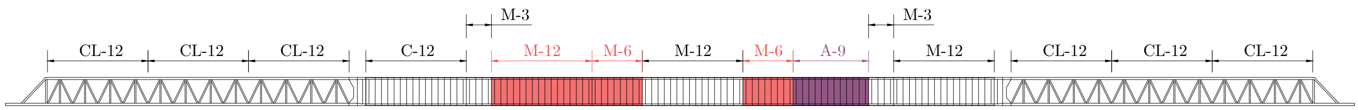

Figure 19. Optimized solution for a pouring span of 70 m without an external active system.

cases there is no axial compression, therefore there is no global buckling.

The optimization procedure is similar when having an active system. First, it is obtained a configuration for a span length of 70 m. Then, by detecting the zones with the need for reinforcement, new modules are introduced that can satisfy all conditions. Next, after a specific optimized configuration of modules is obtained, it is adjusted for a smaller span length and subsequently to the next one. In these cases, there is special attention to minimizing the weight of the MSS.

The fulfilment of the initial condition of the MSS C-60 –without any cross-sectional modification– for a 70 m span without an active system is presented in Table 3. When ULS or SLS requirements are not satisfied, the table specifies the maximum required percentage of additional reinforcement. In this case, the governing constraint was the bending capacity, primarily limited by the plate buckling resistance under normal and tangent stresses during both stationary and launching stages. Particularly, although the structure does not comply with ULS criteria during the stationary stage, SLS requirements are met, confirming that the ultimate strength governs the design.

TABLE 3.
Limit States (SLS and ULS) fulfilment for the initial condition of MSS without an active system

Length [m]	Traffic service	ULS				SLS
		Stationary stage	%	Launching stage	%	
50	Highway	✓		✓		✓
	Railway	✓				✓
60	Highway	✓		✓		✓
	Railway	✓		✓		✓
70	Highway	X	106%	X	106%	✓
	Railway	X	121%	X		X

The final optimized configuration for a span length of 70 m is presented in Figure 19.

For this specific case, since the modules were conceived for span lengths up to 60 m, an almost optimized solution was obtained for a span length of 70 m with the need for reinforcement in specific points. Therefore, the introduction of new modules for this present case is less impactful than the one in the previous sub-section. Specifically, it used the same 106%T module presented in Table 2 and introduced a new module named 121%A that corresponds to the original A box cross-section module with a 21% increase in weight.

4.4. Results and discussion

The results of all the optimization problems in terms of weight are presented in Tables 4 and 5. These solutions correspond to the final configurations after optimization approaches for bridge span lengths of 50 m, 60 m, and 70 m. Since the start of the optimization problem is 70 m, the results are given in reverse order. For the calculation of the steel weight, it was used a density of 78.50 kN/m^3 [39].

Table 4 presents the steel weight, in tonnes, of one MSS launching girder and quantifies the weight reduction achieved when using an active prestressing system compared to the optimized solution without it. The same comparison is made in terms of only the total weight of the box cross-section modules. For example, for a span of 70 m, the reduction of total weight in one girder is 8% when using an active prestressing system than when not using it, comparing both optimized MSSs.

In Table 5, the total weight of the MSS considering the two launching girders and other elements such as formworks, walkways, and other permanent loads is shown also following the same two approaches. Additionally, the lowest weight is contrasted with underslung MSSs found in the literature for both existing and theoretical proposals. Specifically, they are the ones found in [10,13,40–42].

TABLE 4.
Steel weight reduction when using an active system for one launching girder

Span length, *L* [m]	Steel weight on one launching girder [t]		% reduction of total weight	% reduction of box cross-section modules weight
	Without an active system	With an active system		
70	215	198	-8	-12
60	182	163	-10	-14
50	162	144	-11	-19

TABLE 5.
Total weight reduction of the MSS considering all permanent loads

Span length, *L* [m]	Total weight of MSS [t]		% difference compared to other studies	% difference to other existing MSSs
	Without an active system	With an active system		
70	795	761	-10	-1
60	679	641	-22	0
50	589	553	-	-3

From these results, the following conclusions are derived:

- The optimization results demonstrate a clear reduction in self-weight when active systems are integrated, compared to configurations without them. Its impact is more pronounced in the central zone of the main span than in other areas due to the construction process of the bridge deck.
- The effectiveness of the active system in the stationary stage is limited due to the typical pouring sequences of bridge decks, which start on the cantilever zones. Specifically, in the first stages, there is no increment of deflection on the main span which does not activate the control scheme.
- When optimizing the sections using active systems, in the beginning, there is a clear reduction in the sections for the centre of the span, but these same zones are then restricted to the launching stage structural demand. Therefore, it represents a lower bound of optimization.
- A hybrid active-passive system might improve the condition of the first point. For instance, the active system can initially present a higher value of prestressing on the cables, introducing a positive bending moment on the cantilever zone. Nonetheless, this produces on the bridge deck a negative deflection (upward) which is not usually desirable.
- The maximum reduction in terms of weight of an optimized MSS with and without an active prestressing system is a maximum of 11% comparing the total weight and 19% comparing only the weight of the main girders. However, these two values can be reduced to 8% and 12%, respectively, for a longer span.
- Despite there can be optimization reductions of up to 45% of the initial weight on some modules (see Section 4.2), this lands on a maximum reduction of 19% of the weight of the main girders. Also, this reduction is indirectly proportional to the span length, v. g., for span lengths of 70 m, the maximum reduction is 12%, while for 50 m, it is 19%.
- The results of MSSs using an active system land on similar weights of existing MSSs with these assemblies, which validates the optimization results for span lengths of 50 m, 60 m, and 70 m.

5. CONCLUSIONS

This paper presented a comprehensive analysis of the design and optimization strategies for underslung Movable Scaffolding Systems (MSSs), with and without the incorporation of active prestressing systems. The study considered various span lengths and covered all relevant construction stages. Based on the findings, the following conclusions can be drawn:

- The use of active prestressing systems clearly contributes to weight reduction in MSSs, particularly in the central modules during the stationary stage. However, two key limitations constrain the overall optimization potential:
    - Active systems are effective only during the stationary phase, specifically during the deck pouring process. As a result, the launching stage governs the design, imposing stricter structural requirements.
    - Their effectiveness during the pouring stage is limited on the cantilevers due to the construction process in which there is no increase in the deflection when pouring the cantilevers.
- The reduction in the total weight of MSSs with active systems of around 10% might not be sufficient to compensate for the cost of cables, struts, and anchorages, as well as the installation of an active control system, the sensors, and the actuators, among other elements. Therefore, from a cost-effectiveness perspective, the implementation of active prestressing may not always be justified.
- There are other advantages of the active systems that are not mentioned in this paper, such as the continuous monitoring of the MSS during the stationary stage. More information can be found in [43]. This has a direct impact on the safety of the MSSs during these manoeuvres and is of interest in some specific bridge projects.
- Future research on the implementation of active systems on MSSs could focus on the following directions.
    - A more comprehensive and integrated economic assessment should be investigated, incorporating not only the direct costs but also the potential benefits of emerging technologies.
    - The development of active systems capable of operating during both the stationary and launching stages should be explored. Extending their functionality to all construction phases may significantly enhance the overall optimization of MSSs.

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