ENCYCLOPEDIA OF LIFE SUPPORT SYSTEMS

In partnership with

United Nations
Educational, Scientific and
Cultural Organization

EOLSS

Encyclopedia
of Life Support
Systems

This copy is provided for non-commercial research and educational purposes. It shall not be reproduced, distributed or used for commercial purposes.

This material forms part of EOLSS Publications. It is provided to its author(s) with compliments of Eolss Publishers for internal non-commercial research and educational purposes including for instruction at the institution of the author(s) and sharing with colleagues. Other uses including reproduction/distribution/selling/licensing copies or posting to personal/institutional/ third party websites is prohibited.

In most cases authors are permitted to post their version of their contributions to EOLSS Publications (e.g., in Word/PDF formats) to their personal websites or institutional repositories. Authors requiring further information may contact (eolss@easynet.co.uk).

BRIDGE ERECTION MACHINES

Marco Rosignoli
HNTB Corporation, USA

Keywords: Beam launchers, self-launching gantries, telescopic gantries, pivoted gantries, overhead and underslung machines, movable scaffolding systems (MSS's), heavy lifters, lifting frames, form travelers, span carriers with underbridge, design loads, modeling, analysis, load testing, instability, robustness, progressive collapse.

Contents

Summary

Bridge industry is moving to mechanized construction because this saves labor, shortens project duration and improves quality. This trend is evident in many countries and affects most construction methods. Mechanized bridge construction is based on the use of special machines.

New-generation bridge erection machines are complex and delicate structures. They handle heavy loads on long spans under the same constraints that the obstruction to overpass exerts onto the final structure. Safety of operations and quality of the final product depend on complex interactions between human decisions, structural, mechanical and electro-hydraulic components of machines, and the bridge being erected.

In spite of their complexity, the bridge erection machines must be as light as possible. Weight governs the initial investment, the cost of shipping and site assembly, and the launch stresses. Weight limitation dictates the use of high-strength steel and designing for high stress levels in different load and support conditions, which makes these machines potentially prone to instability.

Bridge erection machines are assembled and dismantled many times, in different conditions and by different crews. They are modified and adapted to new work conditions. Structural nodes and field splices are subjected to hundreds of load reversals. The nature of loading is often highly dynamic and the machines may be exposed to impacts and strong wind.

Loads and support reactions are applied eccentrically, the support sections are often devoid of diaphragms, and most machines have flexible support systems. Indeed such design conditions are almost inconceivable in permanent structures subjected to such loads.

The level of sophistication of new-generation bridge erection machines requires adequate technical culture. Long subcontracting chains may lead to loss of communication, the problems not dealt with during planning and design must be solved on the site, the risks of wrong operations are not always evident in so complex machines, and human error is the prime cause of accidents.

Experimenting new solutions without the due preparation may lead to catastrophic results. Several bridge erection machines collapsed in the years, with fatalities and huge delays in the project schedule. A level of technical culture adequate to the complexity of mechanized bridge construction would save human lives and would facilitate the decision-making processes with more appropriate risk evaluations.

1. Introduction to Bridge Construction Methods

Every bridge construction method has its own advantages and weak points. In the absence of particular requirements that make one solution immediately preferable to the others, the evaluation of the possible alternatives is always a difficult task.

Comparisons based on the quantities of structural materials may mislead. The technological costs of processing of raw materials (labor, investments for special equipment, shipping and site assembly of equipment, energy) and the indirect costs related to project duration often govern in industrialized countries. Higher quantities of raw materials due to efficient and rapid construction processes rarely make a solution anti-economical.

Low technological costs are the reason for the success of the incremental launching method for PC bridges. Compared to the use of ground falsework, launching diminishes the cost of labor with similar investments. Compared to the use of an MSS, launching diminishes the investments with similar labor costs. In both cases launching diminishes the technological costs of construction and even if the launch stresses may increase the quantities of raw materials, the balance is positive and the solution is cost effective.

The construction method that comes closest to incremental launching is segmental precasting. The labor costs are similar but the investments are higher and the break-even point shifts to longer bridges. Spans of 30-50m are erected span-by-span with overhead or underslung launching gantries. Longer spans are erected as balanced cantilevers: self-launching gantries reach 100-120m spans and lifting frames cover longer spans and curved bridges.

Heavy self-launching gantries are used for macro-segmental construction of 90-120m spans. Span-by-span erection of macro-segments requires props from foundations. Balanced cantilever erection involves casting long deck segments under the bridge for strand jacking into position. Both solutions require high investments.

On shorter bridges, prefabrication is limited to the girders and the deck slab is cast in-place. Precast beams are often erected with ground cranes. Sensitive environments, inaccessible sites, tall piers, steep slopes and inhabited areas often require assembly with beam launchers, and the technological costs increase.

LRT and HSR bridges with 30-40m spans may be erected by full-span precasting. The investment is so high that the break-even point is reached with hundreds of spans. The precasting plant delivers 2-4 spans per day for fast-track construction of large-scale projects. Optimized material and labor costs add to the high quality of factory production. Road carriers and ground cranes may erect four single-track U-girders (two LRT spans) every night. Heavy carriers with underbridge and gantries fed by SPMT's are the alternatives for ground delivery of HSR spans. Precast spans longer than 100m have been erected with floating cranes.

Medium-span PC bridges may also be cast in-place. For bridges with more than two or three spans it is convenient to advance in line by reusing the same formwork several times, and the deck is built span-by-span. Casting occurs in either fixed or movable formwork. The choice of equipment is governed by economic reasons as the labor cost associated with a fixed falsework and the investment requested for an MSS are both considerable.

Starting from the forties, the original wooden falsework has been replaced with modular steel framing systems. In spite of the refined support structures, labor may exceed 50% of the construction cost of the span. Casting on falsework is a viable solution only with inexpensive labor and small bridges. Obstruction of the area under the bridge is another limitation.

An MSS comprises a casting cell assembled onto a self-launching frame. MSS's are used for span-by-span casting of long bridges with 30-70m spans. If the piers are not tall and the area under the bridge is accessible, 90-120m spans can be cast with 45-60m MSS's supported onto a temporary pier in every span. Repetitive operations diminish the cost of labor, the quantities of raw materials are unaffected, and quality is higher than that achievable with a falsework.

Bridges crossing inaccessible sites with tall piers and spans up to 300m are cast in-place as balanced cantilevers. When the bridge is short or the spans exceed 100-120m the deck supports the form travelers. Overhead travelers are preferred in PC bridges while underslung machines are used in cable-stayed bridges and cable-supported arches. With long bridges and 90-120m spans, two longer casting cells may be suspended from a self-launching girder that also balances the cantilevers during construction.

2. Main Features of Bridge Erection Machines

The industry of bridge erection machines is a highly specialized niche. Every machine is initially conceived for a scope, every manufacturer has its own technological habits, and every contractor has preferences and reuse expectations. The country of fabrication also influences several aspects of design. Nevertheless, the conceptual schemes are not many.

Most beam launchers comprise two triangular trusses made of long welded modules. The diagonals may be bolted to the chords for easier shipping although site assembly is more expensive. Pins or longitudinal bolts are used for the field splices in the chords. New-generation single-girder machines allow robotized welding and have less support saddles and smaller winch-trolleys. 50m spans are rarely exceeded in precast beam bridges.

A launching gantry for span-by-span erection of precast segmental bridges also operates on 30-50m spans but the payload is much higher as the gantry supports the entire span during assembly. The payload of an MSS for in-place span-by-span casting is even higher as it also includes the casting cell, although the nature of loading is less dynamic.

Versatile twin-girder overhead machines comprise two trusses that suspend deck segments or the casting cell and carry runways for winch-trolleys or portal cranes. The field splices are designed for fast assembly and the modular nature of design permits alternative assembly configurations. These machines are easily reusable; however, their weight, labor demand and complexity of operations may suggest the use of more specialized machines on long bridges.

Lighter and more automated single-girder overhead machines are built around a central 3D truss or two braced I-girders. A light front extension controls overturning and a rear C-frame rolls along the completed bridge during launching. Single-girder overhead machines are compact and stable and require ground cranes only for site assembly. Telescopic configurations with a rear main girder and a front underbridge are also available for bridges with tight plan curves.

Underslung machines comprise two 3D trusses or pairs of braced I-girders supported onto pier brackets. Props from foundations may be used to increase the load capacity when the piers are short. A rear C-frame rolling over the completed bridge may be used to shorten the girders. Underslung machines offer a lower level of automation than the single-girder overhead machines and are affected by ground constraints and clearance requirements.

Span-by-span macro-segmental construction requires heavy twin-truss overhead gantries with a rear pendular leg that takes support onto the deck prior to segment lifting. Transverse joints at the span quarters and a longitudinal joint at bridge centerline divide 80-100m continuous spans into four segments. The segments are cast under the gantry with casting cells that roll along the completed bridge and are rotated and fed with the prefabricated cage at the abutment.

Overhead gantries for balanced cantilever erection of precast segments reach 100-120m spans. Compared to span-by-span erection, the payload is lower as no entire span is suspended from the gantry. The negative moment from the long front cantilever and the launch stresses on so long spans govern design. Varying-depth trusses are structurally more efficient while constant-depth trusses are easier to reuse on different span lengths. Stay cables are rarely used in new-generation machines.

Overhead MSS's for balanced cantilever bridges operate in a similar way. Two long casting cells suspended from a self-launching girder shift symmetrically from the pier toward midspan to cast the two cantilevers. After midspan closure and launching to the next pier, the casting cells are set close to each other to cast the new double pier-head segment. These machines can be easily modified for strand-jacking of macro-segments cast on the ground.

The bridge itself can support lifting frames for balanced cantilever erection of precast segments or form travelers for in-place casting. These light machines are used in short or curved bridges, PC spans up to 300m, and cable-stayed bridges. Lifting frames and form travelers permit erection of several hammers at once and different erection sequences than from abutment to abutment, but they require more prestressing and increase the demand for labor and ground cranes.

Carriers with underbridge and heavy gantries fed by SPMT's are used to erect precast spans. Spans are rarely longer than 40m in LRT and HSR bridges and 50m in highway bridges due to the prohibitive load on the carriers and the bridge. Longer spans have been handled with floating cranes when the bridge length permitted amortization of such investments.

3. Beam Launchers

The most common method for erecting precast beams is with ground cranes. Cranes usually give the simplest and most rapid erection procedures with the minimum of investment, and the deck may be built in several places at once. Good access is necessary along the entire length of the bridge to position the cranes and deliver the girders. Tall piers or steep slopes make erection expensive or prevent it at all.

The use of a beam launcher solves any difficulty. A beam launcher is a light self-launching machine comprising two triangular trusses. The truss length is about 2.3 times the typical span but this is rarely a problem as the gantry operates above the deck (Figure 1). Beam launchers easily cope with variations in span length and deck geometry, plan curvatures and ground constraints. Crossbeams support the gantry and allow shifting to erect the edge girders and to traverse the gantry for launching along curves.

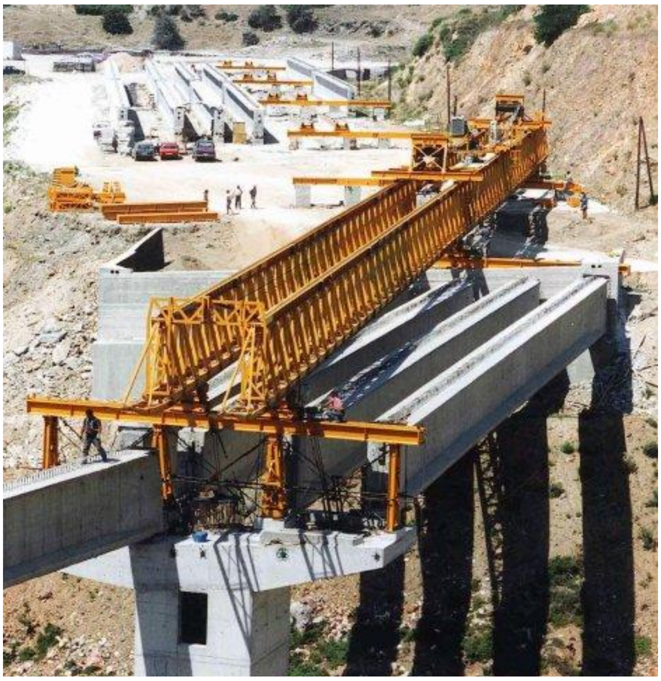

Figure 1: 102m, 90ton launcher for 45m, 120ton beams (Comtec)

Two winch-trolleys span between the top chords of the trusses and lodge two winches each. The main winch suspends the beam and a translation winch acting on a capstan moves the trolley along the gantry. A third trolley carries an electric generator that feeds gantry operations. When the beams are delivered at the abutment, the winches may be replaced with less expensive long-stroke cylinders.

A beam launcher operates in one of two ways depending on how the beams are delivered. If the beams are delivered on the ground, the launcher lifts them up to the deck level and places them onto the bearings. If the beams are delivered at the abutment, the launcher is moved back to the abutment and the winch-trolleys are moved to the rear end of the gantry. The front trolley picks up the front end of the beam and moves it forward with the rear end suspended from a straddle carrier. When the rear end of the beam reaches the rear winch-trolley, the trolley picks it up to release the carrier.

The longitudinal movement of the gantry is a two-step process. Automatic clamps block the trusses to the crossbeams and the winch-trolleys move the beam one span ahead; then the winch-trolleys are anchored to the crossbeams, the blocks are released and the translation winches push the trusses to the next span. Redundancy of anchorages is necessary in both phases for safe launching along inclined planes. The sequence can be repeated many times so when the beams are delivered at the abutment, the gantry can place them several spans ahead. When the bridge is long, moving the gantry over many spans slows the erection down and may be faster to cast the deck slab as soon as the beams are placed and to deliver the next beams along the completed bridge.

Truss deflections at landing at the piers are recovered with alignment wedges. The alignment force is small but the support saddles must be anchored to avoid displacements or overturning. Realignment may also be achieved with long-stroke cylinders that rotate arms pinned to the tip of the truss. Similar devices are also applied to the rear end of the gantry to release the support reaction when launching forward and to recover the deflection when launching backward.

Figure 2: 74m, 98ton single-girder shifter for 28m, 60ton beams (Deal)

New-generation single-girder launchers are based on two braced I-girders. The main girder is less expensive than two triangular trusses due to robotized welding, the winch-trolleys are smaller, the number of support saddles halves, and the crossbeams are shorter. Lightened launching noses may be attained with laser-cut windows in the webs to avoid hand welding. A C-frame supports the rear end of the gantry and allows the beams to pass through when delivered along the completed bridge. The C-frame is not necessary when the beams are delivered on the ground as the launcher lifts and shifts them into position within the same span (Figure 2).

Crossbeams anchored to the pier caps carry rails for lateral shifting of the gantry. The crossbeams have lateral overhangs for placement of the edge girders and to traverse the gantry for launching along curves. Adjustable support legs located so as not to interfere with the precast beams are used to set the crossbeams horizontal. Some launchers have light service cranes at the ends of the trusses to reposition the crossbeams without any need for ground cranes.

The support saddles comprise bottom rollers that shift laterally along the crossbeam and top rollers that support the truss. Equalizer beams allow the top rollers to cope with the flexural rotations in the truss and the gradient of the launch plane. A vertical pivot connects the two roll assemblies to allow rotations in the horizontal plane. Lateral shifting along the crossbeams is achieved with capstans or light long-stroke cylinders.

Automatic clamps block the trusses to the crossbeams during winch-trolley operations. Launching occurs along inclined planes and breaking of any component of the tow system would leave the gantry unrestrained on low-friction supports. Redundancy of tow systems involves oversizing and slow operations.

4. Self-Launching Gantries for Span-By-Span Precast Segmental Erection

Span-by-span erection of precast segmental bridges is used for spans shorter than 50m in highway bridges and 30-45m in dual-track LRT bridges with box- or U-section. Single-track LRT spans with U-section are typically precast full-length for ground delivery and erection with two ground cranes because of the faster erection rate.

All the segments for a span are placed onto or suspended from the gantry before gluing so that no additional deflections can occur. After application of prestress, lowering the gantry releases the span onto the bearings in one operation. The spans of continuous bridges are released onto jacks and connected with concrete stitches to the pier-head segments. The solutions of continuity are locked with concrete shims and partial tensioning of a few permanent tendons before casting the closures. The prestressing tendons are tensioned from a front stressing platform. A typical 40m simply-supported span with epoxy joints is erected in 2 or 3 days. Erection rates of up to a span a day are achievable with an underslung gantry and dry joints.

Overhead and underslung gantries are used to support a complete span of segments. A twin-girder overhead gantry comprises two triangular trusses or braced I-girders supported onto crossbeams (Figure 3). Trusses are lighter while I-girders are more stable and solid and allow robotized welding. Connections designed to develop member strength exploit the modular nature of design with the possibility of alternative assembly configurations. Field splices of new-generation machines are designed for fast site assembly.

Figure 3: 98m, 405ton overhead gantry with 45ton portal crane
for 45m, 500ton dual-track U-girder LRT spans (NRS)

A winch-trolley or a portal crane spanning between the girders lifts and moves the segments into position. Auxiliary support legs at the ends of the gantry are used to erect the pier-head segments of continuous spans and to reposition the support crossbeams without ground cranes.

The overhead gantries are not much affected by ground constraints, straddle bents, C-piers and variations in span length and deck geometry; however, they are more complex to design, assemble and operate than the underslung machines, and they are also more expensive and slower in erecting the segments with spreader beams.

The overhead gantries operate in one of two ways depending on how the segments are delivered. If the segments are delivered along the completed bridge, the winch-trolley picks them up at the rear end of the gantry, moves them forward to the assembly location, and lowers them down to the deck level. If the segments are delivered on the ground, the winch-trolley lifts them up to the deck level. Hangers and spreader beams hold the segments into position during assembly. After reaching the assembly location, the segments are hung to the gantry and the winch-trolley is released for a new cycle. To avoid interference with the hangers, the segments are moved out with the long side in the longitudinal plane (Figure 4) and are rotated before suspension with a hydraulic hook.

Figure 4: Longitudinal movement of the segment (HNTB)

Heavier overhead gantries are used for span-by-span macro-segmental erection of 80-100m spans. The span comprises four segments. A longitudinal joint at bridge centerline divides the box girder into two halves, and transverse joints at the span quarters divide each half into a pier-head segment and a midspan segment. A temporary pier supports the front end of the midspan segments in every span, while the rear end is suspended from the front cantilever of the completed bridge. The temporary pier also balances the pier-head segments (Figure 5). The construction joints have through reinforcement and are closed with in-place stitches and integrative prestressing.

The macro-segments are cast beneath the gantry, on the completed deck. The gantry cannot rotate so long and heavy segments so the two casting cells (Figure 6) roll along the completed bridge back to the abutment, where they are rotated by 180° and fed with the prefabricated cage for the conjugated segment. After reaching the gantry, vertical cylinders lift the casting cells from the rails to apply the casting load over the webs of the box girder.

Figure 5: 46m, 640ton pier-head macro-segment
placed with a 162m, 1280ton overhead gantry

Figure 6: 46m casting cells for midspan (left)
and pier-head (right) macro-segments

The length of the gantry is about 1.8 times the typical span. A pendular W-frame at the rear end of the gantry takes support onto the deck prior to lifting the segment. A front pendular leg (Figure 5) is used during launching to reposition the front crossbeam. The two trusses are connected at both ends and cannot be launched individually. The pier-head segments are inserted under the front crossbeam and temporarily supported onto the pier cap; the front winch-trolley picks them up again in a more advanced location for final placement.

Crossbeams support the gantry at the piers with articulated saddles that allow longitudinal and lateral movements and rotations about the transverse and vertical axes. The support saddles comprise transverse rollers that shift along the crossbeams and longitudinal rollers that support the

Figure 7: 32-roll saddle for 635ton service load

Figure 8: Launch cylinders

truss. Assemblies of equalizer beams follow the flexural rotations in the trusses, allow launching onto grades, and equalize the load in the rolls (Figure 7). Rectangular rails welded to crossbeams and trusses facilitate load dispersal into the webs, transfer lateral forces, and keep the rollers aligned with the webs.

Some support saddles lodge longitudinal lock systems for the truss and all crossbeams are equipped with transverse lock systems. The support legs of the crossbeams include adjustment cylinders with safety nut to set the frame horizontal. The crossbeams are anchored to the piers with tensioned bars that resist uplift forces. The crossbeams have long lateral overhangs and significant uplift forces may arise in the anchor systems.

The lightest twin-girder overhead gantries may be launched with winches and capstans. Hydraulic cylinders lodged within the support saddles and taking contrast into racks anchored to the trusses provide higher thrust forces and safer operations. Paired cylinders are often used (Figure 8) so that one cylinder locks the truss while the adjacent cylinder is repositioned.

A single-girder overhead gantry takes support onto the front pier of the span to erect and the front pier-head segment of the completed bridge. The girder is rigidly framed to the front support legs, a light front extension controls overturning, and a rear C-frame rolls along the completed bridge during launching. No rear nose is necessary so these gantries are shorter and lighter than the twin-girder overhead machines and better suitable for curved bridges.

Lateral bracing connects two I-girders or trusses. Bracing includes X-frames, connections designed to minimize displacement-induced fatigue, field splices designed for fast assembly, and sufficient flexural stiffness to resist vibration stresses. Cross diaphragms connected at the same locations of lateral bracing or crossbeams framed into webs and flanges by vertical stiffeners distribute torsion and provide transverse rigidity. Bracing and field splices are designed so as to allow a winch-trolley suspended from the bottom flanges/chords to run through.

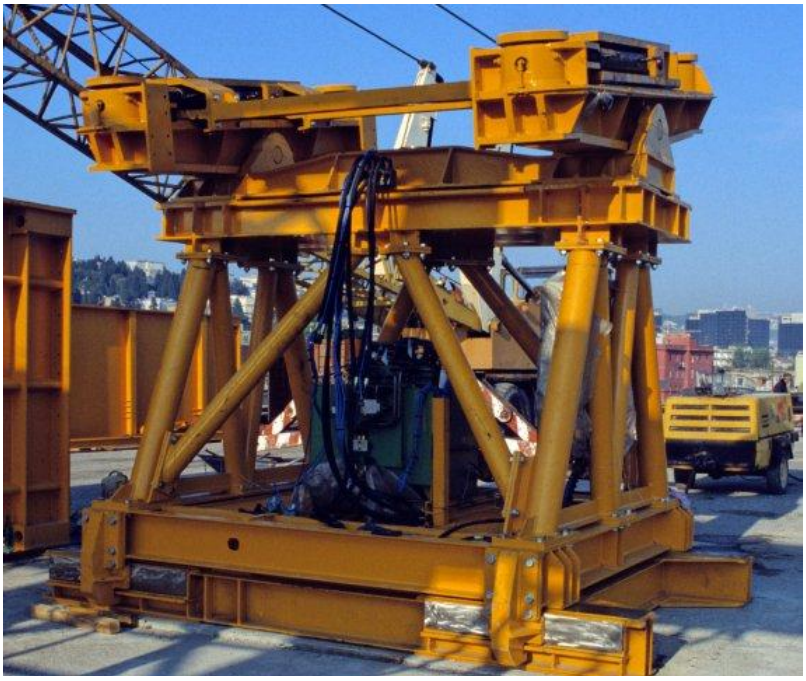

Figure 9: Friction launcher on adjustable support block

Some first-generation overhead machines were equipped with stay cables, a deviation tower applied to the support legs at the rear pier, and a long rear balancing truss with counterweights at the end. Cable-stayed gantries have been abandoned with time in spite of their structural efficiency as the cables complicate and slow down the operations and increase labor demand. Varying-depth trusses are also rarely used in span-by-span erection as they are hardly reusable on different span lengths.

Special launch devices are necessary when the support legs are integral with the main girder. Launching is achieved by friction, taking advantage of the vertical load that the girder applies to the launcher (Figure 9).

Support boxes are located under the bottom flanges of the girder. Longitudinal launch cylinders move the boxes along the low-friction surfaces of two pivoted arms and vertical jacks at the ends of the arms lift and lower the main girder. The working cycle is as follows. (1) The jacks lower the girder onto the support boxes. (2) The launch cylinders push the boxes forward and the thrust force is transferred to the girder by friction. (3) When the boxes reach the front end of the arms, the jacks lift the girder and the launch cylinders pull the support boxes back to the initial position to start this cycle again.

A vertical pivot between friction launcher and support block allows rotations when launching along curves. Low-friction surfaces between support block and base frame allow lateral shifting. The geometry control systems are equipped with sliding clamps so that the entire assembly can be hung to the launching nose during span assembly (Figure 10). The sliding clamps also prevent uplift during launching as the base frame is anchored to the deck with tensioned bars.

The rear support of the gantry is a C-frame that rolls along the completed bridge during launching. Transverse cylinders shift the frame laterally when launching along curves. Longitudinal cylinders rotate the frame about the vertical axis to the local radius of plan curvature. Vertical cylinders at the base of the frame adjust geometry to deck superelevation and control the support reaction that the C-frame applies to the deck during launching. The top crossbeam of the C-frame is inserted into a rectangular slot with low-friction surfaces in the main girder for direct transfer of the support reaction.

Figure 10: Friction launchers suspended from the main girder

After application of prestress, the rear launcher is moved over the front pier-head segment. The span is released onto the bearings by retracting the main cylinders of the front legs and the rear C-frame, and the launcher thus lands onto the deck. After anchoring the launcher to the deck, full retraction of the front cylinders leaves the gantry supported onto the launcher and the rear C-frame, and launching begins.

When the tip of the launching nose reaches the new pier, the winch-trolley places the new pier-head segment, and the front launcher is then moved onto the latter for launch completion. An auxiliary front support leg controls overturning during these operations. At the end of launching the gantry is lifted for span erection, which also disengages the launchers. Finally, both launchers are parked along the launching nose to clear the segment assembly area; these movements are driven by light hydraulic motors.

Friction launchers offer high intrinsic safety as the worst consequence of hydraulic faults is launch stoppage. Equipment can be designed for the launch loads and overloaded without excessive concerns in case of need. PLC’s permit synchronization of the two launchers and setting limit pressures to avoid overloading. Launch-cycle automation with displacement sensors simplifies operations and increases the launch speed.

Telescopic single-girder overhead gantries have been designed for erecting dual-track LRT bridges with tight plan curvature (Figure 11). The winch-trolley is suspended from the main girder and the segments are delivered on the ground or along the completed bridge through the rear C-frame. In order to cope with tight plan curvatures, the gantry comprises a main girder and a front self-launching underbridge. A turntable with hydraulic controls for translation and vertical and horizontal rotations connects the main girder to the underbridge. During launching the turntable pulls the main girder along the underbridge. When the front support legs reach the new pier and the rear C-frame reaches the front end of the completed bridge, the underbridge is launched forward to clear the area under the main girder for erection of the new span.

Figure 11: 41m, 96ton underbridge and 47m, 132ton main girder for 37m, 340ton dual-track LRT spans (Deal)

Many precast segmental bridges have been erected with underslung gantries. These machines are positioned beneath the deck with the main girders on either side of the pier. The gantry supports the box girder segments under the wings with adjustable sliding saddles for control of cambers; underslung gantries are rarely used with U-sections. The gantry takes support onto pier brackets, W-frames on through girders, or crossbeams hung to the pier cap. When the piers are short and slender, the pier brackets may be supported onto props from foundations to avoid sockets in the pier (Figure 12). This solution is frequently used in LRT bridges.

The segments are placed onto the gantry with a ground crane or a lifting frame. When the segments are delivered along the completed bridge, the lifter is placed at the rear end of the gantry. When the

Figure 12: 76m, 325ton underslung gantry with 40ton crane for 35m, 490ton dual-track LRT spans (NRS)

Figure 13: 91m, 333ton pivoted underslung gantry with 40ton crane for 36.7m, 392ton dual-track LRT spans (NRS)

segments are delivered on the ground, the crane is placed at the front end of the gantry. The segments are placed onto the gantry close to the lifter and rolled into position. A portal crane may also be used to lift the segments and move them into position. Upon application of prestress, the span is released onto the bearings by lowering the gantry.

Overturning is controlled with front and rear launching noses and the length of the gantry is more than twice the typical span length. This makes the standard underslung machines hardly compatible with curved bridges as the girders conflict with the piers and the completed bridge. The front ends of the main girders may be connected with a crossbeam that slides along a central self-launching underbridge. A rear C-frame rolling along the completed bridge during launching further shortens the rigid portion of the machine. These telescopic gantries cope with tight plan radii but require a particular V-design of the pier caps to create the launch clearance for the front underbridge.

Pivoted girders with hydraulic hinges have also been used: the machine of Figure 13 may erect 40m dual-track LRT spans with 75m radius. Pivoted girders have also been used in overhead machines: the gantry of Figure 3 may erect 30m dual-track LRT spans with 60m radius. If one considers the constraints of precast segmental erection in congested urban areas, it is not surprising that so many innovative bridge erection machines have been designed for LRT systems.

The underslung gantries are simple to design, assemble and operate. Segment erection is fast and props from foundations can be used to increase the load capacity when working low on the ground. However, these machines project beneath the deck, which may cause interference with straddle bents and C-piers, clearance problems when passing over roads or railroads, and difficulties in the end spans as the abutment walls are wider than the piers. This problem is solved by applying the rear noses after launching the gantry to the second span over props from foundations. The front noses are also dismantled before launching the gantry to the last span. The abutment walls must be tall not to prevent operations in the first and last span.

5. Movable Scaffolding Systems (MSS's) for Span-By-Span Casting

A PC bridge can be cast span-by-span proceeding from an abutment toward the opposite one. When the piers are short and the area under the bridge is accessible, the formwork can be supported onto a ground falsework. In bridges of length sufficient to amortize the investment, the use of an MSS allows transferring the casting cell to the new span in a few hours instead of weeks. The savings of labor are substantial, the area under the bridge is unaffected, and quality of construction is better than that achievable on a falsework.

An MSS is typically designed to cast an entire span. Solid or voided slabs with stiffening haunches at the piers are used for 30-40m highway spans, ribbed slabs with double-T section are used up to 50m spans, and box girders reach 50-70m spans. Box girders for railway bridges rarely exceed 50m spans. Simply-supported spans are cast full length. For continuous decks, the abutment span is cast with a short front cantilever and the subsequent spans extend out over the piers for 20-25% of the typical span length.

The rear end of the MSS takes support onto the front cantilever of the completed bridge to minimize the distance between the supports of the MSS and to diminish the time-dependent stress redistribution of staged construction within the continuous deck. The casting cycle is one or two weeks per span.

If the piers are not tall and the area under the bridge is accessible, 90-120m continuous spans may be divided into two segments with joints at the span quarters. The front end of the midspan segment and the MSS are supported onto a temporary pier, and the rear end of the MSS is suspended from a C-frame that rolls along the completed bridge. In-line casting of 90-120m varying-depth spans is much faster than balanced cantilever construction, with casting cycles of two to four weeks for the entire span.

Solid, voided and ribbed slabs are cast in one phase while box girders are cast in one or two phases. The inner tunnel form for one-phase casting remains within the completed span and is extracted and reopened within the reinforcement cage of the new span. Two-phase casting involves casting bottom slab, webs and support diaphragms in a first time and the top slab after two or three days. A form table supported onto the first-phase concrete is extracted from the previous span to cast the deck slab.

Two-phase casting restricts the quantity of concrete processed daily and facilitates handling of inner forms. Joints at the top slab level also avoid the horizontal cracks that sometimes affect one-phase casting due to settlement of fresh concrete in the webs. The main concerns with two-phase casting are related to the deflections of the MSS. The weight of the top slab deflects the casting cell, which may cause cracking in the non-prestressed first-phase U-section.

Concrete is poured with conveyor belts or pumps. In the simply supported spans, concrete should be poured starting at the center of the span and progressing symmetrically toward the ends to minimize the deflections of the casting cell in the final phases of filling. This sequence is labor intensive and the use of retarding admixtures is often preferred to keep the concrete fluid for the entire duration of filling. This allows casting the span directionally from bulkhead to bulkhead but the shutters must be designed for full hydrostatic loads. In the continuous spans, the casting cell is filled with one of two alternative sequences. In a first procedure, concrete is poured starting at the front pier and proceeding symmetrically until the front cantilever is filled; then the remaining section is filled backward toward the construction joint. This sequence diminishes the flexural rotations in the main girders at the front pier and is preferred when the MSS is supported onto two lines of saddles (W-frames on through girders or two crossbeams on wide towers).

Figure 14: 97m, 690ton underslung MSS for 44m,
1190ton dual-track HSR spans (ThyssenKrupp)

In a second procedure, concrete is poured starting at the front bulkhead and proceeding backward. This sequence requires less labor and facilitates finishing, and larger flexural rotations are not a major issue when the MSS is supported onto one line of saddles (pier brackets). In both cases the construction joint is cast at the end of pouring to avoid settlement. Forms are stripped prior to tensioning of tendons to minimize prestress losses in the forms, and the MSS is then lowered in one operation to transfer the span weight to the bearings.

The self-launching frame of an underslung MSS (Figure 14) supports the bottom crossbeams of the casting cell with adjustable saddles for setting of camber and superelevation. An underslung gantry supports the precast segments under the wings while an MSS supports the bottom crossbeams, and the machine therefore projects deeply under the bridge.

The reinforcement cage for the entire span may be prefabricated behind the abutment and delivered along the completed bridge. This shortens the casting cycle to one week with one shift per day and improves risk mitigation with parallel tasks. Cage insertion is simple because access to the casting cell is free from obstructions in an underslung MSS. The cage carrier moves forward on stiffened strips of the outer form and lowers cage and front bulkhead into the casting cell in one operation. The carrier may be equipped with concrete distribution arms and a covering to protect the casting cell during concrete pouring.

The underslung MSS’s take support onto pier brackets or W-frames on through girders (Figure 38). The support saddles lodge friction launchers or launch cylinders acting into racks. The pier brackets include jacks with safety nut or screw jacks that lift the MSS to the span casting elevation and lower it back onto the launch rollers after application of prestress. Some MSS’s suspend the pier brackets from the main girders after dismantling and hydraulic motors move the brackets to the new pier for crane-less application.

W-frames on through girders are always assembled with ground cranes. Cylinders with safety nut supported onto the through girders lift the W-frame to the span casting elevation and lower it back after application of prestress to release the span. Support saddles designed for the total load (weight and payload) are often based on PTFE skids. At the current state of practice, rollers and PTFE sliders are complementary. Sliders are used for slow launching of high loads and rollers are used for medium loads and fast launching.

Overturning is controlled with launching noses and the length of these machines is more than twice the typical span. The standard underslung MSS’s are not suitable for bridges with tight plan radii; pivoted girders with hydraulic hinges have been used in curved bridges in spite of their cost and complexity and the load eccentricity of the offset casting cell. Underslung MSS’s also project beneath the deck, which may cause interference with straddle bents and C-piers, clearance problems when passing over roads or railroads, and difficulties in the first and last span.

In a twin-girder overhead MSS (Figure 15), hangers suspend the outer form from two trusses or box girders. Assemblies of crossbeams and modular towers support the main girders at the piers. The towers are anchored with tensioned bars that resist uplift forces. The crossbeams have long lateral overhangs and significant uplift forces may arise in the anchor systems.

Figure 15: 110m, 1490ton overhead MSS with 60ton crane for 57.4m, 1380ton single-track HSR spans

An auxiliary tower is placed onto the cantilever of the completed bridge to minimize the distance between the supports of the MSS, to avoid form settlements at the joint, and to control the stress redistribution of staged construction within the deck. Cylinders with safety nut lift the crossbeams to the span casting elevation and lower them back after application of prestress to release the span.
The length of the MSS is more than twice the span length. This is rarely a problem with overhead machines as the girders do not interfere with the deck and the piers. A portal crane with L-frame and pendular leg assists the operations of the casting cell. After releasing the span, the hanger bars are decoupled and the modules of outer form are lowered to the ground and transported under the next span to be lifted after launching. The inner forms remain in the completed spans and are repositioned after cage assembly.

Twin-girder overhead MSS’s cope with different span lengths and straddle bents and C-piers. Being above the deck, they are less affected by ground constraints. However, they are more complex to design, assemble and operate than the underslung MSS’s, and much slower during launching as the outer form is lowered to the ground. Cage prefabrication requires several portal cranes for cage insertion into the casting cell and is rarely used with these machines.

In a single-girder overhead MSS for 40-50m highway spans, the outer form is suspended from a central girder that takes support at the front pier of the span to cast and onto the front cantilever of the completed bridge. These machines are custom-designed for long parallel bridges that allow amortizing of the investment: they are lighter and shorter than the twin-girder overhead MSS’s, able to reposition the support systems, and simpler to assemble and operate. They allow faster launching and form setting with substantial savings in labor costs, operations are more automated, and the casting cell can be covered and equipped with concrete distribution arms.

The main girder comprises two braced trusses or I-girders. Lateral bracing includes X- or K-frames, connections designed for fast site assembly and to minimize displacement-induced fatigue, and sufficient flexural stiffness to resist vibration stresses. Cross diaphragms or crossbeams framed to webs and flanges by vertical stiffeners provide transverse rigidity and distribute torsion. Bracing, crossbeams and stiffeners are designed to allow unrestricted operations of winch-trolleys suspended from the bottom flanges (Figure 16).

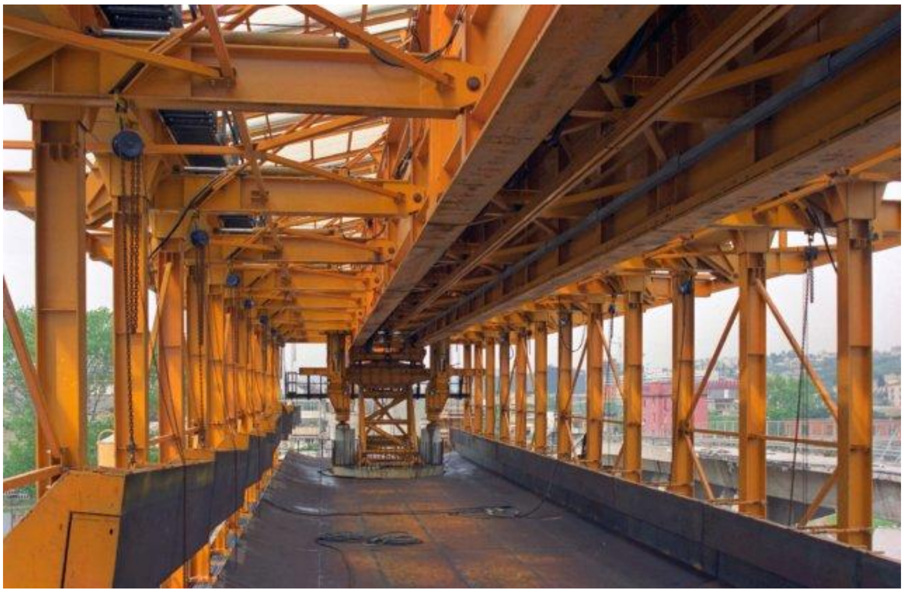

Figure 16: 110m, 890ton single-girder overhead MSS for 47.5m, 860ton spans

Brackets overhanging from the main girder suspend form hangers with telescopic connections for setting of camber. Pinned splices at bridge centerline divide the bottom crossbeams of the outer form into two halves. Hydraulic extractors assist pin removal after release of the span. Long-stroke hydraulic cylinders at the base of the form hangers rotate the two halves of the outer form to vertical to avoid interference with the pier during launching (Figure 17). The single-girder overhead MSS's are launched with the outer form suspended from the main girder and the casting cell is reclosed with an inverse sequence of operations after launching.

Lateral bracing and edge girders connect the form suspension brackets to enhance the lateral stability of the MSS. The form hangers are connected by vertical bracing to enhance torsional stability during span casting. Form hangers and bottom crossbeams may be designed for the full load of the casting cell or may be integrated with hanger bars crossing the casting cell. The outer form is less expensive but many holes have to be sealed in every span and inserting and removing the hanger bars further increases the labor cost.

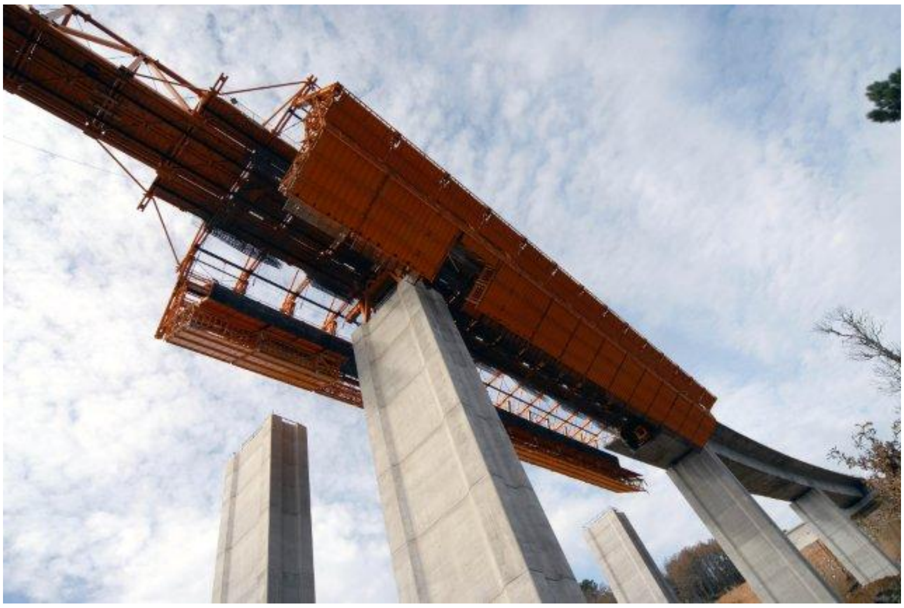

Figure 17: Opened outer form during launching
(AP Bridge Construction Systems)

The front support of the MSS comprises a box leg on either side of the main girder and an upper box diaphragm that creates a C-frame. Every leg includes a base cylinder with safety nut and a telescopic assembly for extraction of the bottom portion of the leg from the deck. The telescopic assembly is locked by a through pin during span casting. A hydraulic extractor assists pin removal after lowering the MSS onto the friction launcher, and long-stroke auxiliary cylinders lift the bottom portion of the leg prior to launching (Figure 18). The leg is protected from fresh concrete with left-in-place plastic pipes or steel forms fixed to the leg.

The rear support of the MSS is an adjustable C-frame designed to allow cage insertion and to cope with deck curvature and superelevation. Hydraulic cylinders with safety nut lower the MSS in one operation after application of prestress. The force applied to the deck during launching is controlled hydraulically.

Launching is achieved with two electronically synchronized friction launchers as in a single-girder overhead gantry for precast segmental erection. The rear launcher moves the MSS in the first phases of launching and the front launcher is placed onto the front pier when the launching nose reaches it.

Figure 18: Front support leg

A front auxiliary leg supports the cantilever during placement of the front launcher onto the pier. Plan geometry is adjusted at the rear launcher and the rear C-frame in curved bridges.

In so refined MSS's the reinforcement cage is always prefabricated behind the abutment for the entire span to shorten the casting cycle to one week or less with one shift of carpenters and ironworkers per day. Parallel tasks also improve risk mitigation. The cage includes front bulkhead, anchorages, ducts, spacers and all embedded items. Strand is typically inserted into the ducts during span curing. The cage carrier (Figure 19) comprises modules hinged to each other and running on the same rails as the rear C-frame of the MSS; the front module is motorized. The cage is tied to a full-length lifting frame to accelerate insertion into the casting cell and avoid distortion.

The MSS has a rear cantilever where the winch-trolleys are parked at cage arrival (Figure 20). The hydraulic legs of the lifting frame are extracted to lift the cage from the bottom platform of the carrier. The front winch-trolley picks up the front module of the lifting frame and moves out along the MSS; this pulls the lifting frame forward along the carrier. The second winch-trolley picks up the second module of the frame, and so on until complete cage suspension.

The lifting frame is moved forward and lowered into the casting cell, the hydraulic legs are retracted to release the cage, and the frame is extracted from the cage and moved back onto the carrier with an inverse sequence of operations. The bottom platform of the carrier is used as rebar jig during cage prefabrication.

Figure 19: Cage carrier for 47.5m spans

Figure 20: Parking area for winch-trolleys

In machines with a lower level of automation, the web cage is assembled over the new span during curing and is suspended from the MSS during launching. Monorail winches assist cage assembly and lowering into the casting cell after launching. New-generation single-girder overhead MSS's are targeting 90m spans in tangent highway bridges and 70m spans in HSR bridges. Constant-depth trusses are generated with stacked assemblies of modular panels and arched overhead trusses further increase the stiffness of the casting cell (Figure 21). The modular nature of assembly facilitates adaptation to shorter spans, although a higher level of automation is often preferred for span-by-span casting of 40-50m spans.

Launching on long spans requires light machines. The MSS of Figure 21 has 1.79 payload/weight ratio. Trusses and space frames are used for form hangers and bottom frame, and hanger bars cross the casting cell to further lighten the outer form. As a drawback of the high structural efficiency, the large number of field splices increases cost and duration of site assembly and complicates inspections.

Figure 21: 140m, 780ton overhead MSS for 70m, 1400ton spans (BERD)

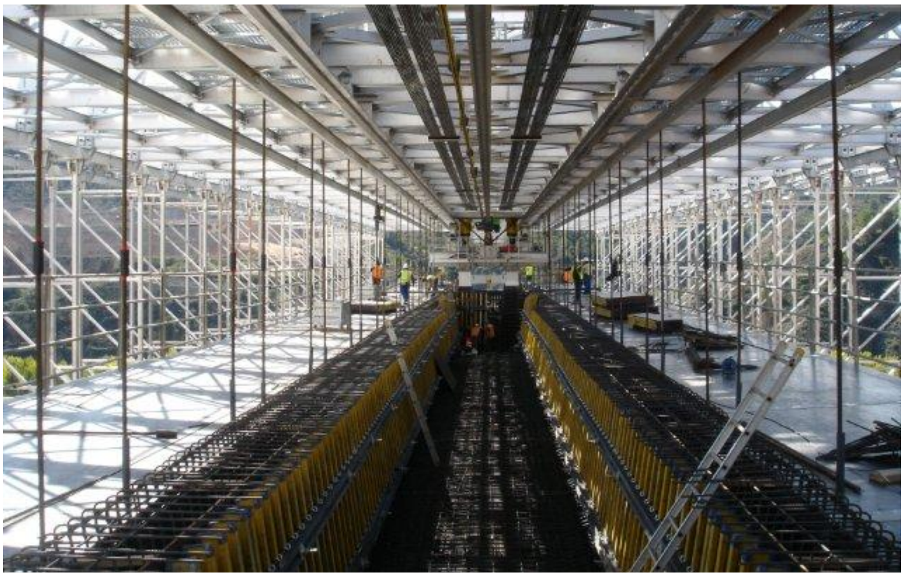

Figure 22: Sensor-controlled 7.0MN prestressing for two-phase casting (BERD)

One-phase casting of 90m box girders would involve handling 700-900m^3 of concrete in a few hours. Two-phase casting reduces the demand on batching plant and concrete delivery lines along the completed bridge but requires control of deflections of the casting cell in so flexible MSS's.

Sensor-controlled tendons (Figure 22) may be automatically tensioned during filling of the casting cell and released during application of prestress. The automation and control systems include sensors, electric boards, PLC, hydraulic groups, prestressing jacks with motorized safety nut, and control and communication systems. The prestressing system response is damped to avoid tendon vibrations.

Prestressing increases cost and complexity of the MSS and the axial load makes the truss more prone to out-of-plane buckling. Combining sophisticated automation and control systems with the skill and attention of workers in constructions involves additional challenges. On the other hand, span-by-span casting of 70-90m spans with weekly casting cycle is much faster than balanced cantilever construction, design of reinforcement and prestressing is more efficient, and the operators of bridge erection machines must be accurately trained anyway.

6. Self-Launching Machines for Balanced Cantilever Construction

Balanced cantilever construction is suited to precast segmental and cast-in-place bridges. Precast segmental construction requires powerful erection machines but allows industrialized casting and faster erection and is therefore addressed to bridges with a great number of spans. Segment assembly with ground cranes or lifting frames permits free erection sequences while the use of a self-launching gantry requires that the deck be erected from one abutment toward the opposite one; however, directional erection permits delivering the segments along the completed bridge.

The deck of in-place bridges is cast in short segments with pairs of form travelers. Time-schedule dictates the number of form travelers to be used simultaneously. When the cantilevers from the two piers face each other at midspan, the closure segment is cast and bottom slab tendons are installed to make the deck continuous. The travelers are then lowered to the ground and repositioned onto a new pier-head segment.

Balanced cantilever bridges have box girder section. Ribbed slabs have been built in the past and are still used in the cable-stayed bridges as torsion and most of the negative moment are resisted by two planes of cables. Box girders may have constant or varying depth. Constant-depth decks are simpler to cast but competitive in a narrow span range (50-70m) while varying-depth decks are used on spans ranging from 70m to 250-300m. Depth variation adapts the flexural capacity to demand but the pier-head segments soon become too tall and heavy for ground transportation and lifting, and spans longer than 120-130m are generally cast in-place.

The construction method dictates the length of the pier-head segments. In a cast-in-place bridge the pier-head segment must accommodate a pair of form travelers in the initial stages of cantilever construction and lengths of 8-10m are frequent. Props from foundations or pier brackets support the casting cell. Geometry is complex, the working space is limited and the segment is typically divided into numerous casting phases. Reinforcement and prestressing are also complex and construction durations of 2 to 4 months for a pier-head segment are not infrequent.

In a precast segmental bridge the pier-head segment should have the same weight as the other segments not to require special lifting devices. The segment contains a thick support diaphragm and the bottom slab is also thick to resist the negative bending from the cantilevers, so the segment is very short. This facilitates placement as the gantry must also take support at the pier during handling of the pier-head segment.

The most common erection methods for precast segments are with ground cranes, lifting frames or gantries at the deck level. Ground cranes require good access to the deck along the entire length of the bridge. Cranes usually give the simplest and most rapid erection procedures with minimum investment. Cranes are readily available in many countries and multiple cantilevers can be erected at once. The main constraints on crane erection are access and tall piers, as balanced cantilever bridges are often selected in response to inaccessible terrains.

Deck-supported lifting frames are used on tall piers, long or curved spans, spans of different length, and spans over water where special lifters can handle heavier segments and barge delivery minimizes geometry and weight constraints. Lifting frames are also the standard solution for erection of cable-stayed bridges when time or site constraints discourage from in-place casting.

Fixed frames anchored to the tip of the cantilever can lift only from the ground and have limited segment handling capability. Derricks have a rotating arm that can lift segments from behind or laterally; they have a large maneuvering area but apply significant loads to the deck and are used

Figure 23: Lifting of 90ton pier-head segment (Comtec)

Figure 24: 30m, 90ton lifting frame for 64ton segments (Deal)

only in cable-stayed bridges. A mobile lifting frame comprises a motorized base frame and a cantilever nose that supports a lifting trolley. Light segments are lifted with winches and heavier segments with strand jacks. A lifting frame is much lighter than a wheeled crane as it is devoid of counterweights. This simplifies placing the machine onto the pier-head segment at the beginning of erection and diminishes deck prestressing but requires anchoring the machine to the deck before lifting of every segment. The pier-head segment is lifted or cast in-place to establish a platform on which one or two lifting frames are secured. An auxiliary frame may be used to lift the pier-head segment with the winch-trolley of the lifting frame (Figure 23).

Straddle carriers with cantilever noses on both sides of the machine move from one side of the pier to the other to lift the segments in turn. Straddle carriers with winch-trolleys and spreader beams wider than the top slab can pick up the segment at the base of the pier and move it out beneath the cantilever (Figure 24). Other types of motorized frames move the segment over the deck and rotate and lower it into position. Most lifting frames also suspend a stressing platform beyond the segment for fabrication and tensioning of the top slab tendons In spite of the single-operation-machine nature and the disruption when moving to the next pier, the lifting frames can solve erection conditions incompatible with ground cranes and gantries. The erection cycle is typically one segment per day.

Launching gantries achieve faster erection rates and minimize ground disruption when the segments are delivered along the completed bridge. Gantries are suited to building over water or other such obstructions; however, they erect the deck from abutment to abutment and are delayed if problems occur at any pier or span. One or two winch-trolleys lift and transport the segments into position. If the segments are delivered along the completed bridge, the winch-trolley picks them up at the rear end of the gantry. If the segments are delivered on the ground, the winch-trolley raises them up to the deck level.

Figure 25: 160m, 320ton gantry for 102m spans and 105ton segments (VSL)

The earliest single-truss overhead gantries were slightly longer than the span to erect. The length of the truss was sufficient to span between the front cantilever of the completed bridge and the next pier during launching, and minimizing the distance between the supports resulted in lighter gantries. Some of these machines were equipped with a deviation tower and symmetrical stay cables that relieved the negative bending in the truss. The use of stay cables complicates the operations and increases labor demand but may be a brilliant solution when few long spans have to be erected (Figure 25) and the remainder of the bridge can be erected without activating the stay-cables or minimizing their adjustment. These light machines are easier to ship and erect than the standard twin-girder overhead gantries.

A single plane of stay cables is generally preferred and a fan layout simplifies pull adjustment from a stressing platform at the top of the tower. A few cables may also be anchored to the bottom chords to provide torsional restraint to the truss. Single-truss gantries are preferred for better control of out-of-plane buckling and simpler structural nodes at the anchor points of the cables. The winch-trolleys run along the bottom chords and the field splices in the truss have longitudinal bolts above the top flange and below the bottom flange to permit the wheels to pass through.

Figure 26: 108m, 278ton gantry for 45m spans and 60ton segments (VSL)

Figure 27: Placement of the first 182ton down-station segment with a 198m, 876ton gantry for 101m spans (HNTB)

Short gantries overload the front cantilever of the completed bridge. Placing the pier-head segments is also more complex. The length of new-generation machines is more than twice the span length (Figure 26). These machines take support at the piers during span erection and the higher cost of a longer gantry is balanced by less reinforcement and prestressing in the entire bridge. Placement of pier-head segments and launching are also simplified, and labor demand is lower.

The typical launch sequence for a new-generation gantry for long balanced cantilever spans is as follows. (1) The cantilevers are erected with the gantry anchored to crossbeams sitting onto the pier-head segments of the completed bridge and the new pier. (2) After midspan closure and tensioning of continuity tendons, the front pendular leg takes support onto the front cantilever and the winch-trolley moves the front crossbeam forward to the 3rd or 4th segment. (3) The front leg is released and the gantry is launched until the rear end reaches the rear crossbeam. (4) The rear auxiliary leg takes support onto the deck and the winch-trolley moves the rear crossbeam to midspan. (5) The rear leg is released and the gantry is launched until the front leg takes support onto the new pier. (6) The gantry places the pier-head segment and the first down-station segment (Figure 27). (7) The winch-trolley moves the front crossbeam onto the new pier-head segment and the rear crossbeam onto the pier-head segment of the completed bridge. (8) The front leg is released and the gantry is launched forward and anchored to the crossbeams in the erection configuration for the new span. No ground cranes are necessary for launching.

When the length of the bridge is insufficient to amortize the investments of segmental precasting, the balanced cantilever bridges are cast in-place. In-place casting is also the standard solution for curved spans and spans longer than 120m.

Figure 28: Overhead form traveler

When form travelers support the casting cells, the segments are 3-5m long for reasons of weight and load unbalance. 5-6m segments are possible although form flexibility may cause cracking and geometry defects and the form travelers are more expensive. The standard convertible traveler is designed for 5m segments up to 500ton heavy, casting cell included.

A typical overhead form traveler consists of a casting cell suspended from a number of trusses equal to the number of webs in the box girder. The trusses of the oldest travelers were heavy and long to enhance the action of rear counterweights. In the new-generation machines the counterweights have been replaced with adjustable tie-downs rolling within launch rails and the trusses are lighter and shorter. Trusses, front and rear crossbeams and bracing systems are modular assemblies of pinned members for fast assembly. The steel frame of an overhead traveler may weigh between 25ton and 95ton (Figure 28).

The casting cell is suspended with hangers and adjustable to varying deck geometry (segment length, box height, thickness of webs and bottom slab) and road alignment (curvature and superelevation). Working platforms are incorporated around the traveler and a stressing platform is suspended beyond the bulkhead for fabrication and tensioning of tendons. The inner form is stripped from the previous segment and pulled forward within the cage of the new segment by rolling along suspended rails.

When the pier-head segment is 7-10m long, two form travelers can be assembled at the same time. It typically takes 2 weeks to assemble a traveler and another 2 weeks to assemble the casting cell. Casting the initial segment takes another 2 to 3 weeks. The segments are typically cast on a 5-day cycle after the learning curve has passed.

The segments are cast in one phase proceeding from the front bulkhead backwards to minimize settlement at the construction joint. The inner shutter is equipped with windows for concrete vibration. Concrete with early high strength is used to shorten the casting cycle.

In the overhead travelers the trusses are supported onto the front deck segment and anchored to the second segment with tie-downs that prevent overturning (Figure 29). Vertical cylinders at the front support lift the traveler from the launch rails for casting. After tensioning the top slab tendons, the outer form is stripped and the traveler is lowered onto the launch rails. Adjustable tie-downs roll along the rails to prevent overturning during launching.

Launching is a two-step process: first the rails are pushed forward and anchored to the new segment, and then the traveler is lowered onto the rails and pulled forward. Rails and traveler are launched with the same set of hydraulic cylinders. Launch cylinders are repositioned alternately during launching to avoid uncontrolled movements of the traveler.

Figure 29: Anchoring and launch devices

In the underslung form travelers for PC box girders, a C-frame supported onto the webs of the front segment suspends a longitudinal 3D truss on either side of the deck, beneath the box wings. In the cable-stayed bridges the C-frame is replaced with hydraulic hangers rolling along the edge girders to avoid interference with the cables (Figure 30). Counter-rollers at the rear end of the trusses take contrast against the deck soffit to prevent overturning.

The forms are stripped by releasing the vertical cylinders of C-frames and hangers. Launch cylinders push the launch rails over the new segment and then pull C-frames and hangers along the rails. Launching an underslung traveler is more complex but the reinforcement cage for the segment can be prefabricated as the casting cell is free from obstructions.

Figure 30: 24m, 202ton underslung traveler
for 9x24m, 320ton deck segments (VSL)

Figure 31: 18.7m, 122ton underslung traveler
for 7.9m, 267ton arch segments (NRS)

The underslung form travelers for cable-stayed bridges are heavy due to the wide deck and the long segments based on cable spacing. Deflections are controlled with stiff longitudinal trusses and transverse 3D trusses or space frames that support the bottom form table of the casting cell and control torsion in the main trusses. Auxiliary stay cables may be anchored to the pylons to control the deflections of the longest segments.

Underslung travelers with full-width C-frame are also used for in-place casting of cable-supported arches (Figure 31). The C-frame is anchored to the arch during operations of the casting cell due to the slope of the arch segments. Strand brakes are incorporated into the launch rails for additional safety from uncontrolled movements. The segment is cast in one phase by filling the casting cell upward. The top shutter is closed with the progress of filling to facilitate inspection and concrete vibration. The support cables of the arch are installed after launching the casting cell to the next segment to avoid interference.

As an alternative to the use of form travelers cantilevering from the deck, a balanced cantilever bridge can be cast with a single- or twin-girder overhead MSS (Figure 32) supported at the pier and onto the front cantilever of the completed bridge. Two long casting cells suspended from one or two girders shift symmetrically from the pier-head segment to midspan to cast the cantilevers. After achieving midspan continuity, the girders are launched to the next span and the casting cells are moved to the next pier and set close to each other to cast the new pier-head segment.

Figure 32: 158m, 1600ton MSS for balanced cantilever casting of 120m spans with 11.3m, 680ton two-phase segments (ThyssenKrupp)

The use of a suspension-girder MSS is suitable for spans up to 100-120m and tangent or slightly curved bridges of adequate length. The length of the main girders is about 1.3 times the maximum span. Despite its cost, an MSS for balanced cantilever construction offers many advantages. The machine provides easy access for workers and materials from the completed bridge. If the deck is supported onto bearings, the MSS stabilizes the cantilevers and avoids temporary lock systems at the piers. Deck balancing is also useful when the deck is continuous with tall piers. Less prestressing is necessary along the entire bridge as no form travelers are suspended from the cantilevers.

Casting cells suspended from many points are so stiff that the segments can be 10-12m long and wider than 20m. Transferring the casting cells to the next pier is much simpler (no dismantling and reassembly work is necessary), no special casting cell is necessary for the pier-head segments, the use of ground cranes is minimized, construction is faster, and labor savings may be substantial. The end deck segments at the abutments are also cast with the MSS. The main limitation is the need for casting the deck from one abutment toward the other.

Figure 33: Strand-jacking of 8.0m, 650ton segment (ThyssenKrupp)

The MSS's for balanced cantilever casting can be easily adapted to macro-segmental erection. The casting cells are replaced with lifting platforms for strand-jacking. Long deck segments are cast under the bridge and lifted into position (Figure 33). The pier-head segments are cast in-place with short casting cells suspended from the machine. Wet joints with through reinforcement avoid the geometry requirements of short-line match-casting and allow bridge design for partial prestressing. The segments are hung to the main girders during casting of 1.0-1.5m stitches and application of top-slab prestressing.

7. Carriers and Gantries for Full-Span Precasting

Many LRT and HSR bridges have been built with precast spans. Full-span precasting allows rapid construction and high quality from repetitive casting processes in factory conditions.

Box girders are used for HSR and highway bridges and U-girders are used for HSR and LRT bridges. The spans may be longer than 100m when floating cranes are used for placement. Ground transportation is rarely used for spans longer than 40m for HSR and LRT bridges and 50m for highway bridges. The investment needed to set up large precasting facilities and to provide heavy span transportation and placement machines limits the cost-effectiveness of full-span precasting to long bridges with many equal spans, small radii of plan curvature and low gradient. These conditions are met more easily in HSR bridges.

Figure 34: 58m, 321ton carrier for placement
of 31.5m, 740ton single-track HSR spans

The spans are placed onto bearings or seismic isolators to simplify the erection process. Simply-supported spans also diminish the thermal stresses in the continuous welded rails of HSR bridges. The spans can be connected with in-place stitches to form a continuous structure, although in-place stitches do not offer the same high levels of quality as the rest of the bridge.

The precasting plant is located near the bridge. The reinforcement cages are prefabricated and different combinations of pre- and post-tensioning are possible. The spans are removed from the casting cells with heavy portal cranes or wheeled carriers and stored on temporary foundations for completion of prestressing, application of bearings and finishing. The precasting plant delivers two to four spans every day in relation to the erection rate of the delivery and assembly lines.
For HSR viaducts over land, the spans are transported along the completed bridge with wheeled carriers. A span carrier (Figure 34) comprises two wheeled trolleys connected by a box girder supporting two winch-trolleys. Movement and steering are governed by hydraulic motors powered by diesel engines.

Picking up the span from the casting cell involves a complex sequence of operations. The carrier is moved alongside the span, the trolleys are rotated by 90° by pivoting about hydraulic props, and the carrier is moved transversely over the span. After applying the spreader beams and lifting the span, the carrier is moved back to the transportation route and realigned with an inverse sequence of operations. The same operations are repeated to place the span onto the supports of the storage area and to pick it up for final delivery.

After reaching the abutment, automatic drive systems controlled by ultrasound sensors govern the movement of the carrier over the webs of the box girders or within the U-section. The automatic-drive speed of the machine of Figure 34 is 3.0 km/h at full load and 6.0 km/h unloaded. The carrier spreads the load onto two spans and the axle load is equalized hydraulically or electronically to compensate for span deflections.

At the front end of the completed bridge, the front trolley of the span carrier reaches the rear end of the underbridge (Figure 35). A self-propelled support saddle rolling along the underbridge is inserted beneath the front trolley. Hydraulic cylinders lift the rear end of the underbridge until the

Figure 35: Carrier moving forward along a 78m, 218ton underbridge

Figure 36: 75m, 520ton gantry with 38m, 80ton underbridge for placement of 33m, 900ton dual-track HSR spans (Beijing Wowjoint Machinery)

wheels of the carrier are released. The motors of front saddle and rear trolley are synchronized to move the carrier along the underbridge. After reaching the span lowering location, the rollers of the underbridge are released and the motor of the support saddle is inverted to launch the underbridge to the next span until the lowering area under the span is cleared. The counter-plates of bearings are installed during pier construction. Three plates are set at the design elevation and the fourth plate is set 4-5mm below. The span is lowered onto electronic load cells placed onto the counter-plates. After adjusting the support reactions to the design tolerance with stainless-steel shims at the fourth plate, the load cells are removed and the span is lowered onto the bearings. Finally, the underbridge is moved backward to release the front trolley onto the new span. Transverse wheel spacing required for operations of the underbridge allows the presence of other machines on the bridge during span delivery for earlier start of finishing work.

Heavy gantries with underbridge are also used for placement of HSR spans in combination with SPMT's that deliver the spans along the completed bridge (Figure 36). The front winch-trolley of the gantry picks up the front end of the span and moves it forward while the rear end slides along a support girder on the SPMT. Then the second winch-trolley picks up the rear end of the span to release the transporter.

Launching the gantry to the next span takes a couple of hours and two or three spans can be erected every day when crossover embankments exist along the bridge and the casting yard is designed for such productions. Compared with the use of span carriers with underbridge, gantries require heavy lifters in the casting yard to handle the spans and to place them onto the transporters. The SPMT's apply higher loads to the bridge and delay the finishing work, which can start only upon completion of span delivery.

The single-track U-girders for LRT bridges are much lighter. Their weight ranges from 130ton for 25m spans to 180ton for 35m spans and they may therefore be transported on public roads. When the area under the bridge is accessible, two ground cranes may erect four U-girders (two complete spans) every night. The U-girders may also be delivered along the completed bridge and erected with twin-girder overhead gantries. The dual-track U-girders are too wide for full-span delivery and are typically erected by segmental precasting.

8. Design Loads of MSS's and Form Travelers

The design loads of MSS's and form travelers are distinguished in permanent loads and varying loads. Permanent loads include self-weight and superimposed dead load. Varying loads include weight and pressure of fresh concrete, the reinforcement cage, the load redistribution at the application of prestress, the actions transferred by lifting devices applied to the MSS, the load of personnel and stored materials on the work platforms, the actions of snow and wind, and the thermal variations.

The casting cell is designed for the weight of forms and reinforcement, the filling sequence and the load redistribution at the application of prestress. Shutters are designed for the pressure of fluid concrete and the stress distribution generated by supports, ties and anti-floating anchorages between inner and outer forms. Lateral pressure of concrete may be computed with hydrostatic distribution in the upper portion and constant value in the lower portion. Form design for full hydrostatic pressure is specified for fast filling or when retarding admixtures are used for one-phase casting. Load unbalance between the webs can displace the inner form and twist the MSS so concrete level is kept controlled during filling.

Wind loads may be determined with reductions of the return period in relation to project duration. For these machines it is possible to identify precise wind conditions for their use and the load combinations distinguish normal operational conditions and out-of-service conditions. MSS's of medium length are unlikely to sustain damage from wind-induced vibrations. Launching is avoided in the presence of strong wind and achieving first lateral frequency higher than 0.20-0.25Hz is often enough to prevent vibrations. Design standards prescribe slenderness limits for the members of a truss and selecting the minimum size members of lateral bracing to satisfy the slenderness ratio is often sufficient to obtain acceptable lateral frequencies and buckling factors.

The loads applied to MSS's and form travelers are grouped into two load conditions. Load Condition I is the normal operational condition, which includes permanent loads, payload, load of personnel and stored items on work platforms, loads applied by lifting devices, and wind and thermal loads. Load Condition I is also used to analyze the launch stresses. Load Condition II is the out-of-service condition, which includes permanent loads, partial load on work platforms (snow if more demanding) and out-of-service wind. Wind in load Condition I is checked for any possible configuration of the machine while out-of-service wind is checked in anchored conditions.

Load Condition I is also used to analyze the application of prestress. As prestress is applied, the span lifts up from the casting cell. As the weight is relieved, however, the casting cell recovers the deflection. An MSS is more flexible than a PC span and the casting cell recovers only a portion of the deflection accumulated during concrete pouring. After application of prestress, therefore, the MSS exerts a residual support action onto the span. Overloading of young concrete is avoided by releasing the span in stages as prestress is applied or by tensioning only a part of the tendons prior to releasing the span. The span is released by lowering the MSS to minimize stress redistribution within the casting cell.

Both service (SLS) and strength (ULS) limit states are checked. SLS's correspond to the loss of functionality of the machine (displacements of components, rotations of field splices that alter the geometry of the casting cell, etc.); unit load factors are used for the two load conditions and the resistance factors are prescribed by the design standards. ULS's are related to critical conditions such as rigid equilibrium (overturning, uncontrolled sliding, etc.), rupture of connections, yielding, and local and global (out-of-plane) buckling, and the two load conditions are checked with different load factors.

9. Design Loads of Heavy Lifters

The load combinations for the design of beam launchers, lifting frames, launching gantries and span carriers are more complex because of the dynamic nature of loading. The discussion that follows is based on FEM-1.001 but load classifications and combinations can be easily adapted to different design standards.

The heavy lifters are grouped into classes in relation to the tasks they perform during their service life. The classification determines the load amplification factor used for the design of the structural components, which varies from 1.00 for A1-class units to 1.20 for A8-class units. The class is determined based on the number of load cycles and the load level. A load spectrum relates the entity of loading with the number of cycles. Since most load cycles of these machines occur at or near the load capacity, the spectral factor is typically high. However, the number of cycles is low and these machines are often designed as A2-class units with load factor 1.02.

A similar classification applies for the mechanical components. The load amplification factor varies from 1.00 for M1-class units to 1.30 for M8-class units. The bridge erection machines are typically designed as M2- or M3-class units with 1.04 and 1.08 load amplification factor, respectively. The amplification factors for structural and mechanical components are applied to the loads and the load combinations are then processed with load and resistance factors per design standard.

The design loads are divided into four groups: forces that act regularly during normal operations, forces that arise occasionally in the machine in service, exceptional forces in service and out-of-service, and forces that arise during assembly and dismantling.

The regular forces include permanent loads, payload and inertial effects of load movements. Weight and mass of members are increased by 20-40% to account for attachments. Concentrated loads and masses represent heavier components such as launch rollers, hydraulic articulations and electric generators. Payload includes lifted accessories.

Vertical inertial forces derive from the sudden application or removal of the load (*e.g.* precast segments on barges with rough sea), positive or negative accelerations during load movements, and the intervention of the emergency brakes upon electric black-out. Longitudinal inertial forces derive from accelerations or decelerations of winch-trolleys or portal cranes along the runways.

The occasional forces are wheel impacts, wind, snow, ice and thermal differences. Wheel impacts are often disregarded when the field splices in the rails are welded and ground away at dismantling of the machine. Snow and ice are often disregarded in ordinary weathers.

The exceptional forces are out-of-service wind, test loads, impacts against end-of-stroke buffers or fixed obstacles, and the design earthquake. Impacts against buffers at the end of runways are often disregarded for translation speed lower than 0.7m/s provided that the runways are equipped with end-of-stroke switches. The effects are computed in relation to the deceleration impressed and are increased by 25% for linear-spring buffers and 60% for constant-force hydraulic buffers.

The design loads are grouped into three load conditions. Load Condition I is the normal operational condition and includes permanent loads, payload inclusive of vertical dynamic amplification, and payload plus weight of winch-trolley or portal crane inclusive of longitudinal dynamic amplification. All these loads are multiplied by the load amplification factor resulting from the classification of the machine.

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, ice and thermal differences. In the presence of strong wind the longitudinal dynamic amplification factor may be different from the value for Load Condition I because the action of wind affects the starting and braking times of the portal cranes.

Load Condition III is the action of exceptional loads. It considers the following combinations: (1) permanent loads and out-of-service wind; (2) permanent loads, payload and impacts against end-of-stroke buffers or obstacles; (3) permanent loads, payload and design earthquake; and (4) permanent loads, wind in service and assembly and dismantling operations. Although conceptually similar to assembly, launching is typically checked as Load Condition II because of the higher frequency of operations. Load testing may require specific checks when the static test load is greater than 140% of the design load or the dynamic test load is greater than 120%

Both SLS's and ULS's are assessed. SLS's correspond to the loss of functionality of the machine; unit load factors are used for the three load conditions and the resistance factors are prescribed by the design standards. ULS's correspond to critical conditions and the three load conditions are checked with progressively lower load factors.

Most design standards do not distinguish between local and global (out-of-plane) buckling and both forms of instability are checked like any other ULS condition. Out-of-plane buckling of primary members is a more risky event than local buckling of web panels or secondary members. No post-critical domain or alternative load paths exist in many cases and the critical load is influenced by geometry imperfections that are difficult to detect. It is therefore common practice to check out-of-plane buckling of trusses and support towers with higher load factors, in the 2.0-2.5 range.

10. Modeling and Analysis

The optimum level of detail for the numerical model of a bridge erection machine depends on numerous factors. The more refined the model, the more accurate the results of analysis and the cambers to assign to the casting cell. However, simple models allow rapid investigation of different load and support conditions, facilitate the research of the design-governing conditions, and provide the stress magnitude to be expected from more refined analyses and the boundary conditions to assign to local models.

The underslung machines are typically supported onto stiff pier brackets and simple beam models are often sufficient for box girders or braced I-girders. Trusses are more complex to analyze and 3D frame models are necessary when the pier brackets are flexible or primary truss members are loaded indirectly. Modeling the supports is also necessary when the self-launching frame is supported onto pier brackets and props from foundations to represent the different stiffness of supports.

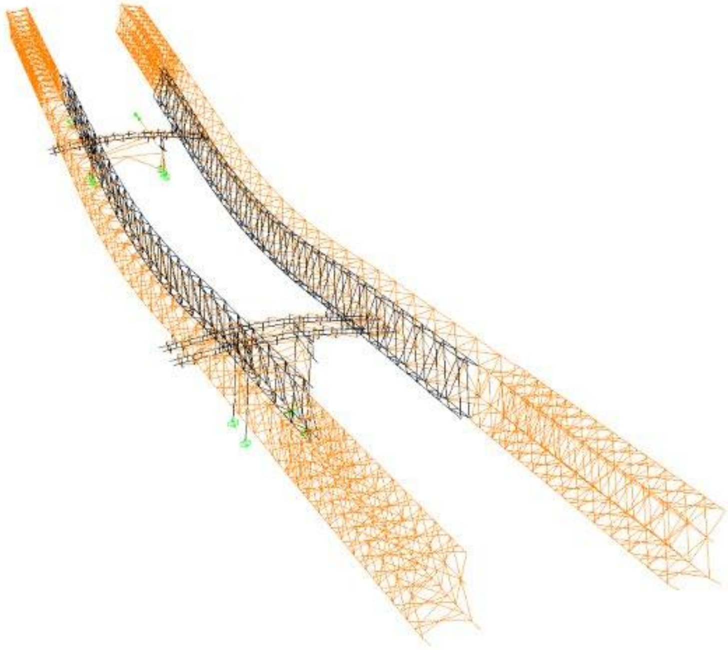

Figure 37: 3D frame model of the MSS of Figure 15

Twin-truss overhead machines are supported onto the overhangs of long crossbeams and 3D frame models of the entire machine are necessary to evaluate the effects of crossbeam deflections. In the MSS of Figure 15 the casting cell is suspended on either side from two paired trusses. A third truss controls out-of-plane buckling and carries the runway for the portal crane. The secondary truss and one of the main trusses are extended into the launching noses while the third truss is interrupted at the ends of the casting cell. The 5300-frame-element model of the MSS (Figure 37) highlights the need for stability of these machines: the brown members resist the payload and the orange members stabilize operations and launching. Most of the machine is aimed at stabilizing a few components.

An ideal truss should fulfill three conditions. (1) The members of diagonals and chords are pinned at the nodes. This condition is never respected in a self-launching machine: the nodes are continuous and when the truss has pinned splices for fast field assembly, the pins are located far from the nodes. (2) The loads are applied at the panel nodes. Also this condition is never respected. Bridge and form design dictates the location of the hangers for segments and casting cell. The load applied by the winch-trolleys migrates along the top chords, the support reactions migrate along the bottom chords during launching, and the trusses may be supported with out-of-node eccentricity even during span casting. (3) The gravity axes of all members converging into a node cross at the geometric panel node. This condition could actually be respected, although in most cases the convergence points of the diagonals onto the chords are staggered to simplify node welding.

Depicting the effects of geometry imperfections requires accurate models. An ideal model describes the entire machine: 3D trusses, winch-trolleys if capable to exert a lateral restraint action between the chords, pendular legs, crossbeams and support towers. Out-of-node eccentricities and steps in the gravity axis at the changes of cross-section are considered. Special joints are located at all points of discontinuity such as internal releases of degrees-of-freedom, changes in cross-section, field splices, support points, and points of application of concentrated loads. Point loads and masses represent non-structural attachments, property modification factors account for distributed weight and mass of attachments, and end offsets account for the finite size of diagonal and chord nodes.

Figure 38: Dismantling of a W-frame on through girders

The reliability of internal releases of degrees-of-freedom should be critically reviewed. The twin-girder overhead machines take support onto flexible tower-crossbeam assemblies. The master tower restrains the girders longitudinally and rollers or PTFE skids allow thermal displacements at the secondary tower. Rollers and skids slide after overcoming breakaway friction. If the longitudinal stiffness of the tower-crossbeam assembly is lower than the breakaway force, rollers and skids cannot slide and thermal deformations in the main girders will cause horizontal bending in the crossbeams and P-delta effects in the towers.

Similar considerations apply for the internal releases of rotations. The friction launchers support the main girder with pivoted arms that can be modeled with eccentric cylindrical hinges. Mechanical articulations are expensive when the tower legs are distant or W-frames on through girders are used on either side of the pier. In such cases the crossbeams are placed onto hydraulic jacks (Figure 38) that also provide geometry adjustment and lower the MSS to release the span. The jacks are equipped with safety nuts that are tightened prior to span erection. Different restraint conditions are therefore to be modeled for the jacks. During launching the jacks are modeled so as to keep the support reactions uniform (the hydraulic circuits are interconnected to create a hydraulic hinge). During span erection the jacks are modeled with vertical frame elements with released top rotations to model the ball-and-socket head. Analysis with tightened jacks will show that the inner crossbeams are more loaded than the outer ones due to flexural rotations in the main girders.

11. Instability of 3D Trusses

The stability of a freestanding truss is influenced by the degree of fixity at the supports, a support condition prompting the truss to twist as it deflects laterally, the lateral restraint exerted by inclined diagonals or lateral bracing on the compression chords, the location of loads in relation to the center of shear of the cross-section, and the level of imperfection in the initial geometry of the truss.

In a twin-truss machine these factors coexist and coalesce. The degree of fixity at the supports is low as the truss is supported onto flexible crossbeams. The truss bends laterally and twists because of the deflections of the crossbeams and the height of the truss amplifies the lateral displacements of the top chord. Triangular trusses are tall and narrow (the typical height-to-width ratio is about 3) and the lateral restraint that so inclined diagonals exert onto the top chord is poor. The winch-trolleys load the truss above the center of shear of the cross-section and the geometry imperfections are amplified by a large number of field splices.

Design standards normally recognize two types of instability. The first type is related to the overall sway of the structure (out-of-plane buckling) and the second type is related to deformations of a member between its end nodes (local buckling). Out-of-plane buckling can rarely be assessed with bibliographic values of the critical elastic moment in so complex structures.

Commercial software for structural analysis can depict buckling in every member of a truss but analyzing many buckling modes with complex numerical models involves long computational times. Out-of-plane buckling is therefore analyzed numerically and the local modes are checked with the load magnification factors prescribed by the design standards in relation to the effective length of members.

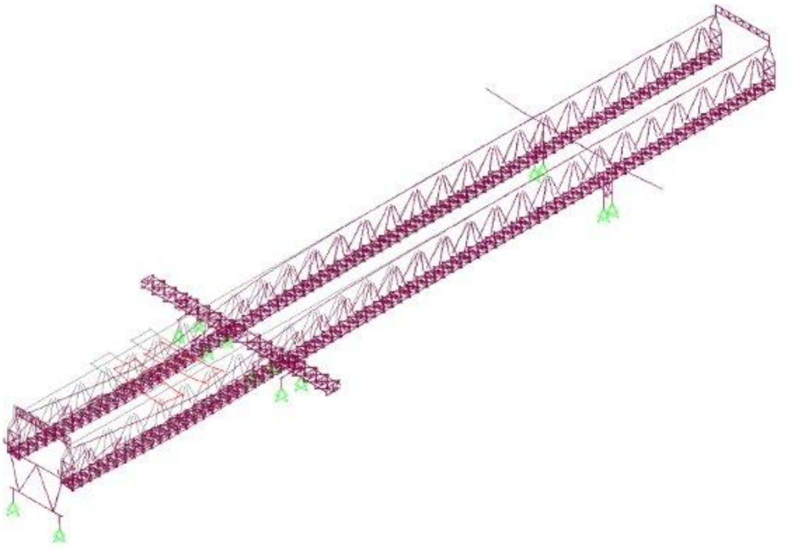

Figure 39: First buckling mode at segment lifting

Buckling analysis investigates the stability of the elastic equilibrium of a structure under a given set of loads. Since buckling modes and factors depend on the load, buckling is analyzed for different load conditions. Inertial load amplification also affects the buckling factor during movements of the load. Out-of-plane buckling of a launching gantry is analyzed by simulating the placement of segments. Analysis is simpler in an MSS as the casting cell is fixed.

Excessive confidence with a gantry due to having handled similar loads in the past may be a serious mistake. Stability depends on the entity of the load but also on how the load is applied to the machine. The buckling factor of the gantry of Figure 5 is lower at lifting of the pier-head macro-segment (Figure 39) than at lifting of the midspan segment because the winch-trolleys are close to each other instead of being at the ends of the segment.

Overloaded members may buckle suddenly and inspections are necessary during assembly and at regular intervals. Damaged diagonals must be reinforced or replaced even when they seem to be in non-critical locations as the load and support conditions vary so much in these machine that they could become the critical element. Diaphragms should also be inspected frequently and the reasons for out-of-flat should be investigated as this makes the members susceptible to local buckling.

The robustness of a machine depends on the stability of members against local buckling and on the overall response of the machine to local failure. Local buckling of a primary member is often critical in the support towers while stable alternative load paths often exist in so redundant trusses; however, local buckling may trigger a chain reaction of failures causing progressive collapse.

The simplest way to ensure robustness and reduce the risk of progressive collapse is to require insensitivity to local failure – *i.e.* local buckling of a primary member must not cause collapse of the machine or of a major part of it. Although the structural damage induced by local buckling is limited, the sudden stress redistribution generated by the loss of carrying capacity of a member is a highly dynamic process that requires analysis in the time domain.

The effects of local buckling can be analyzed with the following approach. (1) Start from an accurate numerical model of the machine. (2) Perform a buckling analysis and compute forces and moments at the ends of the buckling member under the loads that generate buckling. (3) Remove the buckling member from the model and apply end forces and moments with a specific load case. (4) Define a load function that increases from 0 to 1 and holds constant until fading of vibrations. (5) Define an unload function that abruptly drops from 0 to -1 and holds constant for the duration of the analysis. (6) Load the model quasi-statically by applying buckling loads and end nodal loads with the load function. (7) Analyze the dynamic response to member buckling by removing the nodal loads with the unload function.

As regards the integration method, modal superposition in the time domain provides a highly efficient procedure with shorter run-times than direct integration. Closed-form integration of modal equations is used to compute the response so that numerical instability is never encountered and the time step may be any sampling value that is deemed fine enough to capture the peak 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 often solved more efficiently by direct integration. This also applies for the dynamic analysis of loss of segments or impacts against end-of-stroke buffers.

The load path in the support regions of a 3D truss may include several pairs of diagonals (especially when the launch rollers are long) and load redistribution at member buckling is not always critical. The peak response stresses are checked like any other ULS condition. If analysis detects buckling in other members, the same approach may be used to analyze the entire buckling sequence until stress stabilization or collapse. Nonlinear links that drop forces and moments to zero when the local buckling load is reached may be inserted into the model to automate the analysis of progressive collapse, although nonlinear direct integration further increases the run time.

Figure 40: Flange buckling in a 96m, 340ton MSS

Local buckling of flanges can trigger critical situations in the box girders as during launching the support sections are devoid of diaphragms. In a twin-girder overhead MSS the left box girder (on the right in Figure 40) was slightly misaligned left-bound. When the front launch cantilever was 48m long, the operator decided to realign it. A crossbeam was placed at the front support to sustain two flat jacks on PTFE plates. The jacks had to be inserted under the webs to pull the box girder right-bound along the low-friction surface. The procedure was misunderstood and after lifting the box girder with the flat jacks, the PTFE plates were inserted between the box girder and the main support jacks.

In the initial phases of realignment the bottom flange of the box girder resisted the transverse bending generated by the increasing eccentricity in the support reactions. Eventually the outer flange and the central flange panel buckled upwards. This generated two low-friction inclined planes that gave raise to uncontrolled right-bound sliding of the box girder. Collapse was avoided because the edge of the bottom flange impacted against the end block of the crossbeam. Launch rails welded under the webs improve load dispersal, transfer lateral forces and also remind distract operators where the support reactions must be applied.

12. Instability of Vertical Support Members

The load of an erection machine is transferred to the bridge foundations through complex load paths that include structural, mechanical and electro-hydraulic components. The support legs of these machines are affected by specific forms of instability.

The pendular legs are among the most delicate components because their length must be varied to take support onto the pier cap and onto the deck (Figure 5). This is achieved with articulated legs and rotation cylinders, and the presence of multiple hinges along the vertical load path makes the legs prone to out-of-plane buckling when fully extended.

The bottom crossbeam of a pendular W-frame (Figure 41) had a box section over the entire width. Reusing the gantry in a curved bridge required shifting the support cylinders laterally to align them

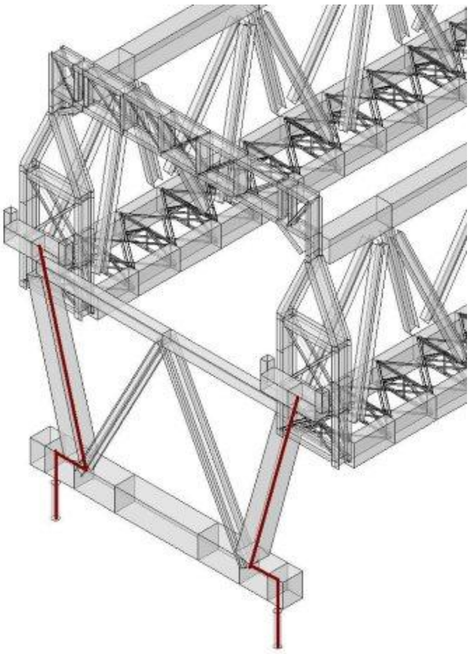

Figure 41: Three-hinge load path in a pendular W-frame

with the deck webs, so the crossbeam was windowed at the ends. As a result, the torsional constant in the windowed end sections dropped to about one-thousandth of the box girder constant.

When the support cylinders are at the ends of the crossbeam, the vertical load path is a three-hinge scheme where the central hinge has minimal rotational stiffness due to the low torsional constant of the windowed section. The buckling factor for self-weight was as low as 0.60. Box-stiffeners were applied to increase the torsional constant and stabilize the frame.

When a machine is supported onto temporary towers, the load applied to the towers is always eccentric. As cantilevers partially fixed at the base, the towers are sensitive to forces and couples applied to the top. If the towers are deformable, buckling analysis must account for the P-delta effect. Flexibility of foundations should also be considered, especially when only some of the tower legs take support onto the pier footing. Figure 42 shows the bracing systems of the rear support tower of an MSS. The upper section is reasonably braced while the lower section is “braced” with light tubes and iron wire. Slenderness ratios and notional design loads for horizontal braces are far from being respected in this machine.

Design of end connections affects strength and stability of the modular towers. When the legs are compressed and the contact surface between column and end plate is machined, the end weld is subjected to minimal stresses. In case of load reversal, the end weld is designed for tension and compression is resisted by the machined surface. If the contact is machined poorly, however, the weld can break in compression and at load reversal, the column can detach from the end plate. This is one of the cases where design details should account for the expected level of QA/QC of fabrication.

Modular towers are also used as props from foundations. These towers have adjustment screws at the base (verticality) and at the top (local gradient) and diagonal turnbuckles assure stability of the adjustment screws when fully extracted. Local buckling in a support tower is the most plausible cause of collapse of two bridge spans, two bridge piers and the erection gantry (Figure 43).

Figure 42: Bracing deficiencies in a 19m support tower

Figure 43: Gantry collapse

Forensic investigation detected design and assembly deficiencies in the tower. Load eccentricity and thermal loads were disregarded in the design. Lateral flexibility prevented sliding at the support saddles and the P-delta effect of thermal deck deformations was also disregarded. The adjustment screws were extracted excessively, the end turnbuckles were all missing, and the lateral connections between auxiliary frames and main tower were installed at the middle of the panels instead of at the nodes, which increased the effective length of compression legs (Figure 44). The subcontractor was certified for ISO 9001 quality management systems. In spite of a 1.29 buckling factor with theoretical geometry, the tower did buckle.

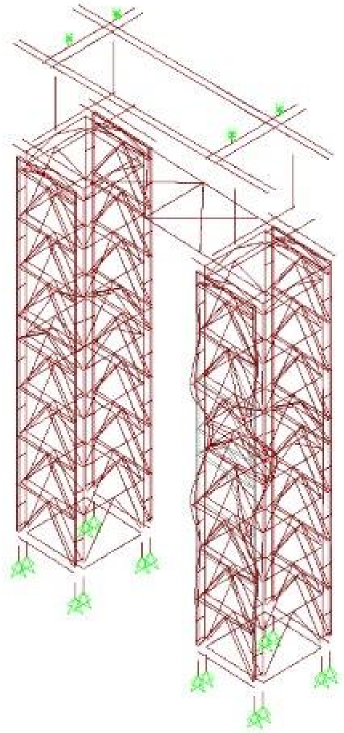

Figure 44: First buckling mode of the collapsed tower

As a matter of fact, buckling should always be checked with prudent load factors in these temporary structures.

All adjustment screws should be regarded as potentially prone to local buckling. Upon completion of launching, gantries and MSS's for span-by-span construction are lifted to the span erection level. Hydraulic cylinders with safety nut or screw jacks are used to support the girders after lifting. When the screw jacks are extracted excessively (Figure 8), local buckling can cause collapse. The allowed extraction of screw jacks should be stated in the operation manual and the risky portion of the screws should be marked.

13. Load Testing

Bridge erection machines are load tested after the first assembly. New load tests and comparisons with previous tests should follow every major reassembly.

Beam launchers, launching gantries, lifting frames and span carriers may be subjected to static and dynamic tests. The static test load is 10 to 40% higher than the design load. Load testing consists of slowly lifting a progressively increasing load until reaching the full test load. The load is lifted at different locations to reach full design stresses in the critical components of the machine and the deflections are compared with the theoretical values. The dynamic test load is typically 10 to 20% higher than the design load. The movements are tested individually at increasing speed. Black-out tests can also be performed to check the intervention of the emergency brakes.

The MSS's are subjected to static tests. The load is increased in steps and the deflections are surveyed at every step. The full load is kept for a certain time, the MSS is unloaded and the residual deflections are measured. Testing the MSS during casting of the first span is not advisable because loading cannot be interrupted. The deflections may also differ from the expectations, which would result in inadequate geometry of the first span. Load testing may be performed by applying a waterproof membrane and filling the casting cell with water. Additional load can be applied by suspending concrete blocks.

14. Conclusions

Innovation in bridge erection methods is a need for industrialized countries to preserve their export capability when competing with countries with less expensive labor. Fabricating bridge erection machines in emerging countries was a way for consolidated manufacturers to maximize profit, but selling cheap cloned machines soon became a new business for those emerging countries. As soon as the new manufacturers reach adequate levels of QA/QC and acquire the capability of providing technical assistance to designers and contractors, the transfer of technology will be completed.

Modern bridge erection machines are light, efficient, and complex. The level of sophistication of new-generation machines requires adequate technical culture. A level of technical culture adequate to the complexity of mechanized bridge construction would save human lives and would facilitate the decision-making processes with more accurate risk analyses.

Acknowledgments

AP Bridge Construction Systems, Beijing Wowjoint Machinery, BERD, Comtec, Deal, HNTB, Impresa Pizzarotti & C., NRS, Rizzani deEccher, ThyssenKrupp and VSL are gratefully thanked for authorizing the publication of photographs of their machines or related to independent design checking or technological consultancy assignments performed by the author.

Glossary

Alignment wedge: Truss extension with inclined bottom chords for progressive recovery of the elastic deflection and release of the support reaction during launching.

Beam launcher: Light self-launching gantry for erection of precast beams.

Capstan: Endless ring cable for longitudinal movement of winch-trolleys.

Casting cell: Assembly of outer form, inner form and front bulkhead for casting of segments or spans.

Casting cycle: Repetitive sequence of operations for casting a bridge segment or span.

C-frame: Adjustable frame that supports/suspends a bridge erection machine by rolling along the completed bridge during launching. It includes vertical cylinders that adjust the frame geometry to bridge superelevation, control the support reaction during launching, lift the machine prior to erecting the span, and lower the machine onto the launch systems after application of prestress. It may include additional hydraulic adjustment systems for transverse shifting and rotation about the vertical axis when launching along curves.

Cylinder: Long-stroke hydraulic jack. It is typically equipped with a safety nut to be tightened for structural safety during unattended operations. The end of the rod has a ball-and-socket joint or other types of articulation that minimize the flexural stresses in the rod.

Equalizer beam: Pivoted beam that equalizes the load in two rolls located at the beam ends. Two equalizer beams may be assembled onto a longer equalizer beam for a 4-roll assembly. 8-roll assemblies are a practical limit for heavy self-launching machines.

Form hangers: Suspension frames for a casting cell hung to an overhead MSS.

Form table: Sliding form for the central top slab strip between webs, used in two-phase casting of box girders. It may be supported onto brackets bolted to the inner web face of the U-segment or onto modular frames supported onto the bottom slab.

Form traveler: Self-launching casting cell for in-place segmental casting of balanced cantilever bridges.

Friction launcher: Support device able to generate longitudinal movements in the main girder by friction.

Hangers: Bars suspending precast segments or the casting cell from an overhead self-launching frame.

Heavy lifter: Self-propelled machine equipped with heavy lifting devices. Cranes, straddle carriers, derricks, cable cranes, beam launchers, lifting frames, gantries and span carriers are designed with standards for heavy lifters.

HSR: High-Speed Railway.

Hydraulic hinge: Hydraulically interconnected cylinders that allow differential movements at the supported points with equalized forces.

Launching nose: Extension applied to the main girder to control overturning during launching. The front nose is applied to the front end of the main girder in the launch direction. The rear nose is applied to the rear end. Both noses are equipped with alignment wedges or lifting arms for progressive recovery of the elastic deflection (front end) and progressive release of the support reaction (rear end).

Lifting arm: Hydraulic system to recover the elastic deflection of the tip of the front nose and to release the support reaction at the rear nose. A long-stroke cylinder rotates a pivoted arm to lift the tip of the launching nose to the launch elevation and to lower it to release the support reaction.

Lifting frame: Beam-and-winch assembly for lifting and handling of precast segments.

LRT: Light Rapid Transit.

MSS: Movable Scaffolding System for in-place casting of PC bridges. A deck-supported MSS for balanced cantilever bridges is called form traveler.

One-phase casting: Casting technique for solid or voided slabs, ribbed slabs and box girders where the entire cross-section is cast at once.

Overhead machine: Bridge erection machine where precast segments or a casting cell are suspended from a self-launching frame.

Payload: weight of the segment or the span before, during and after the application of prestress.

PC: Prestressed Concrete.

Pendular leg: Articulated auxiliary support leg retracted by hydraulic rotation about horizontal pivots.

Pier bracket: Adjustable support bracket of underslung machines anchored to the pier cap.

PLC: Programmable Logical Controller.

PTFE: Poly-Tetra-Fluor-Ethylene (commercial name is Teflon).

QA/QC: Quality Assurance and Quality Control.

Reverse launching: Backward transfer of a bridge erection machine along the completed bridge to erect a second parallel bridge.

Roller: Assembly of cast-iron rolls onto one or more equalizer beams.

Self-launching gantry: Self-launching machine for erection of precast segmental bridges or spans.

SLS: Serviceability Limit State.

Span carrier: Multi-wheel machine for delivery and placement of precast spans along the completed bridge. It includes two motorized trolleys connected by a box girder equipped with lifting winches. The load on the wheels is equalized hydraulically or electronically.

SPMT: Self-Propelled Modular Transporter.

Spreader beam: Adjustable suspension system for precast segments.

Straddle carrier: Wheeled portal crane for handling of precast girders and segments.

Stressing platform: Work area for fabrication and stressing of permanent prestressing tendons.

Support crossbeam: Support girder for overhead machines equipped with adjustable support legs and support saddles for the main girders that shift laterally along the crossbeam. A crossbeam comprises braced I-girders or a box girder with stiffening diaphragms at the support legs.

Support saddle: Pivoted assembly of rollers that supports the main girder and allows rotations about the vertical and transverse axes and longitudinal and transverse movements.

Support tower: Modular structure anchored to a foundation, a pier cap or a bridge deck to support a formwork, precast segments or an overhead machine.

Telescopic gantry: Self-launching machine comprised of a rear main girder and a front underbridge. The front end of the main girder slides along the underbridge during launching.

Traversing: Lateral shifting of the gantry along support brackets/crossbeams during launching along curves.

Two-phase casting: Casting technique for box girders where bottom slab and webs are cast in a first time and the top slab is cast in a second time.

Tunnel form: Collapsible inner form for one-phase casting of box girders.

ULS: Ultimate Limit State.

Underbridge: Self-launching front support girder for telescopic gantries and for placement of precast spans with wheeled carriers.

Underslung machine: Bridge erection machine where precast segments or a casting cell are supported onto a self-launching frame.

W-frame: Trussed assembly of crossbeam and diagonals supported onto through girders crossing the pier longitudinally to support underslung machines. Vertical adjustment is achieved with cylinders located between the through girders and the support frame.

Winch-trolley: Trolley that rolls along the main girders and lodges a main lifting winch and a secondary translation winch acting on a capstan. In some machines the translation capstan is replaced with hydraulic motors.

Bibliography

AASHTO (2003). *Guide Specifications for Design and Construction of Segmental Concrete Bridges*. American Association of State Highway and Transportation Officials (AASHTO). [This standard provides guidance on design and construction of segmental PC bridges in the U.S. It includes loads and load combinations for analysis of staged construction].

AASHTO (2008). *Construction Handbook for Bridge Temporary Works*. American Association of State Highway and Transportation Officials (AASHTO). [This manual provides general information for falsework construction in the U.S.].

AASHTO (2008). *Guide Design Specifications for Bridge Temporary Works*. American Association of State Highway and Transportation Officials (AASHTO). [This manual provides design guidance for ground falsework and other temporary works for bridge construction in the U.S.].

AASHTO (2010). *LRFD Bridge Design Specifications*. American Association of State Highway and Transportation Officials (AASHTO). [This standard rules bridge design practice in the U.S. It includes some guidance on bridge erection equipment].

AASHTO (2010). *LRFD Bridge Construction Specifications*. American Association of State Highway and Transportation Officials (AASHTO). [This standard rules bridge construction in the U.S. It includes some guidance on bridge erection equipment].

ACI (2004). *Guide to Formwork for Concrete*. American Concrete Institute (ACI). [This manual provides general information and design guidance for formwork].

ASBI (2008). *Construction Practices Handbook for Concrete Segmental and Cable-Supported Bridges.* American Segmental Bridge Institute (ASBI). [This handbook is an international reference for construction of segmental PC bridges. It provides broad information on the technical and technological aspects of most erection methods for PC bridges].

AISC (2006). *Base Plate and Anchor Rod Design*. American Institute of Steel Construction (AISC). [This booklet provides guidance for design of base plates and anchor rods].

Boggs, D.; Peterka, J. (1992). *Wind Speeds for Design of Temporary Structures*. Proceedings of the 10th ASCE Structures Congress, San Antonio, USA. American Society of Civil Engineers (ASCE). [This paper defines wind load to be used in the design of falsework and other types of temporary structures].

BSI (1982). *Code of Practice for Falsework*. British Standards Institute (BSI). [This booklet provides general design and technical guidance for falsework in the U.K.].

BSI (2002). *Eurocode 0. Basis of Structural Design*. British Standards Institute (BSI). [EC:0 provides general guidance for design of pedestrian, highway and HSR bridges. EC:0 has been updated with Amendment 1 in 2005. The EC countries integrate the Eurocodes with National Annexes, available in different languages].

BSI (2004). *Eurocode 1. Actions on Structures*. British Standards Institute (BSI). [EC:1 provides state-of-the-art guidance on the actions to be considered for the design of bridges, cranes, machinery, silos and tanks: general actions on structures (EC:1.1-1), actions on structures exposed to fire (EC:1.1-2), snow loads (EC:1.1-3), wind actions (EC:1.1-4), thermal actions (EC:1.1-5), general actions during construction (EC:1.1-6), accidental actions (EC:1.1-7), traffic load on bridges (EC:1.2), actions induced by cranes and machinery (EC:1.3), and actions on silos and tanks (EC:1.4). The EC countries integrate the Eurocodes with National Annexes, available in different languages].

BSI (2005). *Eurocode 2. Design of Concrete Structures.* British Standards Institute. [EC:2 provides state-of-the-art guidance for the design of concrete and PC structures: general rules and rules for buildings (EC:2.1-1), general rules for structural fire design (EC:2.1-2), design and detailing rules for concrete bridges (EC:2.2), and design rules for liquid retaining and containment structures (EC:2.3). The EC countries integrate the Eurocodes with National Annexes, available in different languages].

BSI (2005). *Eurocode 3. Design of Steel Structures*. British Standards Institute (BSI). [EC:3 provides state-of-the-art guidance for the design of steel structures: general rules (EC:3.1-1), general rules for structural fire design (EC:3.1-2), supplementary rules for cold-formed members and sheeting (EC:3.1-3), supplementary rules for stainless steels (EC:3.1-4), design rules for plated structural elements (EC:3.1-5), supplementary rules for shell structures (EC:3.1-6), supplementary rules for planar plated structural elements under out-of-plane loading (EC:3.1-7), design of joints (EC:3.1-8), design for fatigue (EC:3.1-9), material toughness and through-thickness properties (EC:3.1-10), structures with tension components (EC:3.1-11), steel bridges (EC:3.2), towers and masts (EC:3.3-1), chimneys (EC:3.3-2), silos (EC:3.4-1), tanks (EC:3.4-2), pipelines (EC:3.4-3), piling (EC:3.5) and crane supporting structures (EC:3.6). The EC countries integrate the Eurocodes with National Annexes, available in different languages].

BSI (2005). *Eurocode 8. Design of Structures for Earthquake Resistance. Bridges*. British Standards Institute (BSI). [EC:8 includes probabilistic equations for evaluation of the reduced seismic demand during construction based on shorter return periods related to construction duration. The EC countries integrate the Eurocodes with National Annexes, available in different languages].

BSI (2008). *Code of Practice for Temporary Works Procedures and the Permissible Stress Design of Falsework*. British Standards Institute (BSI). [This booklet provides general information and design guidance for falsework in the UK].

BSI (2009). *Execution of Concrete Structures*. British Standards Institute (BSI). [This booklet contains guidance on construction of concrete and PC structures].

CEN (2008) *Falsework. Performance Requirements and General Design*. European Committee for Standardization (CEN). [This booklet provides general design guidance and performance requirements for falsework].

CEN (2009). Design of Fastenings for Use in Concrete. European Committee for Standardization (CEN). [This booklet provides guidance on the design of concrete fasteners].

CSA (1975). *Falsework for Construction Purposes. Design.* Canadian Standards Association (CSA). [This booklet provides general design guidance for design of falsework in Canada].

CSA-S6-00 (2000). *Canadian Highway Bridge Design Code*. Canadian Standards Association (CSA). [This standard provides comprehensive guidance for the design of bridges in Canada].

CIRIA (1977). *Rationalization of Safety and Serviceability Factors in Structural Codes*. Construction Industry Research and Information Association (CIRIA). [This booklet is not directly related to bridge erection equipment, but calibration of load and resistance factors is a major issue in defining future international design standards for bridge erection equipment].

Ellingwood, B. (2008). *Reliability Based Codes in the United States. Challenges to Professional Engineering Practice*. Proceedings of the 4th International ASRANet Colloquium on Integrating for Structural Analysis, Risk & Reliability, Athens, Greece, 2008. [This publication identifies the main challenges of US standards based on reliability].

FEM 1.001 (1987) *Règles pour le calcul des appareils de levage.* Federation Europeenne de la Manutention (FEM). [This standard is an international reference for the design of launching gantries, lifting frames, span carriers, beam launchers, winch-trolleys, portal cranes, strand-jacking platforms and other types of heavy lifters. Classification of structural and mechanical components is compatible with design of bridge erection machines per local standards. Available in three languages].

FIB (2009) *Formwork and Falsework for Heavy Construction. Guide to Good Practice*. International Federation for Structural Concrete (FIB). [This manual mainly addresses form design and ground falsework].

Hewson, N.R. (2003) *Prestressed Concrete Bridges: Design and Construction*. Thomas Telford. [This book contains detailed information on the technological aspects of several bridge erection methods].

Hill, H. (2004). *Rational and Irrational Design Loads for "Temporary"' Structures*. Practice Periodical on Structural Design and Construction, 9, 125-129. [This paper critically reviews the reliability of the design loads used for temporary constructions].

HSE (2001). *Reducing Risks, Protecting People. HSE's Decision-Making Process*. Health and Safety Executive (HSE). [This booklet provides general information on risk analysis in the decision-making process].

HSE (2011). *Preventing Catastrophic Events in Construction*. Health and Safety Executive (HSE). [This manual provides HSE guidance of accident prevention in construction].

ISO (2009). *Risk Management - Principles and Guidelines*. International Organization for Standardization (ISO). [This manual identifies general principles and guidelines of risk management].

ISO (2009). *Risk Management - Risk Assessment Techniques*. International Organization for Standardization (ISO). [This manual identifies general risk assessment techniques and their effectiveness in risk mitigation].

Ratay, R. (2009). *Forensic Structural Engineering Handbook*. McGraw Hill Professional. [This book presents an in-depth coverage of forensic engineering].

Reason, J. (1990). *Human Error*. Cambridge University Press. [This book investigates the most common causes of human error].

Rosignoli, M. (1997). *Incremental Bridge Launching*. Concrete International, 19-2, 36-40. American Concrete Institute (ACI). [This paper compares alternative construction methods for PC bridges in relation to the components of bridge construction cost].

Rosignoli, M. (1997). *Influences of the Incremental Launching Construction Method on the Sizing of Prestressed Concrete Bridge Decks*. Proceedings of the Institution of Civil Engineers, Structures and Buildings. The Institution of Civil Engineers (ICE). [This paper discusses the impacts of incremental launching construction on the dimensions and quantities of structural materials of PC bridges].

Rosignoli, M. (1997). *Solution of the Continuous Beam in Launched Bridges*. Proceedings of the Institution of Civil Engineers, Structures and Buildings, 122, 390-398. The Institution of Civil Engineers (ICE). [This paper describes the Reduced Transfer Matrix method for analysis of temporary erection stresses in bridges built by incremental launching. The RTM method can analyze the hyperstatic launch stresses in every type of self-launching machine].

Rosignoli, M. (1998). *Nose-Deck Interaction in Launched Prestressed Concrete Bridges*. ASCE Journal of Bridge Engineering, 3-1, 21-27. American Society of Civil Engineering (ASCE). [This paper provides closed-form equations for analysis of the interaction between the PC bridge and the hydraulic launching nose and describes optimization techniques for nose-deck interaction].

Rosignoli, M. (1998). *Serio River Bridge, Creep and Incremental Launch*. Proceedings of the Institution of Civil Engineers, Structures and Buildings, 128, 1-11. The Institution of Civil Engineers (ICE). [This paper describes the effects of creep of concrete on the temporary launch stresses and the modifications of launch equipment to overcome creep deflections due to work stoppage].

Rosignoli, M. (1998). *Site Restrictions Challenge Bridge Design*. Concrete International, 20-8, 40-43. American Concrete Institute (ACI). [This paper describes the erection equipment for two road bridges and a cable-stayed LRT bridge built by incremental launching over six railroads with the help of cable-stayed temporary piers].

Rosignoli, M. (1998). *Misplacement of Launching Bearings in P.C. Launched Bridges*. ASCE Journal of Bridge Engineering, 3-4, 170-176. American Society of Civil Engineering (ASCE). [This paper provides closed-form equations for analysis of the temporary stresses generated by misplacement of the launching bearings during incremental launching construction of PC box girders].

Rosignoli, M. (1999). *Prestressing Schemes for Incrementally Launched Bridges*. ASCE Journal of Bridge Engineering, 4-2, 107-115. American Society of Civil Engineering (ASCE). [This paper illustrates the prestressing schemes used to overcome the temporary launch stresses in PC bridges built by incremental launching].

Rosignoli, M. (1999). *Reduced Transfer Matrix Method for Analysis of Launched Bridges*. ACI Structural Journal, 96-4, 603-608. American Concrete Institute (ACI). [This paper deepens the discussion of the RTM method for the analysis of temporary launch stresses in PC bridges].

Rosignoli, M. (1999). *Presizing of Prestressed Concrete Launched Bridges*. ACI Structural Journal, 96-5, 705-710. American Concrete Institute (ACI). [This paper discusses the impacts of incremental launching construction on the dimensions and quantities of structural materials in PC bridges in relation to the main features of launch equipment].

Rosignoli, M. (1999). *Nose Optimization in Launched Bridges*. Proceedings of the Institution of Civil Engineers, Structures and Buildings, 134, 373-375. The Institution of Civil Engineers (ICE). [This paper summarizes the criteria for optimal design of the steel noses for PC bridges built by incremental launching].

Rosignoli, M. (2000). *Thrust and Guide Devices for Launched Bridges*. ASCE Journal of Bridge Engineering, 5-1, 75-83. American Society of Civil Engineering (ASCE). [This paper illustrates strand jacking systems and friction launchers used for the incremental launching of PC bridges. It also describes launch bearings and lateral guides and provides guidance for the most appropriate choice and design of launch equipment].

Rosignoli, M. (2001). *Deck Segmentation and Yard Organization for Launched Bridges*. ACI Structural Journal, 23-2, 2-11. American Concrete Institute (ACI). [This paper compares alternative segmentations of PC bridges built by incremental launching and their impacts on yard organization and the investments for erection equipment].

Rosignoli, M. (2002). *Bridge Launching*. Thomas Telford. [This 340-page book is devoted to the incremental launching of bridges and related erection equipment. It covers design and construction of PC, steel, composite, and prestressed composite box girders with corrugated plate webs and concrete slabs].

Rosignoli, M. (2007). *Monolithic Launch of the Reggiolo Overpass*. ACI Structural Journal, 2, 61-65. American Concrete Institute (ACI). [This paper describes design of bridge and erection equipment for a multi-cellular trapezoidal span launched over an electrified railroad with the help of a temporary pier].

Rosignoli, M.; Rosignoli, C. (2007). *Launch and Shift of the Tiziano Bridge*. ACI Structural Journal, 29-10, 44-49. American Concrete Institute (ACI). [This paper describes design of bridge and erection equipment for a 200m twin-box-girder bridge built by launching a first box girder, shifting the girder laterally, launching a second box girder, and connecting the two girders with a central concrete stitch].

Rosignoli, M. (2007). *Robustness and Stability of Launching Gantries and Movable Shuttering Systems – Lessons Learned*. Structural Engineering International, 17, 133-140. [This paper deals with stability and robustness of self-launching gantries and MSS's. It compares the time-integration techniques for dynamic analysis of out-of-plane buckling and provides additional information on the analysis of progressive collapse].

Rosignoli, M. (2010). *Self-Launching Erection Machines for Precast Concrete Bridges*. PCI Journal. Precast/Prestressed Concrete Institute (PCI). Winter 2010, 36-57. [This long paper presents state-of-the-art information on beam launchers, self-launching gantries and span carriers for precast bridges].

Rosignoli, M. (2010). *Chair's introduction*. 1st IABSE International Seminar "*State-of-the-art Bridge Deck Erection: Safe and Efficient Use of Special Equipment*" Singapore, November 2010. International Association for Bridge and Structural Engineering (IABSE). [Chair's introduction focused on the absence of international standards for design and operations of bridge erection equipment and the impacts on safety of workers and quality of bridges].

Rosignoli, M. (2011). *Industrialized Construction of Large Scale HSR Projects: the Modena Bridges in Italy*. Structural Engineering International, 21-4. [This paper deals with the project organization for full-span precasting of 755 spans of HSR bridges in 30 months under global warranty (time, cost and quality) and the criteria used for the independent design checking of equipment and the QA/QC qualification of casting and erection processes].

Rosowsky, D. (1995). *Estimation of Design Loads for Reduced Reference Periods*. Structural Safety, 17, 17-32. [This paper provides guidance on the analysis of meteorological loads during erection].

SAA (1995). *Formwork for Concrete*. Standards Association of Australia (SAA). [This manual provides general guidance and design instructions for falsework].

SAA (2007). *Bridge Design*. Standards Association of Australia. [This standard provides guidance for the design of bridges in Australia].

Scheer, J. (2010). *Failed Bridges: Case Studies, Causes and Consequences*. Wiley VCH. [This book contains updated information on bridge failures].

Sexsmith, R. (1988). *Reliability During Temporary Erection Phases*. Engineering Structures, 20, 999-1003. [This paper deals with structural safety and other reliability aspects of staged construction].

Sexsmith, R.; Reid, S. (2003). *Safety Factors for Bridge Falsework by Risk Management*, Structural Safety, 25, 227-243. [This paper describes a risk-management-driven approach to the load and resistance factors for the design of temporary structures].

Starossek, U.; Wolff, M. (2005). *Progressive Collapse: Design Strategies*. Proceedings of IABSE Symposium, Structures and Extreme Events, Lisbon, Portugal. International Association for Bridge and Structural Engineering (IABSE). [This paper illustrates design strategies to mitigate the risk of progressive collapse and to provide adequate robustness of structures].

Starossek, U. (2006). *Progressive Collapse of Structures: Nomenclature and Procedures*. Structural Engineering International, 16, 113-117. [This paper defines nomenclature and procedures related to progressive collapse].

Starossek, U. (2009). *Progressive Collapse of Structures*. Thomas Telford. [This book examines causes, analysis methods and design approaches for prevention of progressive collapse of structures].

Bibliographical Sketch

Marco Rosignoli received his Doctorate in Civil Engineering *cum laude* at the University of Ancona (Italy) in 1981. From 1982 to 1997 he served as construction manager, project manager, bridge department lead and technical director with prime European bridge contractors. From 1997 to 2006 he worked as an international free-lance consultant for the design and the independent design checking of major bridges and bridge erection machines. After serving as Chief Bridge Engineer at HNTB for 2 years, he is leading the Southeast Division Bridge and Tunnel Professional Services of HNTB since 2008. Assistant to bridge designers, contractors and owners in 21 countries and 4 continents, expert in bridge design and construction technologies, and international authority on the incremental launching of bridges, Dr. Rosignoli is author of 2 books and 80+ publications on mechanized bridge construction. Author of Chapter 6 of ASBI (American Segmental Bridge Institute) *Construction Practices Handbook* and member of ASBI Board of Directors and ASBI Technical Advisory Committee, he has founded and is chairing IABSE (International Association for Bridge and Structural Engineering) working group WG-6 *Bridge Construction Equipment* for the 2009-2013 period.

CONTENTS

Civil Engineering
Kiyoshi Horikawa, *Musashi Institute of Technology, Tokyo, University of Tokyo, and Saitama University, Japan*

Fields within Civil Engineering - Ports and Canals as Waterborne Transport Facilities
Yoshimi Goda, *Yokohama National University, Japan*

Transportation Engineering
Izumi Okura, *Yokohama National University, Japan*
Masao Kuwahara, *The University of Tokyo, Japan*
Hirokazu Akahane, *Chiba Institute of Technology, Japan*

Fumihiko Nakamura, *Yokohama National University, Japan*

Urban and Community Planning

Kazuaki Miyamoto, *Faculty of Environmental and Information Studies, Musashi Institute of Technology, Japan*
Antonio Paez, *School of Geography and Geology, McMaster University, Canada*

Wastewater Management Engineering

Tomonori Matsuo, *Department of Regional Development Studies, Toyo University, Itakura, Japan*
Eiichi Nakamura, *National Institute for Land and Infrastructure Management, Ministry of Land, Infrastructure and Transport, Tsukuba, Japan*
Masahiro Osako, *Research Center for Material Cycles and Waste Management, National Institute for Environmental Studies, Tsukuba, Japan*

Water Resources Engineering

Nobuyuki Tamai, *Department of Civil Engineering, Kanazawa University, Kanazawa, Japan*

Survey Engineering

Eihan Shimizu, *Department of Civil Engineering, University of Tokyo, Japan*

Control Point Surveying and Topographic Mapping

Shoichi Oki, *Land Bureau, National Land Agency, Japan*

Global Positioning System

Tatsunori Sada, *Mitsui Construction Co., Ltd., Japan*

Photogrammetry

Hirofumi Chikatsu, *College of Science and Engineering, Tokyo Denki University, Japan*

Satellite Remote Sensing
Eihan Shimizu, *Department of Civil Engineering, University of Tokyo, Japan*

Geographic Information System
Myoung-Young Pior, *Faculty of Real Estate Science, University of Meikai, JAPAN*

Construction Techniques
Y. Ito, *Former Senior Vice President and the deputy general manager of the civil engineering division of TAISEI Corporation, JAPAN*

Earthquake Protection
Motohiko Hakuno, *Professor Emeritus, Earthquake Research Institute, University of Tokyo, Japan*

Structural Stability and Nonlinear Behavior
H. Iemura, *Department of Civil Engineering Systems, Kyoto University, Kyoto, Japan*

Geotechnical Engineering
Kenji Ishihara, *Department of Civil Engineering, Chuo University, Tokyo, Japan*

Soil Mechanics
Kenji Ishihara, *Department of Civil Engineering, Chuo University, Tokyo, Japan*

Mining Engineering and Mineral Transportation
Yuichi Nishimatsu, *Mineral Resources Division, Sumitomo Metal Mining Co. Ltd. Japan.*

Surface Mining Methods and Equipment
Jiro Yamatomi, *The University of Tokyo, Japan*
Seisuke Okubo, *The University of Tokyo, Japan*

Underground Mining Methods and Equipment
Seisuke Okubo, *The University of Tokyo, Japan*
Jiro Yamatomi, *The University of Tokyo, Japan*

Drilling Machines
Hideshi Watanabe, *Furukawa Co. Ltd., Japan*

Offshore Drilling and Production Equipment
Shoichi Tanaka, *The University of Tokyo, Japan*
Yo Okada, *Japan Oil Engineering Co., Japan*
Yuichiro Ichikawa, *Japan Drilling Co., Ltd., Japan*

Mineral Comminution and Separation Systems

Toshio Inoue, *Department of Geosystem Engineering, University of Tokyo, Tokyo, Japan*

Surface Mining Transportation Systems

Takao Nagai, *IT Group, Development Division, Komatsu Ltd, Japan*

Underground Mining Transportation Systems

Kikuo Matsui, *Kyushu University, Japan*

Mining and Exploration for Mineral Resources
Takashi Nishiyama, *Kyoto University, Japan*
Katsuhiko Kaneko, *Hokkaido University, Japan*

Bridge Erection Machines
Marco Rosignoli, *HNTB Corp., USA*

Forthcoming...

STRUCTURAL ENGINEERING AND GEOMECHANICS

Structural, Geotechnical and Earthquake Engineering
Sashi K. Kunnath, UC DAVIS, Civil and Environmental Engineering, USA

Mechanics of Structural Materials
Jeff Brown, Department of Engineering,Hope College, USA

Linear Analysis of Structural Systems
Aslam Kassamali, Department of Civil&Environmental Engineering,Southern Illinois University, Illinois

Nonlinear Analysis of Frame Structures
Enrico Spacone, PRICOS-Architettura viale Pindaro ,Universita' di Chieti-Pescara, Italy

Plastic Design vs Elastic Design of Structures
Subash Goel, Department of Civil & Environment Engineering, 2350 Hayward, USA

Structural Stability
Eric Lui, Department of Civil & Environmental Engineering, Syracuse University, USA

Structural Reliability
Siddhartha Ghosh, Department of Civil Engineering, Indian Institute of Technology Bombay, India

Modeling and Analysis of Progressive Collapse Potential for Moment Frames
Sashi K. Kunnath, UC DAVIS, Civil and Environmental Engineering, USA
El-Tawil, Department of Civil & Environment Engineering, University of Michigan, USA

Structural Steel Analysis and Design: Fundamentals
Eric Lui, Department of Civil & Environmental Engineering, Syracruse University, USA

Structural Steel Analysis and Design: Advanced Topics
Amit Kanvinde, Department of Civil Engineering, University of California, USA

Modeling for Geotechnical Engineering Application
Pradeep Kurup, Department of Civil & Environoment Engineering, University of Massachusetts, USA

Foundation Engineering:Shallow Foundations
Dave Chan, Department of Civil Engineering, University of Alberta, Canada

Design and Analysis of Deep Foundations
Rodrigo Salgado, Department of Civil Engineering, Purdue University, Indiana, USA

Structural Dynamics
Joseph Tedesco, Cullen College of Engineering, University of Houston, USA
Ted Krauthammer, Cullen College of Engineering, University of Houston, USA

Pushover Analysis of Structures
Sashi K. Kunnath, UC DAVIS, Civil and Environmental Engineering, USA
Erol Kalkan, Department of Civil Engineering, University of California, USA

Engineering Seismology
Erol Kalkan, Department of Civil Engineering, University of California, USA

Structural Design for Earthquake Resistance
Rajesh Dhakal, Department of Civil Engineering, University of Canterbury, New Zealand

Seismic Design of Concrete Building Structures
CVR Murty, Department of Civil Engineering, Indian Institute of Technology Kanpur, India

Seismic Design of Steel Bridges

Lian Duan, California Department of Transportation, USA

Seismic Isolation of Structural Systems
Satish Nagarajaiah, Department of Civil & Environment Engineering, Rice University, USA

Seismic Energy Dissipation Systems in Struc Engg
Panos Tsopelas, Department of Civil Engineering, Catholic University, USA

Semi-Active Control of Structural Systems
Anil Agrawal, Department. of Civil Engineering, The City College of New York, USA

Seismic Response of Masonry Structures
Benson Shing, Department of Structural Engineering, University of California, USA

Seismic Analysis & Design of Masonry-Infilled Frames
Khalid Mosalam, Department of Civil & Environment Engineering,University of California, USA

Seismic Response & Design of Pile Foudation Systems
Y.H. Chai, Department of Civil Engineering, University of California, USA

Modeling Techniques for Concrete Structures
John Bolander, Department of Civil Engineering, University of California, USA

Computational Methods for Seismic Analysis of Structures
Michael Scott, Department of Structural Engineering, School of Civil and Construction Engineering,Oregon State University , USA

Soil-Foundation-Structure Interaction Analysis
Tahmeed M. Al-Hussaini, Department of Civil Engineering, Bangladesh University of Engineering & Technology(BUET), Bangladesh

Computational Geomechanics
Boris Jeremic, Department of Civil Engineering, University of California, USA

Blast and Impact Effects on Strutures
Shalva Marjanishvili, Hinman Consulting, San Francisco, USA

FRP Composites for Structural Engineering Applications
Giorgio Monti, Dipartmento di Ingegneria Strutturale e Geotecnica,Universita di Roma "La Sapienza", Italy

Computational Geomechanics
Boris Jeremic, Department of Civil Engineering, University of California, USA

Blast and Impact Effects on Structures
Shalva Marjanishvili, Hinman Consulting, San Francisco, USA

Composite Materials and Structures
Vistaph Karbahari, Department of Structural Engineering, University of California, USA

FRP Composites for Structural Engineering Applications
Giorgio Monti, Dipartmento di Ingegneria Strutturale e Geotecnica,Universita di Roma "La Sapienza", Italy

Urban Restoration of Historical Cities
Giorgio Monti, Dipartmento di Ingegneria Strutturale e Geotecnica,Universita di Roma "La Sapienza", Italy

Modeling Techniques for Steel Structures

Modeling for Geotechnical Engineering Applications

Advanced Mechanics of Materials

Rock Mechanics

Seismic Design of Hybrid Steel-Concrete Structures

Inflatable and Skin Structures

Design Experience and Construction of Steel Structures

Emerging Technologies in Structural Steel Systems

Structural Steel Technology