Deck Segmentation and Yard Organization for Launched Bridges

BY MARCO ROSIGNOLI

Incremental launching of prestressed concrete bridges is a competitive construction method for a wide range of spans and bridge dimensions. Because the method's competitiveness derives in part from repetitiveness of operations, the deck segmentation influences the final economic result.

Deck segmentation depends on the bridge length and on the time available for its construction. Clearly this is true when, as in most cases, the deck segments are match-cast against each other in-place. In case of segmental precasting, time is less of a constraint as the segment is a much faster assembly process.

Once the optimum average length of the segments is defined, this dimension should be adapted to the typical span so that segments correspond to the span or constitute a whole fraction of it. In bridges composed of a large number of short, equal spans, segments can be as long as the whole span to reduce the number of construction joints and to allow reuse of the same internal formwork. As the span increases, the segments become shorter than the typical span to limit the cost of the installation; in this case, the segments can be one-half or one-third of the span. In short bridges or in the case of external prestressing, for any given span length, it can be convenient to use shorter segments, building more segments on a continuous support and launching them as a whole.

When the number of segments composing the span is defined, the position of the construction joints should be verified from the structural point of view (in relation to the zero points of the bending moment diagram) and from the construction point of view, as the internal formwork is dismantled by extraction through the joint section. If the diaphragms are cast together with the rest of the section, the joint can be placed immediately before the diaphragm so that most of the formwork can be recovered without obstruction. If the segment is built in two casting phases (bottom slab and webs first and later the top slab), the recovery by extraction affects only the form table for the top slab and the joint can be placed anywhere, provided that the support diaphragms are tapered. As an alternative, diaphragms can be cast in a second stage, even after completion of launching, by means of casting pipes through the top slab.

Finally, if launch prestressing tendons are joined by couplers instead of by overlapping, the area of the couplers decreases the moment of inertia of the joint section, which then should be placed at the quarter span locations.

Yard organization

In most launched bridges, each

segment is match-cast in-place against the previous one, and the whole yard organization therefore hinges on the formwork. Whatever the subdivision in segments and casting phases may be, to build a segment in the shortest time it is necessary to organize production into parallel rather than serial processes.

If the number of segments is high and enough space is available, it is convenient to create a preassembly area for most of the loose material (bent bars, ducts, anchorages, inserts) to transfer them into the formwork as a whole.

Steel cage preassembly outside the formwork presents many advantages. Cage assembly is a slow and delicate operation due to the presence of ducts, anchorages, and minor forms. Preassembly permits extracting these activities from the critical path and confining them to a specific area and organization. By separating the casting yard and a preassembly area, it is possible to reach a better rotation of labor, especially during concrete curing stages. After segment extraction, the formwork can be cleaned, realigned, and prepared without constraints, and transfer of the cage does not compromise results. Usually, the preassembled cage includes the back-joint shutter, complicated by the presence of tendon anchorages, and after transfer of the cage and insertion of the internal form, the segment is ready for casting.

The preassembly template can be adjacent to the formwork or separated from it. The adjacent template does not require cage lifting and makes possible its advancing into the formwork during launching of the superstructure by means of rollers. A separated template requires the use of a specific transfer gantry crane, which can even be used as a roof and makes the two activities more independent.

Cage assembly can also occur by transferring preassembled webs and slab panels into the formwork. In this case (Fig. 1), the template is very simple and cage segments can be handled with a conventional tower crane.


Fig. 1: Preassembled cages of the webs (author).


Fig. 3: Rear end of the self-extracting internal form for the bridge of Fig. 4 (author).

Yard industrialization permits reduction in the duration of each activity compared with the conventional execution. Moreover, operations are simplified, the number of workers in the narrow formwork area is reduced to a minimum, their full personnel utilization is permitted by parallel activities performed during concrete curing, and formwork can be made cleaner and more durable.

Casting phases

The construction cycle of a segment is the sequence of operations between the launching of two subsequent segments. Its duration generally varies from seven to 10 calendar days, though it is generally convenient to reach this lower limit so that the concrete can cure during the weekend.

The sequence of operations depends on the casting procedure, on the eventual cage preassembly, and on the time required for concrete to reach the strength necessary to tension launch tendons and resist launch stresses. Natural hardening of a 35 MPa (5000 psi) concrete is rarely complete within a weekend duration, and appropriate devices should be used, such as precast anchor blocks (Fig. 2), local thermal cycles with electric wires embedded around tendon anchorages, or steam curing of the whole segment. Therefore, it is often convenient to directly increase the design strength of concrete. A higher specified value allows the necessary strength gain in the scheduled time and at the same time lightens the superstructure and reduces the influence of launching stresses, unexpected events, and time-dependent phenomena.


Fig. 2: Preassembled cage of a 24.0 m (80 ft.) segment with precast anchor blocks. On the right, the main formwork (author).

Whatever the chosen solution may be, deck subdivision into segments, subsegments, and casting phases always involves the presence of construction joints between the elements. If the adoption of vertical joints is unavoidable, horizontal joints occur frequently as well. Joints allow the restriction of the quantity of concrete processed daily, the carrying out of subsequent operations without excessive interference, the dismantling of the internal forms (webs and diaphragms) with a tower crane, and the easy removal of rubble. If the horizontal joints are at the top slab level, they also permit support of the form table for the top slab from the webs and help avoid the horizontal cracks that often affect monolithic casting due to the settlement of the fresh concrete in the webs.

Monolithic casting

The operations involved in monolithic casting of box girders

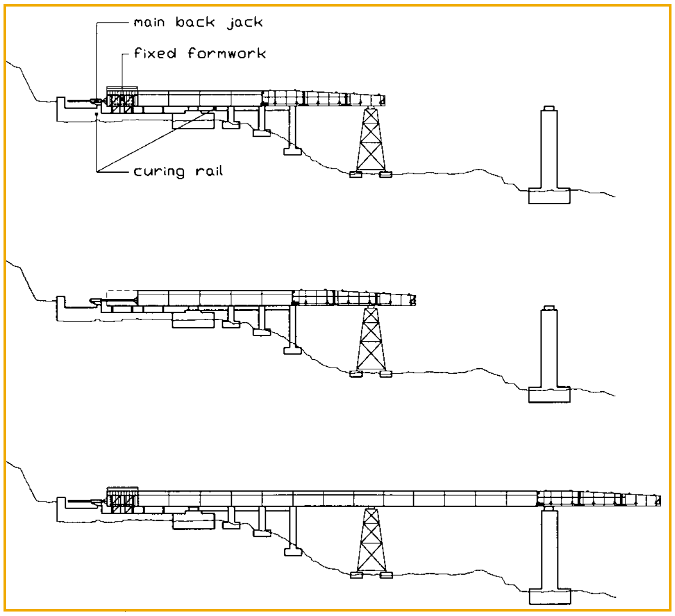

Fig. 4: Fixed casting cell and general launch by back thrust.

are rather complex, having to satisfy requirements of cage assembly, concrete placement, vibration, and internal form dismantling, activities that often conflict with each other. Therefore, for long segments this scheme is so rigid as to limit its adoption almost exclusively to long-span railway bridges (in Fig. 2, a half-span segment for the French TGV) because the depth of their cross section eases the access to the box cell.

Even the construction schedule is rather rigid because of the interference that occurs at the only working location and the dead times for concrete curing. Therefore, cage preassembly is often unavoidable, and this increases the length of the yard and requires expensive handling equipment (Fig. 2).

The use of internal left-in-place forms is economically acceptable only in short bridges. Therefore, the internal formwork is almost always self-extracting through the support diaphragm and adjustable by means of hydraulic pistons (Fig. 3). It advances with the superstructure during launching and is extracted backward to place it in the new casting position only after the preassembled cage of the next segment has been transferred into the formwork. To avoid geometry problems that might jeopardize the speed of the operation, the steel cage is assembled on an internal template that stiffens it during transfer (Fig. 2).

The need for large formworks and heavy handling equipment involves large investments. These can be amortized only in long bridges, and competitive alternatives can be found by subdividing the superstructure into shorter segments. Independent from the span, and sometimes even from the bridge length, a more marked deck segmentation than the conventional one (half of the typical span) can reduce the construction cost of the bridge.

Even with the same general principles, it is possible to single out three different construction schemes that adopt short monolithic segments: (1) the construction in a fixed casting cell with the general launch at the dismantling of each segment; (2) the construction in a mobile formwork with launch only after completion of a certain number of segments; and (3) the construction in a fixed formwork with segment extraction independent from the general launch of the superstructure.

In the first scheme, Fig. 4, the formwork is a casting cell similar to those usually adopted for segmental precasting. It is placed along the deck alignment at a certain distance from the abutment. The construction cycle provides for the addition of a new segment match-cast against the rear end of the superstructure (in perfect analogy with the case of longer segments) and a general launch.

At its extraction from the formwork, the segment, not prestressed, slides along a curing rail that receives progressively all the segments of a span or of a substantial part of it. The presence of the curing rail is indispensable, as without it the delay in clearing formwork produces such long dead times as to make a highly industrialized yard useless. When the planned number of segments is cast, launching prestressing is applied to the whole section of superstructure supported on the rail. To reduce the cost of tendon anchorages, this solution requires a long distance between the casting cell and the abutment. As an alternative, a temporary falsework supporting the superstructure in the bank span can be combined with a temporary pier to reduce the flexural stresses in the nonprestressed portion of the superstructure (Fig. 4).

Advantages reside in a small, automated formwork, repetitive operations, and a more efficient labor rotation. Inconveniences occur in the length of the curing rail, the need for precise regulations and controls (errors accumulate with the number of joints), the multiplication of launch operations that immobilize labor, and the delicate handling required for the back thrust of segments not completely cured and prestressed.

A second scheme avoids the frequency of launch operations over relatively short distances, which is the main inconvenience of the first scheme. In this scheme, represented in Fig. 5, the curing rail supports a deck section as long as the whole span, and a short formwork shifts along the rail to cast the subsequent segments. When the whole deck section is finished, prestressing is introduced in one operation just before launching. This allows a drastic reduction in the number of launch operations and permits movement of the superstructure without risks, as the whole deck is prestressed. Prestressing permits a reduction in bar splicing because reinforcement of the whole span can be assembled on the curing rails. The disadvantages are a more complex formwork than that of the previous scheme (it has to shift too) and the higher cost of foundations.

Deck segments can be cast in two phases (bottom slab and webs first, and top slab later). In long bridges, whose construction can be more industrialized, monolithic casting is often convenient. Where there are many diaphragms (external permanent prestressing or antagonist launch tendons), the construction joints between the segments can coincide with diaphragms. Diaphragms can be cast together with adjacent segments or together with the previously cast ones to assemble their steel cages more freely through the solutions of continuity in the webs. Even in this case, construction proceeds in an opposite sense than launching. As the last segment is subject to the local stresses of tendon anchorages, it is convenient to adopt precast anchor blocks or to anticipate its construction. On the contrary, by proceeding in the opposite direction (toward launch), one can rely on cured anchorages, and the last segment built is subject to homogeneous compressive stresses.

A dramatic savings of labor and equipment can result from a combination of short segment casting with mobile formwork, launching of long superstructure sections, and transverse shifting of the whole superstructure upon completion of its launch to clear the casting yard alignment for the construction of a second parallel superstructure. A 200 m (660 ft) bridge, composed of two parallel box girders joined at the top slab level and spanning four continuous 50 m (164 ft) bays, has been built with a 10 m (33 ft) mobile form, a 50 m (164 ft) curing rail, and a 22 ton launching nose. In spite of the refined structural system (internal launch tendons and totally external permanent prestressing), construction of this bridge has required an investment for specialized equipment less than $80,000 U.S. (Italian costs). After completion of the second branch of the superstructure (Fig. 6), the two box girders have been joined by a cast-in-place continuous curb. Finally, the four temporary piers, placed along the casting yard alignment to half the longitudinal launch span, have been demolished.

A third construction scheme combines the advantages of the two previous schemes and avoids their weak points (Fig. 7). The casting cell is fixed and placed at the rear end of the curing rail. All the segments composing the span are built by match casting and progressively launched along the rail by back thrust as in the first scheme. When the last segment of the span has reached the necessary strength, the whole span is launched by back thrust to the rear end of the superstructure, to which it is connected by a closure joint. After the introduction of launch prestressing, the whole superstructure can be launched convention-

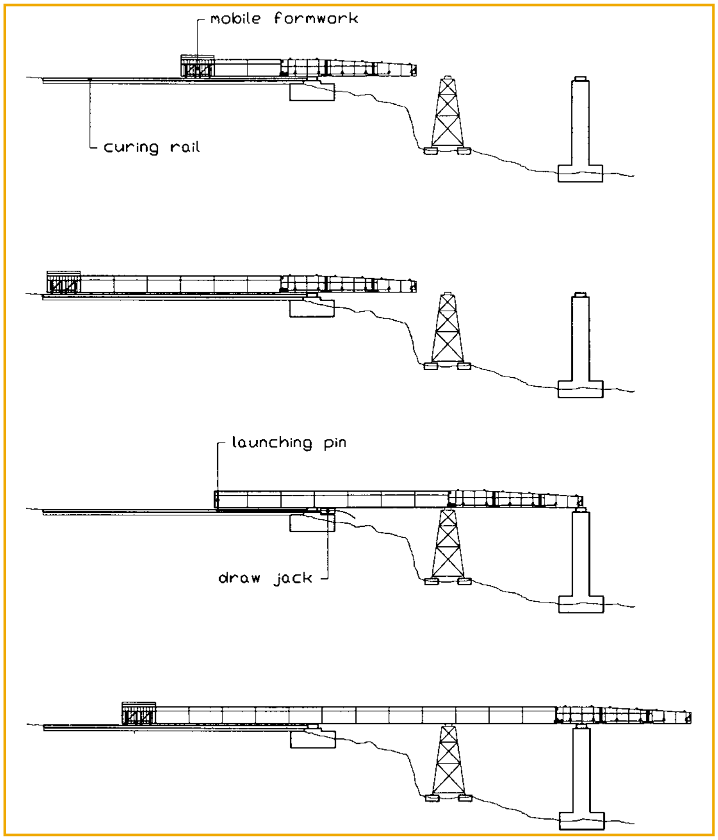

Fig. 5: Shifting formwork and conventional launch.

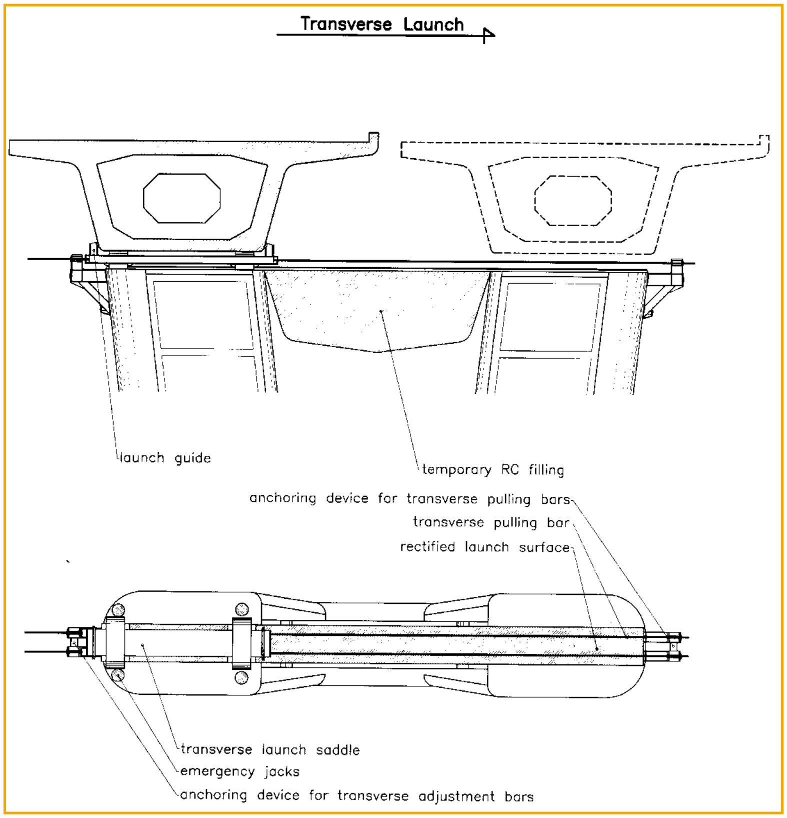

Fig. 6: Pier cap organization for transverse shifting of the first half of the superstructure.

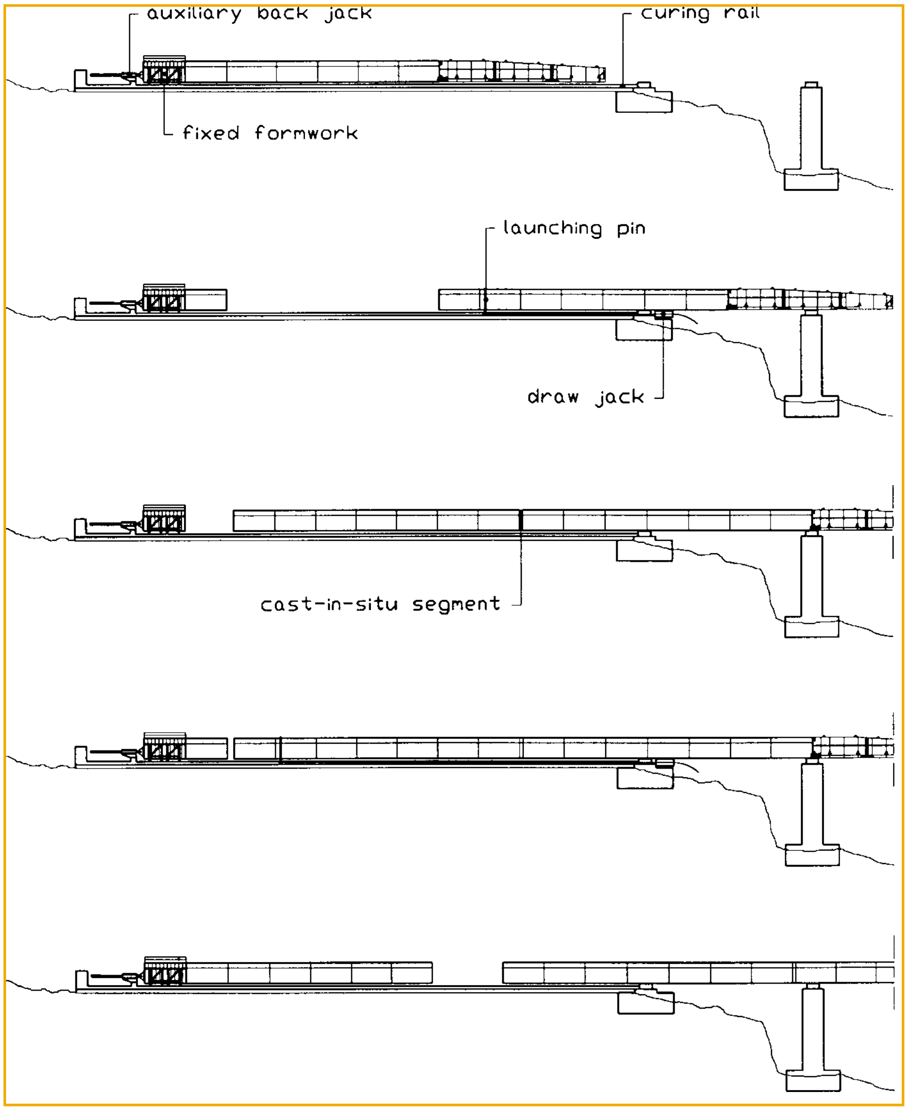

Fig. 7: Fixed casting cell, segment launch by back thrust, and conventional general launch.

ally. If the distance between the fixed casting cell and the rear end of the superstructure is longer than the span, during the operations of closure, prestressing, and main launch it is possible to proceed with the construction of additional segments. Therefore, these additional operations do not lengthen the construction schedule.

With this scheme, the casting cell is fixed and potentially automated, foundations for a mobile formwork are avoided, the general launch operations are still concentrated while the single extraction launches are simple and local, and the closure joint against the rear end of the superstructure avoids accumulation of geometric imperfections. The disadvantages include the long curing rail, the cost of the extraction devices, and the additional closure joint casting.

Compared with the use of longer segments, all these schemes introduce additional operations, and as the bridge length increases, this compromises the savings in equipment with higher labor costs. On the contrary, a common advantage is the possibility of introducing launch prestressing independent from the production of segments, and to reduce the cost of tendon anchorages as prestressing affects the whole span.

With internal prestressing, these schemes can be competitive in relatively short bridges in which the investment required by a 20 m (66 ft) to 30 m (100 ft) formwork cannot make incremental launching competitive compared with other construction methods. In the case of external prestressing, and particularly in the case of antagonist launch tendons, construction joints between segments can coincide with deviation diaphragms, and the use of short formworks can be convenient even in very long bridges. Finally, specific applications permit solving the case of settlement or no embankments (Fig. 8) because the cost of a small formwork supported on piles or temporary piers is still reasonable.

In spite of the lower costs and the higher simplicity, construction duration is substantially the same as for ordinary formworks. A half-span formwork (about 20 m [66 ft]) with a weekly cycle permits a daily progress of about 4 m (13 ft). A 4 m (13 ft) casting cell soon reaches a daily cycle (except for the more complex pier segments) and an 8 m (26 ft) form with two-day cycle and cage preassembly permits better control of unexpected events.

Two-phase casting in a single formwork

In incremental launching, the most popular casting method is the two-phase scheme inside the same formwork (Fig. 9), with a horizontal joint at the level of the top slab, or of the bottom slab, or at the midpoint of the webs.

The external formwork does not present particular problems: its design can aim at the operative simplicity by means of sophisticated devices or at the reuse of modular equipment that is easier to amortize. The most expensive type of external formwork consists of rigid steel frames hinged at the base (Fig. 10). Being designed for a specific cross section, it is rarely reusable and its adoption is justified only in long bridges that make the cost of its whole amortization lower than the labor cost that it avoids. Less-expensive formwork consists of fixed

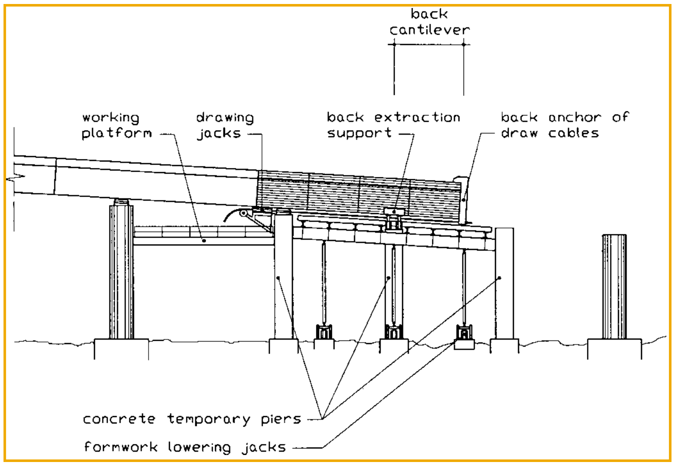

Fig. 8: Aerial casting cell placed on temporary piers.

Fig. 9: Two-phase casting in a single formwork (author).

modular towers that can be dismantled using their manual regulation screws (Fig. 9), or of towers supported on transverse rails and dismantled by side translation. The simplicity of these schemes and the easy amortization of the formwork are balanced by higher labor costs, which limit their use to short bridges. An intermediate type, less expensive and more adaptable than the first, involves the use of modular towers installed on a lowering platform supported by hydraulic jacks.

Unlike external formwork, the shape of the internal form depends on the position of the horizontal joints. In a case of joints placed at the upper nodes of the cross section, the web form is limited to side panels, or includes a bottom slab counter-form in the case of very sloped webs (left cell in Fig. 11). In short bridges, the top slab formwork is accomplished with left-in-place materials. In longer bridges, steel or plywood panels are used, supported on modular towers or on self-supporting steel frames sliding along extraction rails anchored to the webs. In a case of joints placed at the lower nodes of the cross section, internal form is similar to that of monolithic casting and is therefore rather expensive. In a case of intermediate joints, which are adopted quite rarely, both types of formwork can be used.

Compared with monolithic casting of the whole cross section, the scheduling of activities is generally less restrained, and by preassembling the steel cage it is not difficult to achieve an efficient construction schedule. Finally, two-phase casting in a single formwork is generally adopted when launching two parallel bridges at the same time, (Fig. 12) because this scheme produces an optimum rotation of labor even without steel cage preassembly.

Two-phase casting in a double formwork

Fig. 10: Monolithic steel frame formwork (author).

Progressive labor specialization has led to the subdivision of workers operating in the yard into two distinct gangs: the reinforcing bar workers, often working for a subcontractor, and the carpenters.

In the case of a single form, steel cage preassembly largely prevents the activity of one gang from interfering with or impeding the activity of the second one. But even so there is some interference: the adjustment and the completion of the steel cage after its transfer into the formwork, the duct connection, and so on. In the case of long segments, the activities of the two gangs can be staggered longitudinally (for instance, starting the concrete placement on one side while cage assembly is still going on at the opposite side of the segment), but this is generally a remedy for inadequate scheduling rather than an efficient organization. In a case involving short segments, these solutions generally lead to chaotic situations that are in conflict with the cadenced cycles that characterize incremental launching.

When the yard is long enough, it can be convenient to divide the production into two distinct formworks in which different elements of the segment are built in operation sequences staggered both in time and in space. The advantages of this solution are many. By operating in two distinct areas, steel cage assembly in one formwork does not jeopardize the activity of carpenters in the second formwork and does not require hoisting equipment. Also, the time available for each activity increases, the critical situations reduce, and the concrete surface finish improves as dismantling may be delayed. The only

Fig. 11: Construction joints at the top slab level ease dismantling of internal form and removal of rubble (author).

Fig. 12: Twin launching results in optimum labor rotation (author).

disadvantage is the higher cost of the formwork and of the eventual protective structures, whose length is double.

In the less-expensive configuration, with horizontal joints at the top slab level and forward shifting of the rear segment on fixed bearings, the yard is divided into the two zones of Fig. 13. A rear form, shorter than the completed segment, is aimed at casting the bottom slab and the webs. A front form is aimed at casting the top slab and the remaining short portion of the first-phase U-segment.

The U-segment is not match-cast against the front segment, as the presence of a solution of continuity and the adoption of a specific working cycle is necessary as follows: (1) during curing of the rear U-segment, internal web forms are dismantled and the rails for the form table of the top slab are fixed to the concrete webs; (2) when the necessary curing has been reached, the rear U-segment is hoisted from the fixed bottom formwork to insert launch pads (neoprene-Teflon plates) between the segment and the extraction bearings. As the rear U-segment is not yet joined to the front segment, raising does not cause stresses in the young concrete; (3) the rear U-segment is drawn forward by the general launching of the superstructure, sliding above the fixed extraction bearings; and (4) when extraction is completed, the U-segment is lowered onto the extraction rails of the front formwork. The form table for the top slab, which is still inside the previous segment, is drawn backward and placed above the U-segment, and the forms for the cantilevers and the short closure segment are set up. This organization scheme allows construction of a 20 to 30 m segment (66 to 100 ft) per week.

Segment extraction on fixed bearings has been gradually replaced by the use of continuous extraction rails, which, though more expensive, do not require hoisting of the rear segment nor the short closure segment nor additional labor for insertion of neo-flon plates during launch.

Assembly and launching of precast segments

The very first applications of incremental launching were for structures composed of precast segments arranged along temporary support rails and connected by closure joints.

Assembly and launching of precast segments presents many advantages. Construction of most of the superstructure is independent from pier construction, as precast segments can be stored elsewhere. The use of labor and casting equipment is optimized in a series of highly repetitive operations with the best quality control (especially if segments are cast in a precasting plant) and the best amortization of investments (precast segments for launched bridges are absolutely conventional both in dimensions and in handling). Assembly and launching of the superstructure are extremely fast operations that require few specialized equipment (support/launch rails, a launching nose, and a thrust device). Equipment is easily reusable and relatively inexpensive in terms both of initial investment and of assembly and dismantling costs.

Precast segments can be coupled directly by means of dry joints or epoxy, even though this solution presents two weak points. First, geometric imperfections of the superstructure depend on the number of joints, and long bridges can require stringent geometric tolerances during short-line match-casting of segments. This requirement is easily solved if the assembly yard behind the abutment can be as long as a span. In this case, precast segments can be arranged along the support/launch rails and glued to each other with conventional temporary clamping. Then, the long segment so obtained can be joined to the rear end of the launched superstructure with a cast-in-place short segment (as in Fig. 7) that avoids error accumulation. Second, the cost of longitudinal prestressing is generally higher than for cast-in-yard launched bridges because of the need for avoiding joint decompression both during launching and under infrequent service load conditions. Release and repositioning of a part of launch tendons upon completion of launching can reduce higher prestressing costs. This results in more efficient prestressing schemes, even if labor cost slightly increases due to these additional operations.

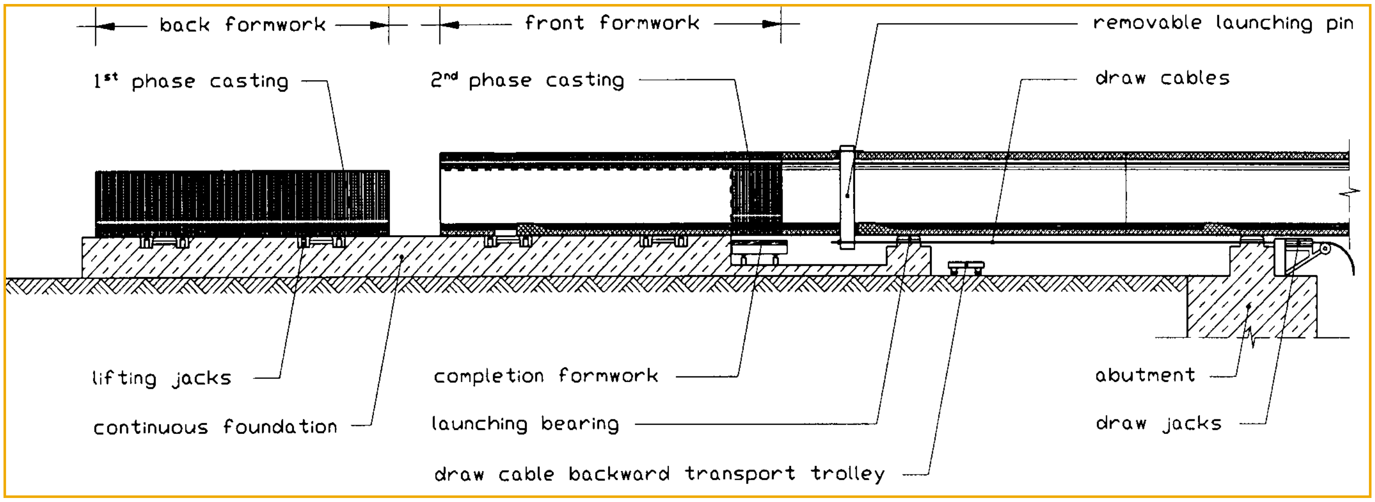

Fig. 13: Two-phase casting in double formwork with transfer of the rear segment on fixed bearings.

Fig. 14: Temporary balancing of launch stresses with cable-stays and counterweights (courtesy IIC).

As an alternative, segments can be precast with reinforcement emerging from the joint surfaces and arranged along the support/launch rails at a distance of 0.20 to 0.60 m (8 to 24 in.) to splice the reinforcement and to fill these solutions of continuity with no-shrink concrete.

In both cases, yard operations are limited to the arrangement of segments along the support/launch rails, joint sealing, and the introduction of prestressing in the new section of the superstructure. The construction speed can double compared with casting in-place, though with additional labor costs because of these additional activities.

So far, the incremental launching construction method has been mainly used for cast-in-place superstructures, as this permits combining the advantages of the industrialized and repetitive work processes with those deriving from a small number of construction joints (weak points of any structure) with continuous reinforcement. In addition, segment length and yard organization can be easily adapted to the specific requirements, thus enhancing the overall competitiveness of the construction method.

Launching of a precast segmental bridge can be a very competitive solution as well. Bridges whose length does not permit amortization of the investment and assembly and dismantling costs of a launching truss for segmental construction can be optimum targets, especially when it is necessary to allow unrestricted use of the areas below (rivers, highways, railways). As an example, several tens of modular highway overpasses might be built with a precasting plant and some sets of inexpensive modular specific equipment (support/launch rails, launching nose, and thrust device), with all the advantages of the box girder continuous beam structural solution. All the conventional launch techniques (incremental launching from one abutment toward the opposite one, monolithic launching from the opposite abutments with midspan closure, rotation about the piers adjacent to the obstacle to overpass, and midspan closure, launch followed by transverse shifting, etc.) might be used as well.

Obviously, a precasting plant can contemporaneously feed production lines with launching-truss assembly and production lines for launched superstructures, thus further improving amortization conditions and planning flexibility of the project.

Launching onto arches

Incremental launching of a continuous superstructure onto an arch represents a brilliant solution to the requirements of short construction duration, high structure quality, safety of workers, and cost savings.

Compared with conventional in-place construction of the superstructure with a movable shuttering system (MSS) assisted by a blondin (suspended cable with lifting devices), incremental launching of the superstructure results in an enormous deal of advantages. The standard equipment is simplest (a formwork, a launch device, and a launching nose) and inexpensive — it can be easily amortized in several projects and involves low assembly and dismantling costs. The formwork, batching plant, and steel cage assembly yard are adjacent and the stocking and handling of materials by means of a conventional tower crane are extremely simplified. The superstructure is built in a fixed, sheltered location, and each operation, from cage assembly to concrete casting or prestressing, is enormously simpler and safer than in an MSS and can be organized in parallel rather than in series, with important savings in labor costs. The formwork is rigidly supported on the ground and unaffected by deflections, settlements, vibrations, and dynamic response of the arch or of the MSS. As a consequence, a high level of quality is easily achievable in each construction stage.

From the structural point of view, a continuous box girder superstructure improves the system response to live loads and seismic demand by providing additional stiffness at the deck level. This makes the system behavior similar to that of a deck-stiffened arch bridge and reduces live load and seismic moments at the arch springings, thus permitting slenderness advantages. Construction by incremental launching permits increasing the spacing of spandrel columns and of the piers of the access bays up to 50 to 60 m (164 to 200 ft) without the restraints deriving from the rapidly increasing costs and deflections of an MSS as the span increases. This in turn permits optimizing the deck/arch interaction and eases the choice between a curved or polygonal design of the arch rib. Finally, the presence of axial launch prestressing in the completed superstructure helps to resist the flexural stresses resulting from the vertical displacements of the deck supports as the arch deflects.

The better construction conditions, the much smaller number of bearings, and the total absence of expansion joints (abutments apart) reduce maintenance costs. Finally, upon completion of the launch, the continuous superstructure supported on the arch and the access bays is usually very fine (Fig. 14).

Load asymmetry on the arch during construction may be avoided by launching two symmetrical superstructures at the same time from the opposite abutments toward midspan. The presence of symmetrical loads on only some of the spandrel columns causes bending stresses in the arch, and the cost of two casting yards rarely makes this scheme competitive. Therefore, launching on arches generally occurs from one abutment toward the other (like conventional construction with an MSS), and the arch must have enough flexural stiffness to resist the asymmetrical loads and the horizontal forces produced by launching.

To avoid overdesign of the arch ribs, launch forces and load asymmetry are reduced with temporary stays that also brace the tallest spandrel columns, sometimes integrated with counterweights (Fig. 14). Temporary staying does not affect the total construction cost much, as the same strand and anchorages used during cantilever construction of the arch are reused during launching of the superstructure.

As the launched superstructure spans both the arch and the access bays, its length can be significant. This usually suggests the adoption of a highly industrialized casting yard, whose organization is the same as that for conventional launching. Therefore, all the yard schemes already discussed (monolithic casting of long or short segments, two-phase casting in one or two adjacent forms, and segmental precasting) are perfectly usable.

Conclusions

Incremental bridge launching is a competitive construction method in a wide range of spans and bridge dimensions. Its competitiveness also derives from the repetitiveness of operations, which can be further enhanced by optimizing the deck segmentation according to the industrialization possibilities of the site.

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