Robustness and Stability of Launching Gantry Systems
and Movable Shuttering Systems – Lessons Learned

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Summary
Launching gantries are frequently used in the erection of precast segmental
and I-beam bridges, while movable shuttering systems (MSS) are used for in situ
span-by-span and balanced-cantilever construction. The use of launching
units is therefore frequent in most types of medium-span, prestressed concrete
bridges.

Launching gantries and MSS are complex and delicate structures. They resist
huge loads during bridge erection and overtake long spans during self-launching.
They are light—i.e. designed for high stress levels in different load and support
conditions, which make them prone to instability. And they are reused many
times, on different projects and by different crews.

As a matter of fact, a number of launching units have collapsed in recent years,
with many fatalities and extreme delays on the project schedule. As a conse-
quence, the launching units are almost always leased or purchased on the basis
of stringent technical specifications, and their design is subjected to independent
checking.

Design and operational failures detected by the author within numerous inde-
pendent design check assignments are discussed in the paper and recommenda-
tions and suggestions are provided to prevent failures and assure adequate
robustness of launching units. Owing to the legal proceedings surrounding such
events, only general causes of collapse are discussed in this paper and no pho-
tographs of gantry collapses are included, and the photographs do not refer to
collapsed units.

Keywords: launching gantries; movable shuttering systems; stability of temporary
structures; robustness of temporary structures; bridge construction equipment.

Introduction
Construction of prestressed concrete bridges spanning from 30 to 120–140 m
is mostly based on the use of self-launching machines. Although the
technological requirements are dif-
ferent, the two families of launching
units—launching gantries for precast
segmental construction and movable
shuttering systems (MSS) for in situ
casting, are so similar that units origi-
nally conceived for in situ casting are
often recycled for segment erection and vice versa.

Launching gantries and MSS are
complex and delicate structures. They resist huge loads—often the entire
span weight, and have full self-launch capability under the same constraints
that the obstacle to overpass exerts on the permanent structure. They must fit
plan and vertical curvatures both in the superstructure to be erected and in the
supporting piers. Also, they must
be easy to transport, assemble, and
operate, i.e. as light as possible, which
dictates the use of high-strength steel
and designing for high stress levels
under many different load and support
conditions.

As a consequence, launching units
are slender and prone to instability.
Overturning, uncontrolled sliding, un-
seating from supports and similar mac-
roscopic events are simple to control.
More complex forms of instability
such as out-of-plane buckling can be
assessed only with numerical analysis.

The conceptual schemes of launching
units are not many [1]. The light gan-
tries for precast beams comprise two
parallel trusses with triangular cross-
section. Two winch-trolleys run along
the upper chords with the beam sus-
pended underneath and no transverse
bracing is installed between the trusses (Fig. 1). The spans are short, the design
load is low, and the winch-trolleys...
operate far from each other, so that these units are usually very light and deformable.

A gantry for span-by-span erection works on similar spans but the design load is much higher as the unit sustains the entire span during segment assembly. The general arrangement of an MSS for span-by-span casting is similar; with the span either suspended from (upper-beam units) or supported on (lower-beam units) a self-launching frame. The twin-upper-beam units comprise two three-dimensional (3D) trusses, box-girders, or paired I-girders braced to each other only at the ends or totally unbraced. Independent 3D trusses or paired I-girders are also used in the twin-lower-beam units (Fig. 2) because the two halves of the casting cell must be separated during launching. A unit of this type collapsed in Italy in the eighties because of breaking of a retaining cable during downhill launching on roller bearings.

The most compact upper-beam units have a central beam comprising two paired I-girders. In the case of tight plan curvatures, the carrying beam can be divided into two sections—the main girder and a front support beam that sustains the front end of the main girder during launching, connected by a hydraulic turntable as in Fig. 3. This solution is also adopted with the twin-upper-truss units, although sustaining two distant trusses with a central support beam may cause problems of torsion stability. A custom-made unit of this latter type collapsed in Ohio in the year 2004, killing four workers. Collapse was apparently caused by improper anchoring of a support leg to the pier cap.

Lower launching beams are also used to sustain the front trolley of the wheeled span carriers in the last stages of placement as in Fig. 4. The carrier moves forward along the support beam until reaching the lowering location, and the support beam is then launched to the next span to clear the area under the carrier for span lowering.

Single- and twin-upper-beam gantries for balanced-cantilever precast segmental erection operate on much longer spans—a stably anchored twin-upper-truss unit of this type was destroyed in Italy in the year 2006 by the collapse of the segmental span being erected. Similar units are also used to carry two casting cells for in situ casting as in Fig. 5. The casting cell can therefore be twice as long as that of conventional form travellers, and no temporary pier-lock systems are necessary for deck stabilization during construction, and having access to the work locations, casting the pier-head segments, and transferring the casting cells to the next span, are all facilitated. The design
Design Loads of Launching Units

The design loads of an MSS are classified into fixed and varying loads. Fixed loads include the self-weight and the superimposed dead load. Varying loads include the weight of the fresh concrete and the reinforcing cage, the load redistribution at the application of prestress, the actions transferred by lifting devices carried by the unit, the actions of snow and wind, and the thermal variations. In the units for balanced-cantilever construction that restrain the deck against overturning (Fig. 5), varying loads also include the restraint forces of segment unbalance.

The load conditions for a launching gantry are more complex because of the dynamic nature of loading. These units are grouped into classes, and the classification governs the load magnification factors to be used in the load combinations. The class of a unit is determined on the basis of the number of load cycles and the loading level, and since most of load cycles take place at the load capacity of the unit, the spectral factor is usually high. Specific classifications also apply for the mechanical components.

The load conditions include regular forces that act during normal operations, occasional forces in the unit in service, exceptional forces both in service and out-of-service (non-operating anchored unit) conditions, and special forces that arise during assembly or locally. The regular forces are the dead load, the service load, and the inertial forces generated by intentional movements and oscillations of load. The occasional forces are the impacts of the wheels of the winch-trolleys against the runways, wind, snow, ice, and thermal differences. These units are reused many times and the meteorological loads are therefore determined without reductions in relation to the work duration. The load combinations distinguish normal operations and out-of-service wind conditions. Gantry of medium length are unlikely to sustain damage from wind-induced vibrations, and launching is always avoided in the presence of strong wind.

The exceptional forces are the out-of-service wind, the test load, impacts against the buffers at the end of the winch-trolley runways, and the design-level earthquake. Impacts against buffers are often disregarded because of the low velocity of the winch-trolleys, provided that the runways are equipped with end-of-stroke switches that stop the movement. End-of-stroke buffers are indispensable where the deck has a longitudinal gradient, as the main trusses follow the gradient and the runways are therefore inclined planes.

The loads are grouped into three load conditions:

- **Load Condition I** is the normal operational condition with regular forces. It combines the dead load and the service load inclusive of dynamic amplification. These loads are multiplied by the load magnification factor resulting from the gantry classification.

- **Load Condition II** is the operational condition in the presence of occasional forces. It combines the actions of Condition I with wind in service, snow or ice, and thermal differences. The occasional loads are not multiplied by the load magnification factor. If the design wind is strong, the longitudinal dynamic amplification factor can differ from the value for Condition I, as the action of wind affects the starting and braking times of the winch-trolleys.

- **Load Condition III** is the action of exceptional loads as identified by
the following combinations: dead load and out-of-service wind; dead load, service load, and impacts against the end-of-stroke buffers; dead load, service load, and design-level earthquake; and assembly and dismantling operations. Although conceptually similar to assembly and dismantling, self-launching is generally assessed in Condition II because of the higher frequency of these operations.

The design codes for launching units prescribe different allowable stresses for the three load conditions. When a limit-state approach is adopted for design, both serviceability limit states (SLS) and ultimate limit states (ULS) are assessed. The SLS corresponds to the loss of functionality of the gantry, whereas the ULS is related to critical conditions such as rigid equilibrium, rupture of connections, yielding of structural elements, and instability. Some codes assess instability like any other ULS condition, although out-of-plane buckling is a sudden event devoid of post-critical domain and the critical load is influenced by geometrical imperfections that are difficult to detect. In the daily design practice, therefore, out-of-plane buckling of launching units is assessed with more conservative load factors, usually $\gamma_C = \gamma_C^* \approx 2.5$. In spite of that, out-of-plane buckling of an overloaded support leg recently led to the loss of a 148 m long, 12,3 MN heavy launching unit, with one worker killed.

**Instability, Structural Modelling, and Assessment with Load Testing**

The buckling modes of a structure depend on the load. In a launching gantry the load shifts along the trusses during placement, and the trusses shift on the pier supports during launching. Instability of a launching unit is therefore assessed for different positions and eccentricities of the service load and of the unit itself during launching.

So complex structures (generally also the cross-section of chords and diagonals along the unit) cannot be assessed with bibliographic values for the critical load. Instability is analysed with numerical models of the entire unit inclusive of main trusses, winches, trolleys if capable of exerting a lateral restraint action between the trusses, and support crossbeams and towers. Linear buckling analysis is used to determine the instability modes under a specified set of loads through the solution of the generalised eigenvalue problem

$$[K - \lambda G(r)]\Psi = 0$$

where $K$ is the mechanical stiffness matrix, $G(r)$ is the P-delta stiffness matrix due to the load vector $r$, $\lambda$ is the diagonal matrix of eigenvalues, and $\Psi$ is the matrix of the corresponding eigenvectors (buckling mode shapes). Each eigenvalue–eigenvector pair is called a buckling mode of the structure. The eigenvalue $\lambda$ is called buckling factor and it is the scale factor that must multiply the loads to cause buckling in the given mode.

Design codes normally recognise two types of instability: the overall sway of the structure (out-of-plane buckling) and the instability of a member between its end nodes or of a web panel between stiffeners and flanges (local buckling). Investigating many buckling modes with complex numerical models involves prohibitive computational times so that it is common practice to analyse out-of-plane stability with buckling analysis and to check local buckling with the stress magnification factors prescribed by code.

The different types of launching units require specific approaches to modelling and analysis. In the case of a twin-lower-beam MSS rigidly supported at the permanent piers, simple beam models can represent the box-girders or paired I-girders adequately. The twin-lower-truss units are more complex and 3D models of the entire unit are necessary when the pier brackets are flexible (Fig. 6) or only some of the trusses sustain the casting cell. Modelling the support structures is also necessary when the MSS is supported on both permanent concrete piers and temporary steel piers, as the different flexibility of supports, the different coefficients of thermal expansion, and the different thermal inertia of massive concrete piers and slender steel piers affect the load distribution in the support structures and the buckling factors accordingly [2].

Analysis of a single-upper-beam unit is also complex because the main support legs are close to each other (Fig. 7) to take support on the front pier while the rear legs are distant to feed segments (Fig. 3) or preassembled cages (Fig. 7) through the completed deck. The rear legs are adjustable in plan to fit the deck curvature, and all the legs have hydraulic lowering systems for fast release of the completed span. In the presence of so many technological restraints, the structural nodes between the legs and the I-girders are very complex. Single-beam models are useful to...
analyse span casting, the application of prestressing, and self-launching, but 3D shell-element models are often indispensable to assess the structural nodes.

The twin-upper-truss units take support on flexible crossbeams, and disregarding the deflections of supports leads to inaccurate stability analyses. In the MSS of Fig. 8, the casting cell is suspended on either side from two paired trusses (light grey trusses in Fig. 9), while a third external truss controls out-of-plane buckling and carries the gantry runway. The flexural deflection of the support crossbeams is evident in the photograph. So, complex units require refined analyses (in Fig. 9 a view of the 5300-frame-element model is shown with the main load-carrying members in light grey and the bracing and stabilization systems in dark grey) for accurate evaluation of the load distribution.

The model of a launching truss should have joints at the convergence points of the gravity axes of members. The actual location of joints is critical, as in one of the many load and support conditions, the initial geometry imperfections might have the same shape as that of a buckling mode. Therefore, chord misalignments and verticality errors in the support towers should always be surveyed and reproduced in the models by adjusting the joint coordinates. Some general design codes prescribe allowable tolerances and equivalent loads for the analysis of their effects. However, the launching units are subjected to many assemblies and hundreds of stress reversals, and the code provisions are therefore often inadequate.

The reliability of the internal releases of the degrees of freedom must always be critically reviewed. The twin-upper-beam units take support on flexible towers, with the main tower that restrains the trusses longitudinally and the secondary tower with free rollers or Teflon skids. If friction and wear prevent sliding of bearings, the thermal elongations of the trusses generate horizontal bending in the support crossbeams and P-delta effects in the towers. Before releasing the longitudinal bearing displacements in the model, it is therefore necessary to check that the longitudinal stiffness of the secondary tower is greater than the expected upper-bound resistance to sliding.

Similar considerations apply for the rotations. When the main beams take support on pivoted frames that do not restrain the flexural rotations, the articulation can be modelled with a cylindrical hinge at the pin axis. But when the support tower has four distant legs, the crossbeams are placed on jacks to create a hydraulic hinge during launching. The safety ring nuts of the jacks are tightened before camber adjustment and are released at form-stripping so that during span casting and the application of prestress, the jacks can be modelled with rigid frame elements. During launching, the support reactions are kept uniform by the hydraulic circuit and the jacks are modelled with kinematic systems capable of undertaking differential deflections without unbalancing the support reactions.

The model capability to represent the unit behaviour should always be assessed with load testing. Launching units should be subjected to load testing before the first use and after every major reassembly. Launching gantries are subjected to both static and dynamic tests, whereas the MSS are subjected to only static tests. After applying a waterproof membrane and inserting the internal forms, the casting cell is filled with water. Concrete blocks may be suspended from the main trusses not to overload the casting cell with an excessive water load as in Fig. 8.

Out-of-Plane Buckling of Twin-Upper-Truss Units

The main trusses of the twin-upper-beam units are either braced to each other at the ends or totally unbraced, and out-of-plane buckling is a major design concern. The critical load for out-of-plane buckling of a freestanding truss depends on the degree of fixity at supports, a support condition prompting the truss to twist as it deflects laterally, the lateral restraint action exerted by the inclined diagonals on the compression chord, the location and entity of concentrated loads, and the level of imperfection in the initial geometry.

In a twin-upper-truss unit, these factors coexist and coalesce. The degree of fixity at supports is modest, the trusses being supported on flexible crossbeams, with out-of-node eccentricity, and without cross diaphragms. The trusses bend laterally and twist because of differential deflections in the support crossbeams, and the depth of truss and rollers amplifies the lateral displacements of the upper chords. The triangular cross-section is tall and narrow and the lateral restraint action exerted by the inclined diagonals is therefore low. The load is applied to the upper chord—i.e. above the centre of shear of the cross-section, and the geometry imperfections may be significant because of the high number of field splices and the tolerances accumulated in previous assemblies.

Out-of-plane buckling of a twin-upper-truss gantry is investigated by analysing the placement cycle of some characteristic segments. Buckling analysis of an MSS is simpler because of the absence of load movements. The buckling modes of the gantry of Figs. 10 and 11 have been computed at hoisting and lowering of the heaviest segment with...
a 3800-frame-element model; in the two figures, the segment is right underneath the winch-trolleys, represented in blue. Many intermediate conditions have also been investigated as triangular trusses can and do buckle also when the load is close to the support crossbeams. In the presence of transverse load eccentricity, out-of-plane buckling can be controlled by equipping the winch-trolleys with transverse sliding skids or rolls that take contrast against the runways to exert a lateral restraint action between the compression chords.

Excessive confidence with a launching gantry as a result of having already handled similar loads in the past may be a serious mistake. Instability does not only depend on the entity of load but also on how the load is applied to the unit. When a gantry handles a long precast beam, the winch-trolleys are at the opposite ends of the beam—i.e. almost one-half of the gantry length apart. When the load geometry is such that the winch-trolleys work adjacent to each other (in the macro-segmental erection of Fig. 12 the winch-trolleys operated in tandem to handle 4.3 MN heavy, 34 m long deck segments), the total load may be the same, but the stresses in the trusses are much higher. Shifting the load transversely with the winch-trolleys (this is often necessary in bridges curved in plan) also overloads one of the two trusses.

Neither is self-launching less demanding. Fig. 13 shows the first out-of-plane buckling mode of a longer twin-upper-truss gantry (4200 frame-element model) at pier contact, with the winch-trolleys at the rear crossbeam that suspend anti-overturning counterweights. Also such load concentrations can affect local stability of the unit.

Fig. 11: First buckling mode at segment release

Fig. 12: Pivoted front launch support

Fig. 13: First buckling mode at the maximum launch cantilever

Excessive attention must be paid to the pivoted support legs. In the support frame of Fig. 14, the bottom crossbeam originally had a box-section over its entire width. To reuse the gantry in a curved bridge, the support pistons had to shift transversely and the crossbeam was windowed to lodge their mobile heads, with the result that the cross-sectional torsion constant in the windowed end portions of the crossbeam became less than one-thousandth of the original value. When the support piston is at the end of the crossbeam, the vertical load path is the three-aligned-hinge scheme of Fig. 14, in which the central cylindrical hinge has minimum rotational stiffness. The scheme is more stable when the piston is under the inclined portal leg so that the support frame would likely buckle (leading to the loss of the unit) only in curved bridges. As a result of the independent design check process, the crossbeam was stiffened by welding lateral flanges and webs to create box-girders on both sides of the windowed portions, Fig. 15.

Modelling the entire unit is necessary not only for buckling analysis. The crossbeam deflections overload the stiffer support members, and single-truss models on rigid supports therefore tend to underestimate the stresses in the pivoted support legs and the concentrated loads transferred to the deck. The same applies for the front pivoted legs that support the unit during launching of the main support crossbeams, Fig. 12.
Dynamic Effects of Local Buckling and Prevention of Progressive Collapse

Overloaded members of launching units may buckle suddenly. Therefore, careful inspections are necessary during assembly and at regular intervals during the use of the unit. Any damaged diagonals must be reinforced or replaced and also the braces must be inspected frequently. The reasons for out-of-flat must be investigated, as this makes the members susceptible to local buckling.

The global safety of a launching unit depends on the safety of members against local failure and on the unit response to local failure. Local buckling of a primary load-carrying member is critical in the support towers, while stable alternate load paths often exist in such redundant 3D trusses; however, local buckling could trigger a chain reaction of failures causing progressive collapse.

One of the main approaches to ensure the robustness of a launching unit and to reduce the risk of progressive collapse is to require insensitivity to local failure—i.e. local buckling of a primary load-carrying member must not trigger collapse of the gantry or of a major part of it. Clear verification procedures must be stated in the technical specifications for the unit at this purpose.

Although the structural damage induced by local buckling is often limited, the sudden stress redistribution is a highly dynamic process that requires non-linear analysis in the time domain. The following approach can be used:

a) Start from an accurate model of the unit and apply the loads that generate local buckling.

b) Compute the forces and moments at the end nodes of the buckling member.

c) Remove the buckled member from the model and apply the end-node forces and moments with inverted sign.

d) Define a loading function that increases linearly from 0 to 1 over a length of time about 10 times longer than the first period of the gantry, and then holds constant for an equal length of time.

e) Define an unloading function that abruptly jumps from 0 to –1 and holds constant to –1 for the duration of the analysis.

f) Load the model by applying the external and nodal loads with the loading ramp function.

g) Analyse the dynamic response of the gantry by removing the nodal loads with the unloading ramp function.

The resulting stresses can be assessed like any other ULS condition. The dynamic amplification factor detected by time-history analysis is often low because of the flexibility of these units. If the analysis shows overloading of the alternate load path and buckling of another member, the same approach can be followed to analyse the entire buckling sequence until either stress stabilization or collapse. Axial plastic hinges that drop the load at buckling can be inserted in the diagonals to automate the analysis of the buckling sequence.

As regards the time-integration technique, modal superposition in the time domain provides a highly efficient procedure with shorter run times than direct integration. Closed-form integration of the modal equations is used to compute the response so that numerical instability problems are never encountered, and the time step may be any sampling value that is deemed fine enough to capture the maximum response values. Direct integration requires longer run times and the results are sensitive to time-step size; however, impact problems that excite a large number of modes are usually solved more efficiently by direct integration.

Fig. 16 illustrates the axial force in the left diagonal at the front support of the MSS of Fig. 9 as the adjacent diagonal buckles. The thicker line has been computed by direct integration (Hilber–Hughes–Taylor method) and the grey lines have been computed by modal superposition (50, 100, 150, 200 and 250 modes). The time step is 0.01 second in both cases. Direct integration closely matches the initial and final static forces (which are a precious interpretation means for such complex analyses), while the Wilson method converges slowly and only with so many vibration modes that the saving in run time is insignificant. Direct integration is also recommended for investigating impacts against the end-of-stroke buffers or the sudden loss of a precast segment.

Local Buckling of Plate Girders at Supports

A plate girder subjected to mainly flexural stresses may be affected by three forms of instability: the lateral-torsional instability of compression flange; the torsion instability of compression flange; and buckling of web panels. In the paired I-girder units, the first two forms of instability are controlled by cross diaphragms that avoid relative movements between flanges and by two planes of horizontal braces that resist torsion and distribute the stiffening action of cross diaphragms along the girders. Buckling of web panels is controlled by flanges and stiffeners and it is rarely a critical situation because of the presence of the post-critical domain.

A non-stiffened web panel subjected to a concentrated load applied through the bottom flange may be affected by three forms of instability: web-yielding above the load followed by the plastic deformation of the bottom flange, localised
buckling at the base of the web panel followed by web-yielding and the onset of a plastic mechanism in the bottom flange, and general buckling of the web panel. These three forms of instability are controlled with the length and flexibility of the support rollers. In the most delicate cases, the support rollers may be placed on jacks that create hydraulic torsion hinges for uniform load distribution between the I-girders.

The axial stresses in the bottom flange of a support section depend on the type of girder. For an I-girder, the stress–strain relationship is bilinear. The behaviour of a box-girder is more complex because plane sections do not remain plane and both the first-yield moment and the plastic moment capacity are smaller than their theoretical values, and buckling of the bottom flange can be very dangerous.

In the twin-upper-beam unit of Fig. 17, one of the two box-girders was slightly misaligned during launching, so when the front cantilever was already 48 m long, the manufacturer of the unit decided to realign it. A crossbeam was installed close to the main support jacks and two flat jacks placed on Teflon plates, were to be inserted under the webs to then pull the jacks and box-girder rightward. But the procedure was misunderstood and after raising the box-girder with the flat jacks, the Teflon plates were inserted between the box-girder and the main support jacks.

In the initial stage of realignment, the unstiffened box-girder resisted the transverse bending generated by the increasing eccentricity in the support reactions. But afterwards both the outer flange and the central flange panel buckled upwards. This generated two low-friction inclined planes, which gave rise to uncontrolled rightward movement of the box-girder. Flange buckling further increased and both webs also buckled. Collapse of the unit was avoided because the end blocks of the auxiliary crossbeam had not been dismantled and this stopped the box-girder stroke.

Local buckling at supports can also be triggered by the vertical-adjustment devices. The screws at the support rollers are aimed at raising the form to the casting level and lowering the casting cell back onto the launch rollers after application of prestressing. When the screws are extracted excessively (e.g. to compensate for macroscopic level errors as in Fig. 18), local buckling of the screw can cause collapse of the gantry. Therefore, the allowable extension of the adjustment screws should always be stated in the operational manuals of the unit.

Conclusion

The paper illustrates the many potentially catastrophic design and operational failings detected by the author within numerous independent design check assignments of launching gantries and MSS. Recommendations and suggestions are also provided. The paper, however, deals only with the structural aspects of the design check of the launching units and disregards the mechanical aspects and the procedures and checks during operations of the units.

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