Technical Challenges of Large Movable Scaffolding Systems

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Abstract

The method of construction of decks of bridges and viaducts with several spans using movable scaffolding systems (MSS) is very efficient and competitive. This solution is generally used for the 40 to 60 m span range. Over the last few years, new experiences have been acquired and new solutions have been developed for the 70 to 90 m range (large MSS or LMSS). In this range, unexpected economical results may be achieved if the number of spans is high and/or if the costs of piers and foundations are relatively high. With LMSS it is possible to achieve very high productivity ratios.

The application of LMSS implies significant technical challenges. Some are similar to the more common MSS, but others become more relevant.

This paper discusses bridge–equipment interaction including main vertical loads on the bridge, horizontal forces on piers, wind actions, wind-induced vibrations on piers with MSS stabilization, accidental MSS-induced actions, thermally induced horizontal displacements, and deflection control. Two real examples are presented. The design criteria recommendations are listed in the conclusion section.

Keywords: bridge engineering; bridge construction equipments; movable scaffolding system; organic prestressing system; large scaffoldings.

Introduction

Construction of decks of bridges and viaducts with several spans using movable scaffolding systems (MSS) is very efficient and competitive. This solution is generally used for the 40 to 60 m span range. Over the last few years new experiences have been acquired and new solutions have been developed for the 70 to 90 m range (large MSS or LMSS). In this range, unexpected economical results may be achieved if the costs of piers and foundations are relatively high and/or if access is difficult, for example, bridges over water. With LMSS it is possible to achieve very high productivity ratios.

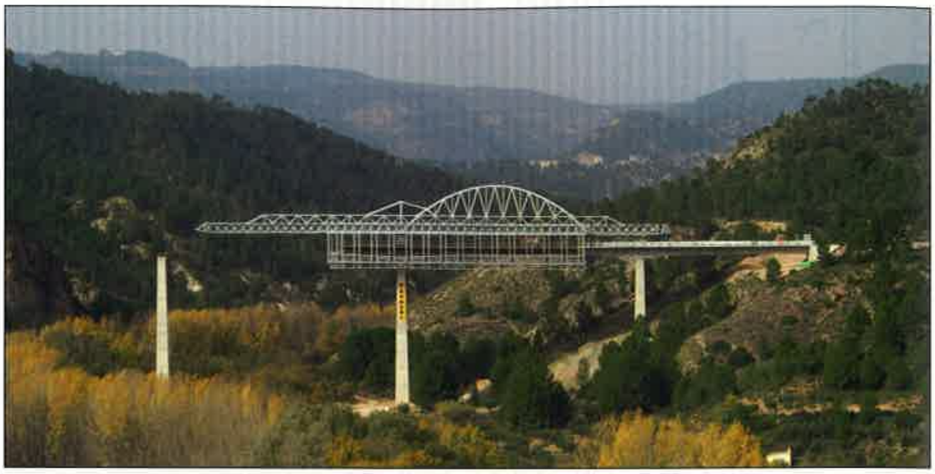

Fig. 1: Rio Cabriel Bridge, Spain

For this span range (70–90 m), as recent studies have proven,[1] the span-by-span construction also ensures important advantages such as continuity of the deck and a significant optimization of material consumption (in particular that of prestressing steel) because the construction stage may be almost neutral to the deck design.

Until the last few years, bridges with 70 to 90 m span were typically constructed by precast solutions, metallic solutions or cantilever method.[2]

With recent developments in span-by-span construction equipments, a new strong alternative is now available.

However, this construction method requires a complete and thorough study of all the main technical challenges involved in its application, both for the bridge designers and for the bridge-building equipment suppliers.

In international documentation[3,4] there is a significant lack of information about MSS' or LMSS' actions on bridges. Although in some countries there are important contributions on this subject,[5,6] it is clear that there is a lot of research and code standardization to be done.

In this paper, besides the presentation of general aspects regarding the use and conception of LMSS, these construction equipments are discussed, with two clear objectives:

1. to provide bridge designers information about the presented construction method;
2. to contribute for a discussion among MSS specialists considering that there is an obvious lack of normative documentation in this specific area.

Some of the presented issues are empiric and some are from different scientific works in progress (not published).

Along the text two examples of LMSS applications are presented, allowing a more direct perception of the presented issues. In the conclusion, recommendations are proposed, both for bridge designers and for MSS specialists.

General Aspects Regarding the Use and Conception of an LMSS

Adopting span-by-span cast *in situ* construction with LMSS is a strong possible solution for bridges and viaducts of several spans (especially in the conditions described earlier).

If the particular aspects discussed in this paper are considered, it is possible to achieve a deck conception and design, mainly conditioned for bridge service actions.

The Rio Cabriel Bridge near Valencia, Spain (*Fig. 1*), and the bridge across

Fig. 2: Bridge across the Hostovsky Creek Valley, Slovakia

Fig. 3: Bridge across the Hostovsky Creek Valley (night works)

the Hostovsky Creek Valley, near Nitra in Slovakia (*Figs. 2 and 3*), are two examples of bridges where the use of LMSS is a rational choice. In both there are several spans, the piers are relatively high (about 45 m), and the cost of alternative methods would be quite high.

In the Rio Cabriel Bridge, with a current span of 70 m, the probable alternative would be the cantilever method. With that option it would be possible to achieve a productivity of only about 120 m/month (with 6 form travelers) against the normal productivity of 140 m/month achieved with LMSS. Moreover, the alternative method would imply a very significant consumption of additional prestressing steel because of the implicit needs of the cantilever method.

In the bridge across the Hostovsky Creek Valley, with a current span of 69 m, the probable alternative method would be the span-by-span construction with conventional MSS (42 m span) implying construction of provisional piers to reduce the deck span. This solution would imply significant additional costs related to provisional pier construction and demolition.

Recent LMSS are very productive, having plethora of operational tools and being suitable for safe operations at night (see *Fig. 3*).

Another particular aspect of LMSS is the volume of concrete per span, which may be very significant. Concrete pouring operations above 500 m^3 are frequently avoided, and horizontal joints are frequently introduced. This has implications on the formwork design and on the deformation control at the second-stage of concrete pouring operation, because concrete cracks are to be avoided in the first stage.

LMSS Span Limits

One general question that may arise is: what are the span limits of LMSS?

The answer is as dynamic as the state of art. Presently, there are two main conditioning issues: the scaffold weight and the stability while launching operation considering the wind action.

Another conditioning issue, mostly depending on the LMSS type, may also be considered: the deflection limitation. Indeed the maximum acceptable deflection for current MSS, *L*/400, may represent values over 200 mm for LMSS, which might imply technical problems. This issue is discussed later in this paper.

In the current MSS (40–60 m span), the equipment weight does not usually affect the bridge design, which can be rigorously verified by specific calculation techniques.[7] But in larger spans (70–90 m), this might not be the case, depending on the LMSS weight.

The LMSS weight is greatly influenced by the location of the deck joints. The most common location for joints in medium span (40–60 m) bridges is at *L*/5 (*L* being the current span). But experience has shown that for larger spans (70–90 m) the most appropriate location for joints is near *L*/4. This solution enables reduction in flexural moments on the deck section over the penultimate pier during construction and allows for a better deflection control. Both the Rio Cabriel Bridge and the bridge across the Hostovsky Creek Valley were constructed with joints located at *L*/4, with good results.

In *Fig. 4*, two curves of LMSS weights neutral to the deck design are shown (deck width 12,0 and 14,0 m, respectively). These curves are based on a simplified study that equalizes the deck flexural moment over the last pier with a deck for the maximum constructive vertical loading scenario and for bridge service vertical loading (the same pier with the complete deck).

Thus, if the LMSS design is optimized, its use can be neutral to the deck design, not implying additional material consumption because of construction stage.

Both the presented examples—LMSS of Rio Cabriel Bridge and LMSS of the bridge across the Hostovsky Creek Valley—were not conditioned for deck design, with LMSS traveling weights of nearly 770 t for spans of about 70 m.

Regarding the stability of LMSS considering the wind action during launching operation, although such operation is to be conditioned by actual winds measured during the operation, if natural frequencies are too low, the well-known stability assessments related to launching operation may not be sufficient to provide safety, and specific studies have to be done (eventually wind tunnel tests). Considering a basis of 16 modeled MSS and LMSS, approximated curves of natural frequencies related to horizontal transversal mode at maximum

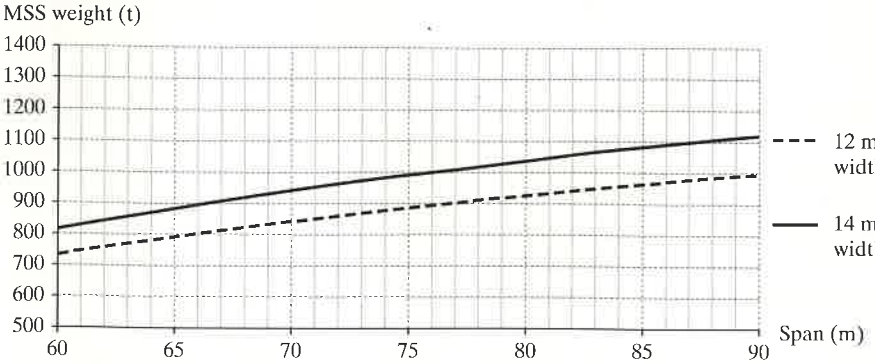

Fig. 4: Indicative limits of LMSS traveling weights neutral to deck design

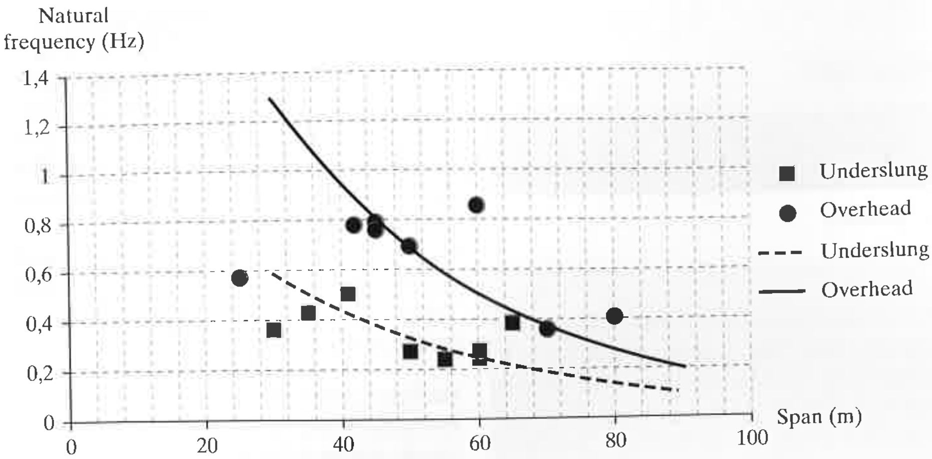

Fig. 5: Natural frequencies on MSS (horizontal transversal mode) at maximum cantilever position during launching

cantilever position, for different spans, are shown, for underslung (two main girders) and for overhead equipments (see *Fig. 5*).

In the absence of scientific research, the limit of the lower frequency is established by experience. There are several MSS worldwide with frequencies of about 0,2 to 0,25 Hz (horizontal transversal mode).

For equipments that reasonably accomplish the weight limits shown in *Fig. 4*, actual limit of spans for LMSS is about 90 m (for overhead equipments).

Horizontal Forces on Piers due to LMSS

Horizontal forces on piers due to LMSS mainly result from the following six actions: (a) horizontal projections of LMSS weight (sliding supports with slope), (b) friction (during launching), (c) braking loads (during launching), (d) forces in locomotion reaction points, (e) wind actions (transversal and longitudinal), and (f) accidental LMSS-induced forces (actions e and f are elaborated in subsequent text).

Usually, if there are no relevant seismic actions and if the wind is not conditioning, piers may have horizontal forces H_{ref} of about 4 to 5% of the deck weight (related to the pot bearings friction). Of course, this must be studied by the bridge designer on a case-by-case basis, but for conceptual references, this value gives a first hand approach of the importance of admissible LMSS-induced horizontal forces (not to condition pier design through LMSS actions).

Horizontal projections of LMSS weight (sliding supports with slope) may be relevant for pier design if the longitudinal slope is high. For example, if the longitudinal slope is near 5%, it may represent about 0,5 H_{ref} (if the LMSS traveling weight is about 50% of the deck weight per span).

Current sliding solutions in MSS are bogies with wheels (typical frictions of about 2–5%) or bogies with low-friction sliding materials (typical frictions of about 6–10%). Thus, considering the bridge design, during the LMSS conception it is preferable to adopt bogies with wheels. In this solution, friction on launching would imply forces of about 0,5 H_{ref}.

The action due to LMSS braking operation (during launching) strongly depends on the locomotion (mechanical) solution but should be carefully analyzed by the LMSS designer/manufacturer and transmitted to the bridge designer.

Obviously, this action may be more severe than the launching friction, if friction braking devices are adopted. Moreover, if the braking operation is too fast, relevant dynamic phenomenon has to be considered. Nevertheless, if the LMSS are moved with hydraulic locomotion solutions, braking operation may be "soft" and neutral to the bridge piers.

In some MSS and LMSS, the point of reaction of the locomotion system may be far from the more-loaded bogie. This applies, for example, when locomotion is promoted by winches that are fixed on the scaffold (the main body) and on an MSS support (the extremity of the cable), which is fixed on a pier. This force value is usually of the same magnitude of the sum of friction with the longitudinal slope horizontal projection (unless accidental actions are induced by the equipment).

The combination of these actions leads to several combination cases, from which a few typical cases are selected. In *Fig. 6*, as a reference example, six severe cases are presented for Rio Cabriel piers design. Although Rio Cabriel piers are considerably high (>45 m) these actions did not condition the design.

Wind Actions

Wind actions on MSS or LMSS are clearly different during launching operation stages and during equipment stationary stages, considering the duration of the stages/operations and adequate return period.

Usually, the most critical wind directions are the transversal winds associated with vertical winds during launching stage. Of course, longitudinal winds may be conditioning for the design of specific components (locomotion system and bracings) but such assessment is no more than a common design task.

For current MSS there are sustainable recommendations of wind design and wind operation velocities[6] (see *Table* 1). For LMSS there is no normative documentation and there is no statistic information to determine fixed values, because the piers may be especially high. Nevertheless, there is documented information (in projects where authors were involved) which confirms that mentioned values for MSS may not be safe for high bridges where LMSS may be used. Thus, a case-by-case analysis is recommended for LMSS design.

It should be emphasized that LMSS with natural frequencies lower than 0,2 Hz (horizontal transverse mode) in maximum cantilever position (during launching operation or eventually with low frequencies in other relevant modes) should be evaluated with proper tools (eventually wind tunnel tests).

Wind-Induced Vibrations on Piers with Eventual MSS Stabilization

Currently, bridge designers take into account the necessary dynamic assessments of the bridges, both in construction and service stages, considering

		Fz (kN)	Fy (kN)	Fx (kN)	Mx (kN.m)	My (kN.m)	Mz (kN.m)
Case 1	Concrete pouring —wind 60 Km/h	14 354	174	8	922	32	24
Case 2	Launching—wind 60 Km/h	5493	230	330	6824	2541	224
Case 3	LMSS fixed—wind 170 Km/h	5374	1398	4	7478	51	445
Case 4	Concrete cure—wind 170 Km/h	14 756	1398	5	7490	112	436
Case 5	Accidental launching (position 1)	4392	0	828	3490	6380	1880
Case 6	Accidental launching (position 2)	3458	0	787	2743	6071	1827

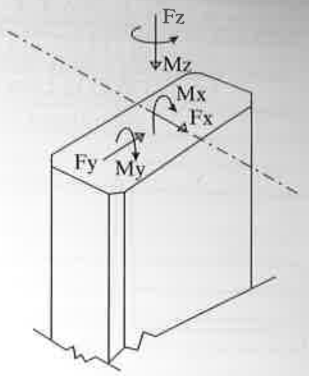

Fig. 6: Service loads on the front pier in the Rio Cabriel Bridge

	Launching operation (average wind) (km/h)	**Launching operation (peak) (km/h)**	**Equipment fixed (storms) (km/h)**
MSS^6	40	60	140–170

Table 1: MSS wind design velocities

the structure by itself. Nevertheless, there is one particular aspect of the construction stage, which is not obvious even for skilled designers, because it is not identified by any bridge calculation model and becomes more relevant in high pier bridges where typically LMSS are to be used.

During the concrete pouring operation, there is a significant increase of mass in the front pier, without immediate increase in stiffness (because the concrete is still liquid). Indeed, the concrete filled on the MSS formwork significantly reduces the natural frequencies of the front pier (in Rio Cabriel that reduction was from 0,49 to 0,34 Hz), because there is significant mass on top of the pier (see mass MA2 in *Fig. 7*) but not a stiff deck to provide its bracing yet. The vortex-induced bending oscillation and the transverse galloping[8] are two possible wind-induced vibration forms of the piers.

In the Rio Cabriel Bridge, the most relevant potential phenomenon was the vortex-induced bending oscillation leading to a critical wind velocity of 20,3 m/s, due to low natural frequency of the pier (0,34 Hz).[8]

This critical wind velocity (very low) could not be accepted, and additional measures were taken in cooperation between the bridge designer and the LMSS designer (an interaction model was developed). The connections between the LMSS and the bridge were studied to provide a horizontal elastic support of the pier (33 000 kN/m), which led to a critical wind velocity higher than the maximum concrete pouring operational wind velocity of 25 m/s.

In LMSS applications this particular issue has to be studied by the bridge designer, particularly if the piers are high.

Accidental LMSS-Induced Actions on the Bridge

An analysis of 47 recorded accidents and incidents (in four continents) with bridge-building equipments (PhD research, in progress, of one of the authors, not published) gives relevant information on bridge construction equipment (BCE). Although, at present evidence of the accident cause is available only in 36% of the cases (firmly identified accidental causes [FIAC]), it is quite obvious that the primordial cause of the accidents is the human factor (75% of FIAC). Another important factor is the failure of fundamental mechanical components without redundancy (about 12% of FIAC). Natural catastrophes represent only 2% of all registered accidents.

This information gives the idea that some human errors may be thought of as "characteristic actions" and probably they should be treated that way in the design of a BCE.

Two recommendations for LMSS designers result from the following:

1. Characteristic values of operational tolerance magnitudes should be calculated by considering the corresponding values in the Operation Manual multiplied by a partial safety factor.
2. Fundamental connections of elements with structural function, which are connected/disconnected for every cycle, should have redundancy.

This study clearly indicates that a greater number of the accident situations are much more relevant for equipments design than for bridge design. Nevertheless, there are two accident situations that should be considered in bridge design:

1. imbrication of LMSS in sliding devices or wheels;
2. dynamic force on structural elements where winches are fixed, due to collapse of one winch.

The first typically results from the geometric defects of the steel structure of the LMSS main girder on the sliding surface. If there is a vertical step in a two modules connection, depending on the step magnitude, during launching operation the locomotion force is incremented when the step passes the sliding device or wheel, until locomotion unit power limit is reached. If the step is significant, that action may lead to significant horizontal displacements on the pier. This must be computed by the LMSS designer after taking into consideration the steel construction tolerances (or measured values) and geometric characterization of the sliding device or wheel and must be communicated to the bridge

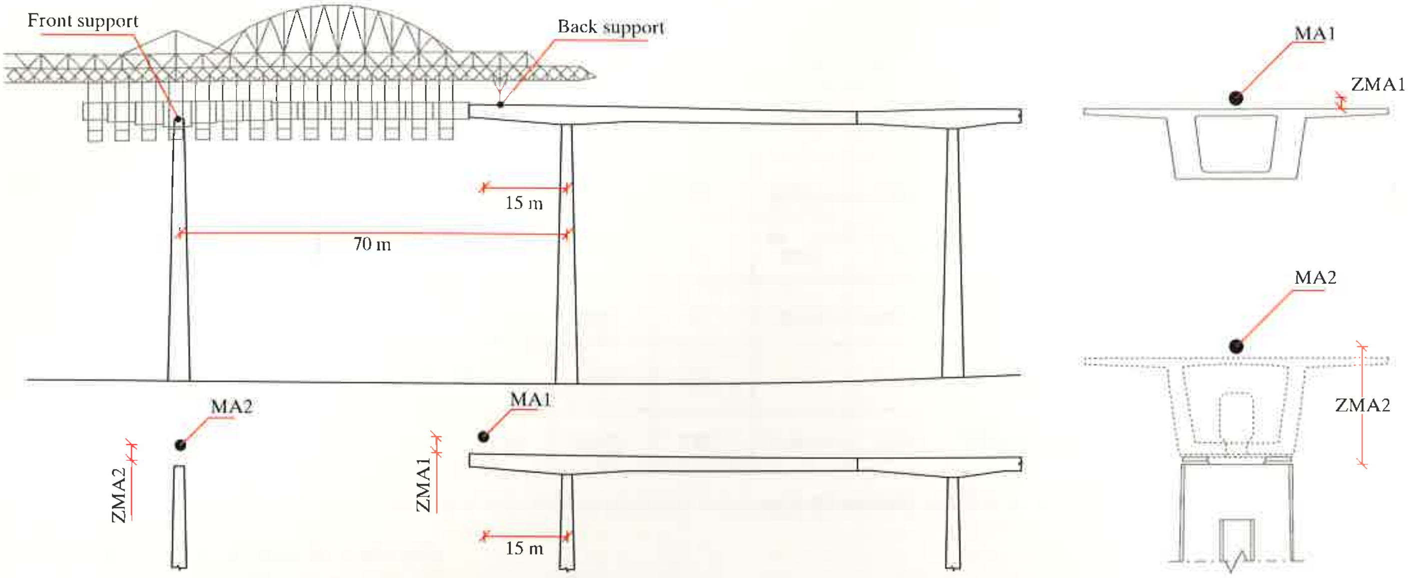

Fig. 7: Location of LMSS plus liquid concrete mass in Rio Cabriel Bridge during concrete pouring operation

designer. This may be treated as a major "equivalent accidental friction coefficient".

The second is exclusively related to LMSS with winch locomotion, typically characterized by having two winches, for redundancy. In this case, if one winch collapses, the other assumes the force of the first. This may be a fast phenomenon which implies dynamic amplification. Hence if the service force of each winch is F (the global force on the two winches is $2F$), the structural elements where the winches are fixed should be designed for the accidental force $3F = F \times (1 + 1 \times \text{DAF})$, where DAF is the dynamic amplification factor, considering a conservative value of DAF = 2,0 (unless more accurate calculation is done).

Heat-Induced Horizontal Displacements on the LMSS Supports

In the construction of the closing span of a bridge an LMSS is longitudinally typically supported on two supports with independent movements (Δ_1 and Δ_2). This may happen near an abutment, where the support displacements Δ_1 are nearly null, or may happen in the middle of a bridge, where both displacements are to be evaluated. These displacements may produce important internal efforts in the LMSS structure, unless other measures are taken. In long bridges this should be evaluated by the bridge designer and transmitted to the LMSS designer.

In *Fig. 8* the closing position of the bridge across the Hostovsky Creek Valley is shown, where horizontal displacements on the LMSS are indicated. In this bridge, special sliding devices on the LMSS were conceived for the "closing" span.

Deflection Control

The common practice in the specification of scaffoldings is to limit their maximum deformation to (L/400[9]; L being the deck span). In LMSS this limit should be more restrictive because such deformation may imply structural problems in the deck during prestressing application,[9] and because operational difficulties may arise in the LMSS as problems regarding lowering of the LMSS after deck prestressing and regarding adjustment of the formwork.

Moreover, the geometric tolerances for bridge construction are absolute values[10] which represent very low relative values for LMSS span ranges (from L/3500 to L/4500).

According to previous experience, for LMSS, good results are achieved if the mid-span deflection limit is L/1000.

One effective solution to achieve reduced deflection on MSS and LMSS is the application of organic prestressing system (OPS).[11,12] This solution also provides other relevant additional advantages.[11,12]

OPS is mainly an active control system which controls the tensions and deformations in the LMSS main girder by means of increasing or decreasing the prestressing on the LMSS prestressing cables.

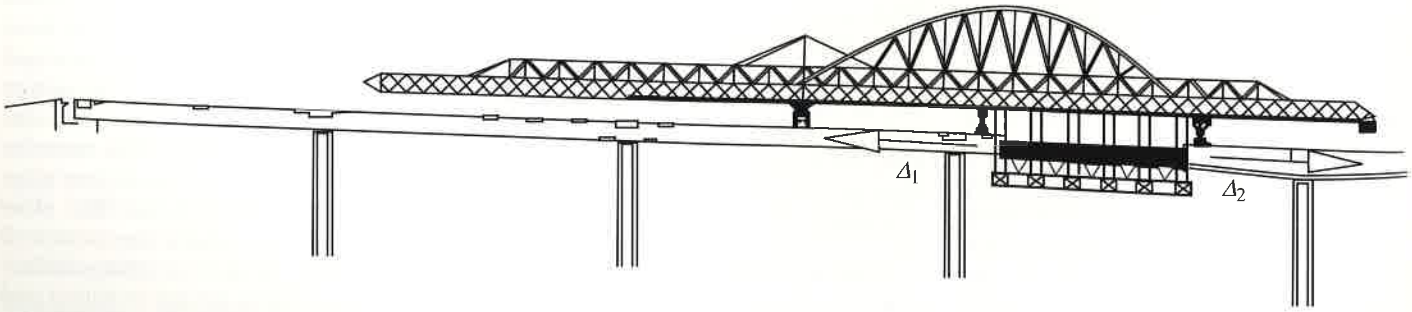

Fig. 8: Picture of the closing position of the bridge across the Hostovsky Creek Valley

1	Maximum actual span with LMSS: 90 m
2	Location of joints: at $L/4$
3	Prestressing layout: classical span-by-span solution
4	Consideration of horizontal loads at front piers: (a) horizontal projections of LMSS weight, (b) LMSS sliding friction, (c) braking loads, (d) forces in locomotion reaction points, (e) wind actions on LMSS, and (f) accidental LMSS-induced forces
5	Consideration of adequate combinations of horizontal forces and vertical forces, according to LMSS functioning
6	Eventual consideration of wind-induced vibrations on piers, eventual need of LMSS bracing
7	Consideration of accidental LMSS-induced actions on the deck

Table 2: Bridge design recommendations

1	Minimum natural frequency (horizontal transversal mode): 0,2 to 0,25 Hz
2	LMSS traveling weight nearby: (0,75 × L + 15) × B t (L is the span in m, B is the deck width in m)
3	Desirable friction in bogies: 2 to 5% (wheels)
4	Use of hydraulic "soft" braking system
5	Eventual consideration of higher wind velocities for LMSS—a case-by-case analysis is recommended
6	Consideration of thermally induced displacements on LMSS (closing spans)
7	Maximum mid-span deflection of about $L/1000$ (under full concrete weight)
8	$T_d = T_o \times \Phi$ (T_d = design tolerances, T_o = tolerances indicated in the Operation Manual, and Φ a safety factor)
9	Connections of elements with structural function—connected/disconnected every cycle—should have redundancy

Table 3: LMSS design recommendations

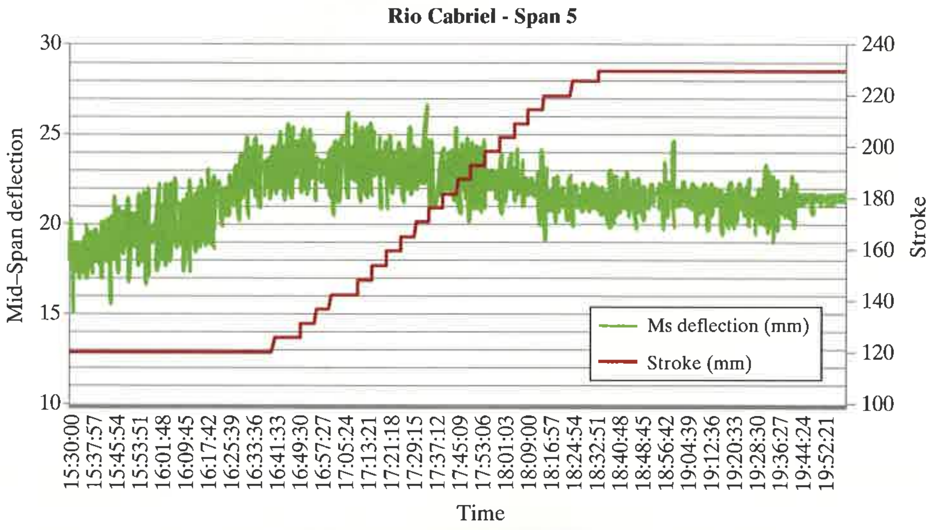

Fig. 9: Measures of mid-span deflection and OPS actuators stroke during a concrete pouring operation in Rio Cabriel Bridge

In the presented examples, the Rio Cabriel Bridge and the Hostovsky Creek Valley Bridge, with OPS-strengthened overhead arches the maximum mid-span deflections registered were clearly below $L/2000$ (see *Fig. 9*).

Conclusions

The main conclusions are presented in *Tables 2 and 3*.

If these recommendations (or similar) are followed, the building of 70 to 90 m span bridges adopting span-by-span construction with LMSS will become very economical, safe, and fast, as in the successful cases of the Rio Cabriel Bridge and Bridge across the Hostovsky Creek Valley Bridge.

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