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Movable Bridge Lightweight Concrete Deck Design & Construction Considerations

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Introduction

The deck and floor system are key features of movable bridges. These components contribute to a large portion of the overall superstructure weight and thus significantly influence the movable span design. Lightweight deck systems and steel framing systems are typically used on movable bridges to reduce the mass that must be moved and supported. A lower weight reduces frictional and inertial resistance, with corresponding lower operating power, and smaller equipment. It also yields savings in material quantities throughout the movable span including smaller counterweight, steel framing members, pier and foundation components. Historically, movable bridges have typically consisted of steel open grid deck supported by a steel framing system of stringers, floorbeams and pair of main longitudinal load carrying members (girders or trusses) to achieve a lightweight solution. In recent years, more owners and designers of movable bridges have opted for lightweight concrete deck systems (e.g. solid reinforced concrete deck, grid reinforced concrete deck, or Exodermic deck) despite the increase in weight and higher initial construction cost. This decision is based on numerous factors including:

- Lower overall life cycle costs
- Increased durability and longer service life
- Improved protection of the steel framing
- Greater skid resistance
- Reduced traffic generated noise
- Increased structural efficiency with:
    - Longer span capability that reduces number of steel members
    - Greater stiffness with reduced deflections and vibrations
    - Better fatigue resistance
- Consistent concrete surface throughout the bridge
- Bicycle friendly surface
- Improved water quality with ability to collect and treat stormwater.

New design strategies and advancements in materials allow for continued refinement and optimization of the movable span to achieve greater economy and durability. As movable bridges utilize different deck systems, structural framing, and support configurations than other bridge types, there are additional aspects that must be considered in the design and construction. This paper discusses the latest design strategies for movable bridges with lightweight concrete deck systems, and the various design and construction aspects that must be considered for successful implementation.

Structural Lightweight Concrete

One of the primary material components of the deck systems is lightweight concrete. Structural lightweight concrete is available in a range of unit weights from 90 to 135 pcf and minimum 28-day compressive strengths of 2.5 ksi to 10.0 ksi. Lightweight concrete is typically 25 to 35 percent lighter than normal weight concrete. The constituents of lightweight concrete are generally the same as normal weight concrete except for the coarse and/or fine aggregate, which consists of lightweight material. Lightweight aggregate consists of lightweight expanded shale, clay or slate produced by heating in rotary kiln to around 2000 deg. F. Coarse aggregates are graded like normal weight aggregate with coarse aggregates graded from 3/4" or 1/2" to #4, 3/8" to #8 or #16, and fine aggregates from #4 to pan. Coarse aggregate with a maximum size of 3/8" (i.e. pea-gravel) is required where used in conjunction with steel grids (e.g. grid reinforced deck and Exodermic deck.) Specifications for lightweight aggregates are governed by ASTM C330 (AASHTO M195) which addresses grading, bulk density, split tensile strength, drying shrinkage limits, freeze/thaw. Additional resources on lightweight concrete can be found at the Expanded Shale, Clay and Slate Institute (ESCSI) website, (https://www.escsi.org/).

Lightweight concrete can be made in different combinations of lightweight and normal weight coarse and fine aggregates. Sand-lightweight concrete uses lightweight coarse aggregate with normal weight silica-sand fine aggregate with equilibrium unit weight in the range of 110 to 120 pcf and compressive strength in the range of 2.5 to 10.0 ksi. All-lightweight concrete uses lightweight coarse aggregate with lightweight fines for the fine aggregate with equilibrium unit weight in the range of 90 to 100 pcf and compressive strength in the range of 2.5 to 6.0 ksi. *AASHTO LRFD Bridge Design Specifications* no longer distinguishes between sand-lightweight and all-lightweight concrete. Designers typically need only specify density and compressive strength. Equilibrium density customarily is in the range of 3 to 8 pcf lighter than freshly batched concrete. Concrete can typically be batched to the specified density with a tolerance of +/- 3 pcf. Unit weight testing is performed in accordance with ASTM C567.

Per *AASHTO LRFD Bridge Design Specifications*, design factors that differ between lightweight concrete and normal weight concrete are generally minor and are as follows:

Coefficient of Thermal Expansion: Lightweight concrete has a lower effective coefficient of thermal expansion of 5.0×10^{-6}/deg. F vs. 6.0×10^{-6}/deg. F for normal weight concrete.

Modulus of Elasticity: The same formula used to compute the modulus of elasticity for normal weight concrete is used for lightweight concrete. ($E_c = 120{,}000 K_1 w_c^{2.0} f'_c{}^{0.33}$) The lower unit weight of lightweight concrete yields lower modulus of elasticity which effects stiffness, deflections, composite section properties, camber and shear connector design.

Density Modification Factor: The lower density of lightweight concrete affects calculation of several design factors including shear resistance, modulus of rupture and corresponding cracking stress/moment, crack control distribution reinforcement, and mild reinforcement development length. *AASHTO LRFD Bridge Design Specifications* addresses this with a density modification factor, λ. The density modification factor is a function of the lightweight concrete split tensile strength, f_{ct}. Split tensile strength can be specified during design, and verified during mix design development, to achieve a density modification equal to or near 1.0 to minimize the effect of the lower density (recommended). The split tensile strength does not need to be verified during batching. ($\lambda = 4.7 f_{ct} / (f'_c)^{0.5} \leq 1.0$, where f_{ct} specified, and $0.75 \leq \lambda = 7.5 w_c \leq 1.0$ where f_{ct} not specified).

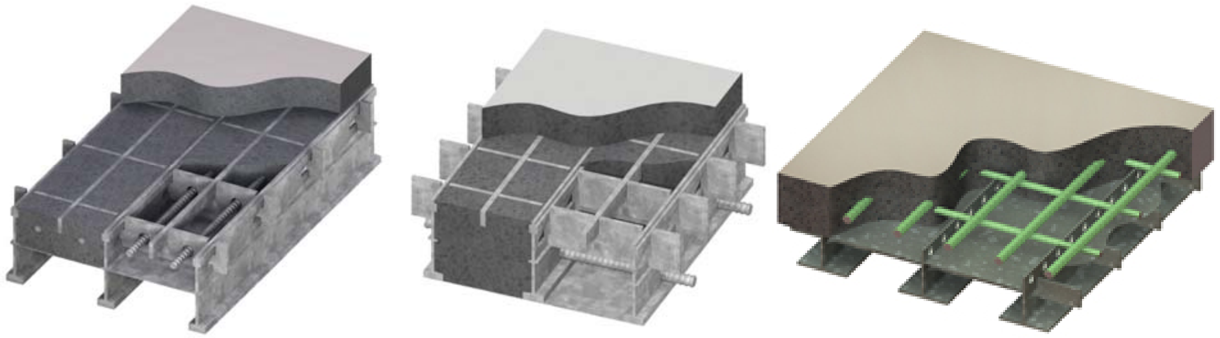
Lightweight concrete is generally considered to have equal or greater durability than normal weight concrete due to several factors:

- The elastic modulus of lightweight aggregate and cement matrix are more closely matched, which reduces internal stress concentrations and corresponding microcracking.
- With the lower elastic modulus, lightweight concrete has greater ductility with higher endurance limit and lower cracking from thermal and shrinkage strains.
- Retained water within the aggregate slowly releases after the concrete sets, which achieves "internal curing". Internal curing improves the mechanical and durability properties with more complete hydration and continued reaction of supplementary cementitious materials. This also results in reduced drying shrinkage which can offset poor curing.
- Lightweight aggregates typically have greater hardness and are more resistant to wear and polishing, and thus are less susceptible to reductions in skid resistance.
- Lightweight concrete has a superior bond and transition zone between aggregate and cement matrix.
- Lightweight concrete has a high resistance to freeze-thaw.
- Low permeability of lightweight concrete yields greater resistance to deicing salts and chemicals.

Deck and Steel Framing Development

Deck System Selection

There are several deck systems that utilize lightweight concrete that can be considered for movable bridges including a conventional solid reinforced concrete deck, grid reinforced concrete deck (filled half-depth or full-depth) and Exodermic deck. The latter two are described and discussed in greater detail at the Bridge Grid Flooring Manufacturers Association (BGFMA) website (http://www.bgfma.org/). (Figure 1.)



Half Filled Grid Deck Fully Filled Grid Deck Exodermic Deck

Figure 1 - Steel Grid Options

Grid reinforced concrete and Exodermic deck are similar. Both consist of a fabricated and hot dip galvanized steel grid panels that consist of a series of orthogonal main bars and cross bars made composite with concrete. Panels are typically limited to widths of 8.5′ and lengths of 45′ as dictated by maximum shipping width, fabrication tolerances and size of galvanizing bins. Main bars include punched holes that allow slotted cross bars to be inserted flat and turned up vertically to lock the components together. Puddle welds at the top of the intersecting grid bars secure the components for filled grid systems, and a one-quadrant fillet weld for Exodermic systems. Stay-in-place steel sheet metal forms integrated into the grid permit placement of cast-in-place concrete with minimal supplemental forming.

For grid reinforced concrete, main bars consist of special 4-1/4″ or 5-3/16″ deep steel I-beams at 6″, 8″ or 10″ spacing. Cross bars consist of 1/4″ x 2″ flat bars at 4″ spacing. Between the main bars are supplemental bar(s) that consist of 5/16″ x 1″ flat bars, with one for 6″ and 8″ main bar spacing and two bars for 10″ spacing. The top of the cross bars and supplemental bars are flush with the top of the main bars. Full-depth filled grid also includes a series of #5 lower reinforcing bars at 8″ spacing installed through holes in the main bars. Concrete is placed either half-depth with forms supported on main bar intermediate flanges near mid-height or full depth with the forms supported on main bar bottom flanges. Although the concrete can be finished flush with the top of the steel grid, concrete is typically placed with a 1.5” to 2” overfill above the steel grid to increase corrosion protection and better achieve a quality finish. An additional 0.5″ of sacrificial cover can be specified for profiling and grooving.

For Exodermic deck, main bars consist of inverted tees (WT4x5, WT5x6 or WT6x7) at 8″, 10″ or 12″ spacing. Cross bars consist of 1/4″ x 1-1/2″ flat bars (for WT4x5) or 1/4″ x 2″ flat bars (for WT5x6 or WT6x7) at 6″ spacing. The tops of the cross bars are recessed 1″ below the top of the tees and support steel sheet metal forms between the tees. A 4″ to 4.25″ reinforced concrete slab with 2″ top cover for the reinforcing is placed on the forms with the top 1″ of tees extending into the slab. An additional 0.5″ of sacrificial cover can be specified for profiling and grooving. The tops of the tees include a series of 3/4″ diameter punched holes at 2″ spacing that connect the slab and tees. The slab includes a single two-way

mat of reinforcing with secondary reinforcing perpendicular to and bearing directly on top of the main bars and primary reinforcing parallel to the main bars and bearing on the secondary reinforcing.
Selection of the deck system is typically based on initial construction cost with consideration of the following:

- Weight of the system including deck, stringers (if used), and floorbeams including concrete haunches over the steel framing members.
- Weight of counterweight ballast to balance the deck and floor system weight (not applicable on equal arm swing spans).
- Effect of weight on the size of machinery components including support machinery (e.g. trunnions, rolling track and treads, pivot bearings) and operating machinery (e.g. motors and drive train).

Life cycle costs can also be considered in the evaluation including anticipated future maintenance (e.g. cleaning/painting of steel, repair of steel members and connections, deck replacement, machinery component replacement). However, in general a life cycle cost evaluation will yield the same result as the initial construction cost evaluation. Each of the lightweight concrete deck systems are anticipated to last the service life of the bridge (75 to 100 years). In areas where deicing salts are used, a sacrificial overlay (e.g. latex modified concrete) can replace the top 0.75″ to 1″ of cover to avoid need to replace the structural portion of the concrete deck. For steel grid solutions, the combination of hot dip galvanized coatings and solid concrete deck with 1.5″ to 2″ of cover provides excellent corrosion protection of the steel grid.

In Table 1 below, the weight of various lightweight concrete deck systems are compared. It is generally found that the lowest weight and lowest cost solution is achieved by maximizing the deck span and minimizing the number of steel framing members. The comparison is based on a steel framing configuration where the deck spans longitudinally across floorbeams with no stringers.

TABLE 1 – SAMPLE COMPARISON OF LIGHTWEIGHT CONCRETE DECK SYSTEMS

Deck System	Deck Depth[1] (in)	Deck System Description[2]	Maximum Span[3] (ft)	Deck Unit Weight[3] (psf)
Solid Reinforced Concrete Deck	9.25	#5 Bars at 6″ (Top & Bott.) #5 Bars at 9″ (Top & Bott.)	14.0′	94.0
Grid Reinforced Concrete Deck (Half Filled)	7.19	5-3/16″ Main Bars at 6″ 5/16″x1″ Suppl. Bars at 6″ 1/4″x2″ Cross Bars at 4″	9.0′	60.4
Grid Reinforced Concrete Deck (Fully Filled)	7.19	5-3/16″ Main Bars at 6″ 5/16″x1″ Suppl. Bars at 6″ 1/4″x2″ Cross Bars at 4″ #5 Bars at 8″ (Bott.)	9.2′	85.7
Exodermic Deck	9.21	WT6x7 Main Bars at 8″ 1/4″x2″ Cross Bars at 6″ #6 Bars at 4″, #4 Bars at 6″	13.9′	60.7

Assumptions:

1. Includes 2″ top concrete cover/overfill. A 0.5″ sacrificial thickness can be considered for profiling and grooving at an additional weight of 4.8 psf.
2. Lightweight concrete with 5.5 ksi compressive strength and equilibrium unit weight of 115 pcf.
3. From BGFMA Design Program (V3.1). Longitudinal span direction (main bars parallel to traffic). Deck system only. Weight excludes haunches and steel framing members.

The above comparison reveals that the half-filled grid reinforced concrete and Exodermic decks have the lowest unit weight, and thus yield the lowest overall movable span weight and initial construction cost, by inspection.

With a longitudinal span, the Exodermic deck can span up to 13.9′ with a total deck depth of 9.21″. With this span length, stringers are unnecessary. In comparison, grid reinforced concrete can span longitudinally a maximum of only 9.2′ with a total deck depth of 7.19″. The span capability of grid reinforced concrete is limited by the depth of the fabricated steel grid, which is dictated by the main bars used. The shorter deck span requires additional floorbeams at a ratio of 1.5 to 1 compared to Exodermic deck. Exodermic deck utilizes similar quantity of concrete and steel grid material as half-filled grid reinforced concrete, but in a significantly more efficient manner. The details of the steel grid component of Exodermic deck are simpler than that for grid reinforced concrete, and thus the fabrication cost is less.

A solid reinforced concrete deck can be designed to span a similar distance as Exodermic deck, with a similar total deck depth, but this solution is significantly heavier. Although the solid reinforced concrete deck does not include the cost of steel grid, the cost of additional lightweight concrete and reinforcing steel, deck form costs, increased counterweight ballast, and increased size of operating equipment, more than offsets this cost savings.

As Exodermic deck is a more economical lightweight concrete deck system solution, the remaining discussion will focus only on this deck system.

Additional savings in deck system weight can be achieved with the use of lower density all-lightweight concrete (100 pcf rather than 115 pcf) and reduced concrete cover (1″ rather than 2″). The reduced cover requires use of corrosion resistant stainless-steel reinforcing. For the above Exodermic deck example, this yields a deck system unit weight of 47.3 psf, a savings of 13.4 psf. With this approach, the maximum span length is reduced by approximately 15% to 11.9′ due to the reduced deck stiffness and deck design governed by live load deflection. The reduction in counterweight ballast, and size of operating equipment, more than offsets the higher cost of all-lightweight concrete, stainless-steel reinforcing, and closer floorbeam spacing.

Deck and Floor System Configuration

Exodermic deck can span transversely (Figure 2) or longitudinally (Figure 3).

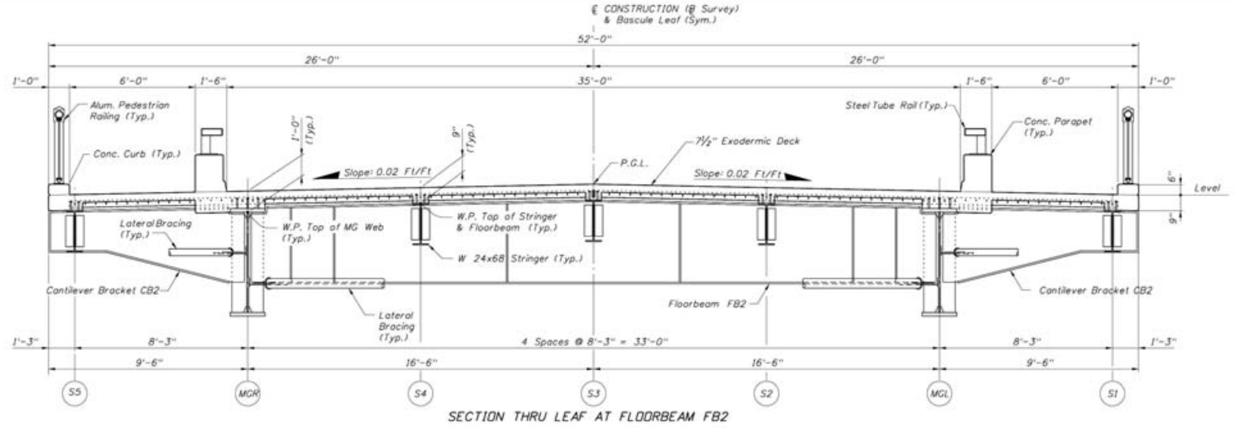


Figure 2 - Transverse Deck Span Configuration

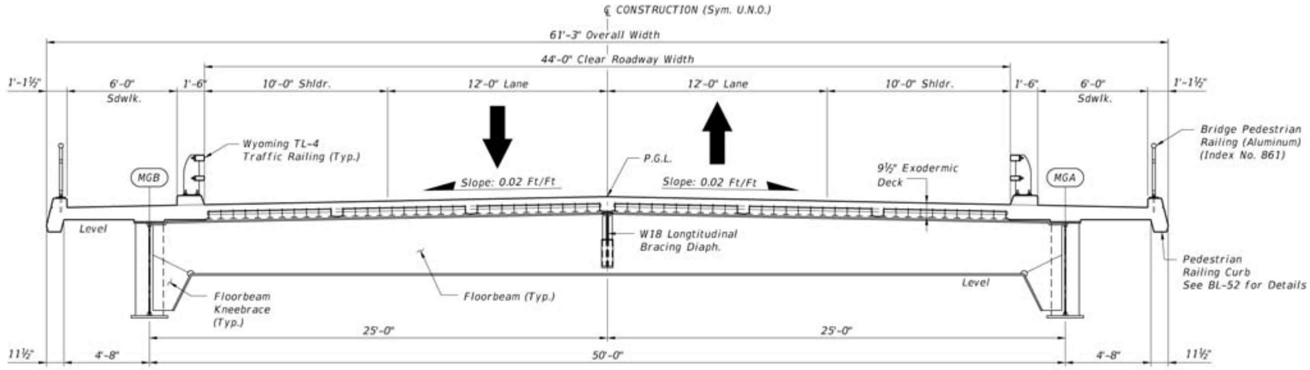


Figure 3 - Longitudinal Deck Span Configuration

With a typical transverse deck span configuration, the deck spans across a series of stringers spaced at 5′ to 10′ that span between floorbeams spaced at 15′ to 25′. With a typical longitudinal span configuration, the deck spans across a series of floorbeams spaced at 9′ to 14′ without stringers.

In Table 2 below, the weight of transverse and longitudinal deck span configurations is compared. An optimized configuration is typically achieved by maximizing spans and minimizing the number of floor system members.

TABLE 2 - SAMPLE COMPARISON OF TRANVERSE VS. LONGITUDINAL DECK SPAN WEIGHTS

Component	Transverse Deck Span		Longitudinal Deck Span	
	Parameters	Unit Weight (psf)	Parameters	Unit Weight (psf)
Steel Grid and Reinforcing Unit Weight[1]		10.2		15.5
Concrete Slab Unit Weight[2]		44.5		45.2
Stringer Spacing	8.25′		N/A	
Stringer Weight[3]	72 plf	8.7	N/A	--
Stringer Flange Width	9″		N/A	
Stringer Haunch Thickness	4.5″		N/A	
Stringer Haunch Weight[2]	32.3 plf	3.9	N/A	--
Floorbeam Spacing	25.0′		13.5′	
Floorbeam Weight (Plate Girder)[4]	180 plf	7.2	180 plf	13.3
Floorbeam Flange Width	14″		14″	
Floorbeam Haunch Thickness	4.5″		65″	
Floorbeam Haunch Weight[2]	50.3 plf	2.0	72.7 plf	5.4
TOTALS		76.5		79.4

Assumptions:

1. From BGFMA brochure and BGFMA Design Program (V3.1). (Transverse Deck Span: WT4x5 at 10″ and #6 Bars at 5″ and Longitudinal Deck Span: WT6x7 at 8″ and #6 Bars at 4″.)
2. Lightweight concrete with 5.5 ksi compressive strength and equilibrium unit weight of 115 pcf.
3. W24x68 rolled steel stringers with allowance for end connections, shear connectors, etc.
4. Welded built-up section with 1″x14″ flanges and 0.625″x36″ web with allowance for end connections, stiffeners, shear connectors, etc.

Optimized arrangements of each of these two configurations yield similar combined deck and floor system unit weights, in the range of 76 to 80 psf. Although, a transverse configuration uses a shorter deck span and permits use of a lighter steel grid, the additional weight of steel stringers and corresponding concrete haunches offsets the weight savings. The steel grid and reinforcing steel contributes to only 20 to 25% of the overall deck system weight, which range in unit weight from 10.2 to 15.5 psf, a variation of only 5.3 psf. Steel stringers add 9 to 18 psf to the floor system and corresponding concrete haunches add 3 to 6 psf depending on the stringer spacing and size. With a transverse deck span configuration, stringers permit floorbeams to be spaced further apart, yielding fewer floorbeams and corresponding concrete haunches. With a longitudinal deck span configuration, elimination of stringers and corresponding concrete haunches significantly reduces the weight of the system. However, a closer floorbeam spacing yields a greater number of floorbeams and corresponding concrete haunches. Steel floorbeams add 7 to 14 psf to the floor system and corresponding concrete haunches add 5 to 8 psf, depending on floorbeam spacing and size.

Although the transverse and longitudinal deck span configurations yield similar weight, the longitudinal configuration yields other advantages. With the deck made composite with the steel framing, orientation of the steel grid main bars and primary reinforcing parallel to the main girders, increases the deck steel area, which reduces the risk of deck cracking. Elimination of steel stringers simplifies the steel framing with fewer members and member connections.

For both configurations, additional simplification of the steel framing can be achieved with placement of the main girders near the edge of the deck so that short cantilever deck overhangs can be used, which permits elimination of cantilevered floorbeam brackets outboard the main girders. Exodermic deck also permits elimination of the lateral bracing system. The deck is a stiff horizontal diaphragm that laterally braces the steel framing system. The series of floorbeams with deep knee braces act to brace the main girders and distribute lateral loads to the deck. A temporary lateral bracing system, consisting of a series of rods, clevises, and turnbuckles, can be used to brace the steel framing and maintain alignment during erection until the deck is constructed. In addition to weight savings, the simplified steel framing reduces steel fabrication unit price and reduces future maintenance costs with fewer steel framing members and connections to maintain.

Exodermic deck is made composite with the floorbeams and main girders for additional structural efficiency from the increased strength and stiffness. Connection and composite action between the deck and steel framing is achieved with welded headed studs installed on the top flanges of the steel members between the grid main bars and a full-depth concrete haunch. Steel grid panels are typically supported on leveling bolts integrated into the panels. A small gap of 1.5″ to 2″ between the panels and top flange facilitates placement and consolidation of haunch concrete.

Deck System Flexural Design

Exodermic deck is a type of orthotropic deck with different flexural rigidity in primary and secondary directions. Like other deck systems, Exodermic deck design considers a combination of flexure (negative and positive moment) for loading between the supports, and axial forces from composite action and flexure of the supporting steel framing members. Wheel patch distribution to the steel grid components, composite behavior, and equations in *AASHTO LRFD Bridge Design Specifications* for computing the moment intensity (i.e. moment per unit width) were developed empirically with a combination of physical testing and three-dimensional finite element modeling. (NOTE: Terminology in the Design Specifications describe Exodermic deck as “Unfilled Grid Decks Composite with Reinforced Concrete Slabs”.)

For loading between supports, there are separate live load moment intensity equations (units of kip-in/in) for transverse and longitudinal (parallel) configurations, and deck span lengths above and below a threshold of 120″:

$$M_{transverse} = 1.28\ D^{0.197}\ L^{0.459}\ C, \text{ for } L \leq 120''$$
$$M_{transverse} = D^{0.188}(3.7\ L^{1.350} - 956.3)\ C / L, \text{ for } L > 120''$$

$$M_{parallel} = 0.73\ D^{0.123} L^{0.640}\ C, \text{ for } L \leq 120''$$
$$M_{parallel} = D^{0.138}\ (3.1\ L^{1.429} - 1088.5)\ C / L, \text{ for } L > 120''$$

Live load deflection limits (L/800) for Exodermic deck are mandatory and can govern the deck design. Similarly, there are separate live load deflection equations (units of in) for transverse and longitudinal (parallel) configurations:

$$\Delta_{transverse} = 0.0052\ D^{0.19}\ L^3\ C / D_x$$
$$\Delta_{parallel} = 0.0072\ D^{0.11}\ L^3\ C / D_x$$

where:

D is ratio of primary to secondary flexural rigidity, D_x / D_y
D_x is flexural rigidity ($E\ I_x$) in the primary direction per unit width of deck (units of kip-in^2/in)
D_y is flexural rigidity ($E\ I_y$) in the secondary direction per unit width of deck (units of kip-in^2/in)
L is deck span length center-to-center of supports (units of in)
C is continuity factor, 1.0 for simple span, and 0.8 for spans continuous over three or more supports.

Section properties including flexural rigidity for the composite deck system are computed using the transformed area method with cracked concrete properties, for evaluation of both negative and positive moment regions. Deductions are made for punched holes or slots in steel grid members.

Due to complexity of loading and load distribution, the above equations consider and envelope moment intensity and deflections for HL-93 design truck and tandem, already include live load factors (Strength I for moment intensity and Service I for deflections), dynamic load allowance and multiple presence factors, and account for load positioning to produce maximum effects.

For fatigue evaluation, moment intensity is computed by dividing the moment intensity values from the above equations for L < 120″ (regardless of actual span length) by 1.5. The equations for shorter spans more accurately estimate fatigue moment intensity as these equations appropriately reflect influence of a single truck or tandem, while the equations for longer spans reflect influence from multiple trucks or tandems. The 1.5 factor accounts for the smaller fatigue dynamic load allowance (15% vs. 33%), smaller load factor (Fatigue I Load Factor of 1.5 vs. Strength I Load Factor of 1.75), and elimination of multiple presence factor. Fatigue is evaluated for positive moment only with the deck conservatively supported as simple span between supports.

Concrete and reinforcing steel are continuous throughout the deck and discrete steel grid panels are typically continuous over multiple intermediate supports. The BGFMA has developed economical details for establishing flexural continuity of the steel grid deck panels at the joints between panels. In the primary direction, joints between steel grid panels are typically located over the intermediate supports, where the deck is subject to negative bending. The tension component is resisted by reinforcing steel in the top of the deck. The compression component in the main bar tees is transferred through the concrete haunch over the intermediate steel beam. The ends of the steel grid main bars include a short height bearing plate welded across the bottom ends, embedded within the concrete haunch with a gap between panels (Fig. 4). In the secondary direction, connection is with a full-depth haunch (Fig. 5).

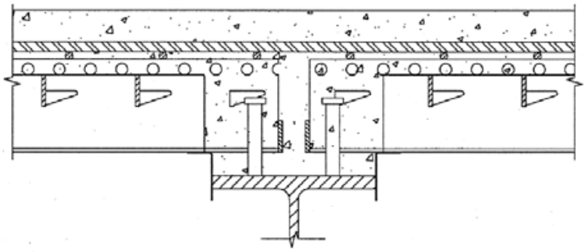


Figure 4 - Primary Direction Deck Splice

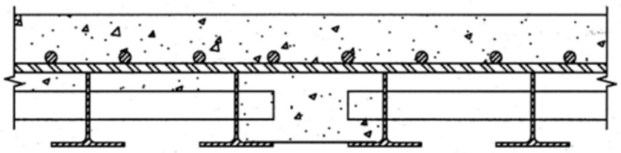


Figure 5 – Secondary Direction Deck Splice

Deck System Composite Design

Composite design for movable spans is generally like fixed bridges. However, there are some distinctions due to differences with the movable span structural configuration and introduction of Exodermic deck.

The elastic stress at any location on the composite section due to the applied loads shall be the sum of stresses caused by the loads applied separately to the steel section, short-term composite section (modular ratio, $n = E_s/E_c$), and long-term composite section (modular ratio, $3n$). For composite design, the stiffness of the design cross section used in computing member forces and deformations shall be based upon cracked (neglect concrete) and/or uncracked (concrete considered) section properties consistent with the anticipated behavior. Appropriate selection of cracked or uncracked section properties depend on the net combined force in the deck for the specified load combination. Where forces result in net deck compression, then the composite section assumptions (long or short term modular ratio and cracked or uncracked condition) corresponding to each force component should be used. Otherwise, cracked conditions should be used for all components of force.

Movable Span Specific Support, Loading and Member Forces

Dead load including deck, steel framing self-weight, and majority of counterweight ballast acts on the non-composite section (unshored construction), while superimposed dead load including traffic railing, pedestrian railing, span locks, navigation lights, counterweight adjustment blocks, etc., dead load dynamic load allowance during operation, and live load act on the composite section.

Although bascule spans are cantilevered during operation and top of the main girders subject to tension, because the deck concrete is placed while main girders are cantilevered, the concrete is subject to relatively small dead load flexural tension force from superimposed dead load and dynamic load allowance. Under live load, different regions of bascule and swing span main girders are subject to flexural compression, tension or combination of both. For double-leaf bascule spans, the engaged span locks change the support condition from cantilever to three-span continuous with central hinge, with each leaf effectively a propped cantilever with a flexible end support. The main girders are subject to negative flexure near the piers, and both positive and negative bending in the center region of the span. For single-leaf bascule spans, support of the tip end of the main girders at the rest pier changes the support condition from cantilever to simple span with overhang. The main girders are subject to positive bending for loading between the supports and negative bending on the overhang over the counterweight. For swing spans, the end lifts change the support condition from cantilever to two-span continuous. End lift reactions including corresponding reactions from temperature gradients introduce negative bending the length of the span.

The bascule leaf construction sequence can introduce large dead load forces in the composite deck that can increase risk of deck cracking. Care must be taken in design and construction to sequence the work to avoid these effects. Deck concrete is typically placed and cured while the main girders are in a cantilevered support condition with concrete placement starting at the tip end of the cantilever. The structure must be supported and ballasted such that bascule leaf remains stable during concrete placement. To maintain stability, the center of gravity must remain between two points of support. Prior to deck concrete placement, the bascule leaf is initially supported on the trunnions and temporary shoring below the counterweight. Counterweight ballast is added such that the bascule leaf is initially counterweight heavy with the center of gravity between the trunnions and shoring. As deck concrete is placed, the center of gravity shifts forward, near the trunnion. It is important that the majority of counterweight ballast be added before the deck becomes composite. Ballast placed after the deck becomes composite introduces tension force in the deck. If necessary, temporary ballast can be added to the span before deck concrete placement to simulate weight of superimposed dead load components and further reduce dead forces in the deck. Detailed construction balance calculations and support reaction monitoring is recommended to control the magnitude of dead load forces in the deck.

Swing span construction is like that of bascule spans, with two arms balanced about a pivot point, and require similar considerations. Two concurrent deck placement operations are typically used, with simultaneous placement starting at the tip ends of the two cantilevers.

With composite stringers, structural continuity is achieved by way of continuous deck and reinforcing steel and occasionally top and/or bottom flange splice plates (a.k.a. tie or strap plates) and are subject to a combination of positive bending in the center region of the span and negative bending near the floorbeams.

Where main girders consist of plate girders with limited torsional stiffness, floorbeams are effectively simple span and subject to positive bending between the main girders. Where main girders consist of box girders with high torsional stiffness, floorbeams experience negative bending near the main girders and positive bending in the center region. Where the deck cantilevers outboard the main girders, with or without cantilevered floorbeam brackets, the floorbeams are subject to negative bending for loading outboard the main girders.

Composite Section Properties

Plastic and yield moment capacity of the composite section is computed like that of steel girders with conventional reinforced concrete deck, but with steel area of the continuous steel grid components also considered in the calculation. In cases where the neutral axis falls within the limit of the steel grid main bar tees, the tees should be divided into tension and compression components as appropriate, like other structural steel components. Section properties are computed using transformed area method with cracked or uncracked properties as appropriate. Where members frame into other members (e.g. stringers and floorbeams), section properties must account for discontinuity, copes, connection angles and plates.

To control cracking, the *AASHTO LRFD Bridge Design Specifications* specifies minimum longitudinal deck reinforcement equal to 1% of the deck concrete area for the width of deck effective for the composite section. With Exodermic deck, the primary and secondary reinforcing is typically sufficient to meet this requirement for the slab portion of the deck. Supplemental steel reinforcing is needed in the concrete haunches to account for the additional concrete area. The Design Specifications permit the concrete to be considered effective for both positive and negative flexure for Service II loads if the tensile stresses in the concrete is less than twice the modulus of rupture. The additional steel area of the full section of continuous steel grid main bars can be considered in the composite section properties to reduce concrete flexural tension stresses.

For a transverse deck span configuration with series of closely spaced stringers, the effective flange width of the composite deck is like other parallel multi-girder bridges and taken as the tributary width between stringers. However, in both transverse and longitudinal deck span configurations, the effective flange width for main girders and floorbeams is computed differently. Due to shear lag effects associated with large spacing between main girders and floorbeams (greater than 16′), only a portion of the deck is effective in resisting flexure for these members. Per *AASHTO LRFD Bridge Design Specifications*, the effective flange width for these members shall be computed using refined analysis methods. The tributary width assumption may lead to an underestimation of the shear connector requirements and axial forces in the deck due to the global effects. The effective flange width overhanging each side of the member shall not exceed six times the slab thickness, one-tenth of the span length, or half the spacing between members. The slab thickness used in these calculations is the depth of the Exodermic deck, from top of concrete slab to the bottom of steel grid main bars. For cantilevered members, the span length shall be taken as two times the length of the cantilever span. Steel box girders have a significantly wider effective flange width than steel plate girders and can be used to increase main girder flexural tension resistance and crack control. For determination of live load deflection, the entire width of deck and structurally continuous portions of traffic railing curbs shall be considered.

Only components that are continuous can be considered in composite section properties. With Exodermic deck, concrete and reinforcing steel are continuous, while main bars and cross bars of the discrete panels are typically discontinuous. To increase flexural tension resistance and improve crack control, it is advantageous to establish continuity of the steel grid main bars in the region of deck subject to flexural tension. With a longitudinal deck span configuration, main bars and primary reinforcing bars are parallel to the main girders. Continuity of the main bars can be achieved by welding transverse plates to each end of the main bars and bolting the panels together. With a transverse deck span configuration, the smaller cross bars and secondary reinforcing bars are parallel to the main girders. As the primary direction includes 4 to 5 times more steel area than the secondary direction, the longitudinal deck span is significantly more effective than the transverse deck span in resisting main girder flexural tension and reducing concrete cracking. Where a transverse deck span configuration is used, a significant amount of supplemental reinforcing steel is needed to limit concrete cracking. Although plates can be welded to the cross bars, this is not commonly performed, due to the limited steel area added. As Exodermic deck already contains a relatively tight reinforcing spacing, supplemental reinforcing steel can be added to the concrete haunches as required. The region of deck subject only to positive bending does not typically require continuity of the steel grid bars or addition of supplemental reinforcing steel. Compressive resistance of the deck concrete and reinforcing steel is usually sufficient for flexural resistance.

Shear Connector Design

As with typical shear connector design, the design must satisfy both fatigue and strength provisions. Fatigue load combinations should consider shear range from both live load and dead load variation during bascule and swing span operation.

Like other longitudinal members, shear connector fatigue design for bascule and swing span main girders and stringers should be performed using a sectional analysis, with maximum longitudinal shear range computed by placing the fatigue live load immediately forward and back of each point under consideration. The shear influence line at each section can be used to identify proper load placement for maximum positive and negative fatigue shear values, with the shear range computed as the difference between these values. For floorbeams, maximum transverse shear range is the maximum positive or maximum negative shear resulting from lateral position of wheel lines that produces maximum effect, rather than the difference between maximum positive and negative shear. Shorter stringers and transverse floorbeams are subject to multiple cycles of fatigue loading from a single truck as multiple axle or axle groups separately load and unload the member during passage. For stringers and floorbeams, the fatigue resistance must be modified, accounting for the greater number of fatigue cycles. Concrete can be considered effective in fatigue design for positive and negative bending conditions if shear connectors are provided full length and minimum deck reinforcing area is provided. As bascule and swing span members are typically straight and have limited torsional resistance, the radial shear range component is usually small and can be neglected. The radial shear range component should be considered for torsionally stiff steel box main girders.

The geometrics of bascule and bobtail swing spans are such that the main girder top flange length is limited on the counterweight side of the cantilevered support point (live load shoes, trunnions, center of roll, center pivot bearing, etc.) and may not provide sufficient area to accommodate the number of shear connectors required to develop composite strength of the deck. The region over the support point is the location of maximum moment and typically governs the strength of the composite deck. It is necessary to develop the strength of the composite deck both forward and back of this point. The longer cantilever arm usually has sufficient length to accommodate the required number of studs, while the shorter counterweight arm may not have sufficient length. The geometrics of bascule and bobtail swings spans should be developed with consideration of the need to develop the deck strength in the region back of the support point.

As a significant length of bascule and swing span main girders is subject to negative bending or combination of positive and negative bending, the permitted omission of shear connectors in regions of negative bending is generally not practical. In addition, it is advantageous to use the provision that permits concrete to be considered effective in resisting flexural tension for additional efficiency; however, this also requires that shear connectors be provided full length. As such, it should be anticipated that shear connectors will be required the full length of main girders, and the steel girder design consider fatigue stress limits appropriate for the shear connector fatigue details.

Steel stringers typically consist of small rolled steel I-beams with relatively narrow top flange widths. Care must be taken in sizing the stringers to accommodate the number of shear connectors required to satisfy fatigue and strength provisions. A wide stringer spacing will typically yield greater structural efficiency but can result in a larger effective width and large composite deck strength that must be developed by a significant number of shear connectors. Minimum shear connector spacing and edge distance, narrow top flange width, and need to coordinate shear connector spacing with the steel grid bars limits the number of studs that can be accommodated.

All members within the steel framing system should preferably be made composite. Composite floorbeams and non-composite main girders should be avoided as this can result in localized spikes in deck forces at the intersections of these members from strain compatibility. For similar reasons, composite stringers and non-composite floorbeams should be avoided.

Lateral Bracing

The composite deck is effectively a large horizontal diaphragm that resists lateral loads and distributes these forces to the supports. The deck diaphragm action eliminates the need for a permanent lateral bracing system. Wind load on the upper half of the main girder, traffic and/or pedestrian railing, and vehicles is assumed to be directly transmitted to the deck. Wind load on the lower half of the main girder is assumed to be transmitted to the bottom flange. The bottom flange is subject to lateral flange bending between the floorbeams. Wind reactions at the floorbeams are transferred to the deck by way of the floorbeams and floorbeam knee braces.

The composite deck similarly acts as a large diaphragm when a bascule leaf is raised. The floor system weight is transmitted to the deck by way of their connection to the deck. The weight of deck and floor system is distributed to the main girders by way of diaphragm action, and then to the supports at the pier. When the bascule leaf is raised, floorbeams are subject to lateral loading from their self-weight. While the floorbeam top flange is restrained at the deck, the bottom flange is subject to lateral flange bending. For larger main girder spacing, intermediate support of the floorbeam bottom flange may be necessary to reduce the magnitude of the lateral flange bending. Rather than introduce a detail intensive “X” or “K” lateral bracing system, one or more lines of longitudinal bracing diaphragms that connect to the deck and utilize deck diaphragm action can be used. Longitudinal bracing diaphragms can consist of simple shallow rolled or welded built-up members with knees at the floorbeams that increase depth and brace the bottom flange. Where a transverse deck span configuration with stringers is used, one or more of the stringer lines can be used as the longitudinal bracing diaphragms.

Without a permanent lateral bracing system, a temporary lateral bracing system is needed during construction to maintain alignment of the steel framing and resist lateral loads until deck construction is complete. The temporary lateral bracing can consist of a simple system of steel rods, clevises and turnbuckles attached to temporary connection plates attached to the steel framing. Temporary bracing attached in the plane of the top flange will brace the steel framing in a manner like the deck. The temporary lateral bracing system can be removed after deck constriction is complete.

Deck Details

Recommended details, technical information, specifications, research documents, and guidance for Exodermic deck are available online at the website sponsored by the Bridge Grid Flooring Manufacturer's Association (http://www.bgfma.org/). Use of steel grid in the composite deck system requires additional detailing considerations and coordination during design and construction. Layout of the various components of the system must be considered including steel grid main bars, cross bars, reinforcing, splice plates and bolts, leveling devices, shear connectors, steel framing top flange splice plates and bolts, traffic railing post anchorage assemblies, and armored joint assemblies. Although the BGFMA recommended details can be incorporated in most movable bridges, as each movable bridge is effectively a prototype, customizing of these details and development of additional details should be anticipated.

As with other bridges with solid decks, deck drainage on bascule and swing spans should be considered. Although movement takes place at the joints between the movable span and fixed approach span, seals can be incorporated into the steel armored joint assemblies to minimize the amount of stormwater that passes the joints and collects on steel and machinery components below deck. The armored joint design and construction must consider the range of span movement, fabrication and erection tolerances to avoid interference during operation that can damage joint seals.

Construction

Lightweight concrete deck systems on movable bridges require construction considerations not typically required on conventional fixed bridges.

Fabrication tolerances for the deck steel grid components can be found on the BGFMA website and must be accounted for in the detailing and coordination. As steel grid panel weights can vary, especially with hot dip galvanized coatings, each panel should be shop weighed after fabrication, galvanizing, and installation of horizontal form pans for use in the construction balance calculations.

The lightweight concrete mix design must be developed so that the key physical properties assumed in the design are achieved. Strict control of the concrete density is critical on movable spans as the deck concrete accounts for a significant portion of the overall span weight and operating equipment design is significantly influenced by the weight. On bascule spans, concrete density also significantly affects the span balance and amount of counterweight ballast required to balance the span. As lightweight concrete density varies significantly between initial batching and equilibrium density, unit weight testing is performed during concrete mix development. The relationship between plastic and equilibrium density must be established during mix development, as the equilibrium density is considered for the final condition and plastic density is verified at time of placement. Ample time must be allotted to allow the test batches to reach equilibrium density, which can take more than 30 days. The verified equilibrium density must be available before construction balance calculations are completed. Unit weight testing is performed for each batch as the concrete is delivered to the site to verify that the density is within the specified tolerance. It is recommended to track the density of each batch as it is placed within the deck to assess the effect of the range in density on the balance. If the density of delivered concrete is found to be out of tolerance, adjustments can be made to subsequent batches so that the overall deck weight remains within the target range.

As deck concrete accounts for a significant portion of overall bascule span weight, and there is significant variation in concrete dimensions (deck slab and haunch thickness) and lightweight concrete density, larger adjustment pockets in the counterweights should be considered to permit a greater amount of balance adjustment. Counterweight adjustment pockets sized for a backward moment with pockets empty equal to 5% under the forward moment, and backward moment with pockets full equal to 7.5% over the forward moment, are typically sufficient to balance the span with adjustment blocks.

On most bridges, the deck is screeded to a specified profile grade. Due to the importance of controlling weight of the movable span, it is more critical to control the thickness of the deck and haunches than it is to achieve a specific profile grade. Small variations in profile grade are typically imperceptible over the length of the movable span. It is also important to control deck alignment at the joints between the movable span and fixed approaches. Differential surfaces on opposite sides of the joints and discontinuities should be avoided as these conditions can be felt by motorists and increase dynamic effects. Adjustment of live load shoes on bascule spans and end lifts on swing spans can be used to vertically align the joints. However, as it is preferable to maintain equal reactions on these devices, there are limits to which they should be used to twist the span and adjust cross slope. Work should be planned, and alignment monitored throughout shop fabrication, field erection, and deck construction to achieve proper deck vertical alignment and cross slope. Blockouts in the approach deck can be used to transition deck surfaces after the movable span is properly aligned and adjusted. On double-leaf bascule spans, care must be taken to match cross slopes at the joint between the two leaves. After the deck on the first leaf is constructed, the deck on the second leaf can be adjusted to match. To achieve a uniform deck and haunch thickness and alignment of the deck surfaces at the joints, steel grid panels are adjusted and aligned using leveling devices built into the panels and/or shims between the main bars and steel framing members. It is critical that the steel grid panels are properly supported at each steel framing member at multiple positions, so that deformation of the panels is minimal during concrete placement. When properly supported, deflection of the steel grid panels is minimal. With uniform deck and haunch thickness, profile grade is dependent largely on the built-in cambered shape in the steel framing, and corresponding fabrication and erection tolerances. After the panels are properly adjusted and aligned, deck reinforcing can be placed and tied, and screed rails installed and aligned. Screed alignment should be tested prior to concrete placement to verify that the proper deck thickness will be achieved.

Although Exodermic deck includes built-in horizontal form pans for the slab and vertical form pans for the haunches, supplemental forms are typically required along the edges of the steel framing due to the gap between the bottom of the steel grid panels and top of the steel members. Supplemental forms typically consist of, stay-in-place sheet metal angles, or removable timber studs temporarily secured to the sides of the top flange and underside of the panels. Adhesive backed foam strips secured to the top flange of the steel beams below the vertical form pans can also be considered if haunch heights are less than 1". This may require the installation of a high strength pourable grout prior to the concrete pour to ensure complete bearing between the bottom of the WT main bearing bar and the support. Holes in the steel grid main bars should be taped and seams along the form pans and supplemental forms should be caulked on the concrete sides to minimize leakage during concrete placement. Additional supplemental forming is also typically required for the coping and edge beams.

Where a short cantilever deck overhang is used outboard the main girder, standard temporary overhang brackets can be used. As screed rails are supported directly or indirectly from the steel framing, the screed rails normally deflect consistently with the steel framing and deck during concrete placement, and thus no vertical adjustment of the screed rails is required. Where screed rails are supported by overhang brackets, care must be taken to select brackets so that the bottom of the bracket diagonal strut bears near the main girder bottom flange. If the strut bears on the main girder web away from the bottom flange, the horizontal component of the strut reaction can cause the web to deform out of plane with corresponding vertical deflection of the ends of overhang bracket that can affect screed rail vertical alignment. With variable depth main girders, a series of overhang brackets with different heights should be used so that the horizontal strut bears near the main girder bottom flange.

Welded headed studs are typically installed through the deck after steel grid panels are in place to meet OSHA fall protection requirements.

Movable bridges typically require electrical conduit and wiring that extends along the deck from the piers to the tip end of the spans for equipment such as span mounted span locks, end lifts, navigation lights, and roadway lighting. Size and routing of the conduit and location of junction boxes should be planned. Due to the limited thickness of the deck slab, routing of the conduit in the slab is generally not recommended. Routing through main girder and floorbeam haunches and/or traffic or pedestrian railing curbs is preferable.

As discussed above, deck placement and support conditions must be planned to minimize the amount of weight added to the span after the deck becomes composite to reduce the risk of cracking. The construction balance plan must be consistent with the assumptions made in the design.

Concrete placement can be performed using crane and buckets hoppers, manual or propelled buggies, chutes and drop pipes, conveyor belts or pumping. As lightweight concrete is more prone to segregation, it should not be allowed to free fall more than 5′. Pumping of lightweight concrete should be planned well in advance beginning from concrete mix development. Pumping may result in the reduction of slump and/or air content. Therefore, the concrete mixture should be proportioned to achieve the desired fresh concrete properties at the point of placement. Aggregate must be adequately pre-soaked as pressure during pumping will drive water into the aggregate pores and cause slump loss that may result in plugging of the pump line and difficulties in placement and finishing. Pump lines should be as large as possible, preferably 5″ diameter, with a minimum number of elbows, reducers or rubber hose sections. Lowest practical pump pressure should be used. Pump location should be such that vertical fall of the concrete is minimized. Air entrainment in the range of 4 to 7% should be specified for optimal pumpability, workability, finishing, and durability. Concrete testing should be performed at the end of the discharge line rather than at the truck.

Concrete can be screeded with either Bidwell or razorback type screeds. Experience has shown that the more heavy-duty Bidwell screeds are typically more effective with lightweight concrete and yield more uniform deck thickness and superior finish. Workability of lightweight concrete is generally comparable to normal weight concrete having 1 to 2″ greater slump. Slump ranging from 1 to 3″ is typically recommended for floor slabs, although this slump can be increased with addition of admixtures. Care should be taken to avoid excessive floating and vibrating due to potential for the lighter aggregate to segregate (float). Vibrators should be used to properly consolidate the concrete in the deck, haunches, and gaps between the steel grid main bars and top of the steel framing.

Exodermic deck with lightweight concrete can be cured like other normal decks. A 7-day wet cure is recommended. A cast-in-place concrete deck for a bascule span must remain lowered until the concrete has achieved a minimum compressive strength. As the cantilever flexure is partially relieved when the span is raised, the deck will undergo compression as it is raised. Typically, a compressive strength of 50% of the specified minimum compressive strength or 2.5 ksi is sufficient for moving the span. Experience has shown that it is difficult to effectively wet cure bascule span decks in the raised position. A temporary piping system can be considered; however, the water system must have sufficient head to deliver water to the top of the raised span. Curing blankets must be adequately secured against wind so that they remain in contact with the concrete surface. Due to these challenges, the bascule span usually remains in the lowered position during curing. The span can be raised for a brief period, if an opening is required, provided it is returned to the lowered position. Lightweight concrete can be profiled and grooved like normal weight concrete after curing.

The overall deck construction sequence can take 3 to 4 weeks per bascule leaf for cast-in-place deck system. The bascule leaf steel framing must remain lowered while the deck panels are placed, adjusted and aligned, reinforcing placed and tied, haunches formed, screed rails installed and aligned, deck concrete placed, finished, and cured. Alternatively, precast Exodermic deck panels can be used on a bascule span to reduce the duration that navigation traffic is impacted. Reinforcing steel and concrete is added to the steel grid panels at an offsite location with blockouts over the steel framing members that permit cast-in-place field closures. Deck continuity is achieved with reinforcing lap splices and steel grid main bar bolted splices in the blockouts between panels. The precast panels contain temporary angles bolted to the underside of the panel that bear against the floorbeam top flange, to secure the panels in the raised position. After all panels are installed and aligned, haunches formed, and shear connectors installed, the bascule span is lowered, and high-early strength lightweight concrete placed in the blockouts. As the cast-in-place concrete only consists of closure strips, screed rails are not required. Closures can be placed and cured with the span lowered for no more than 8 hours. Additional concrete cover is added to permit profiling the entire deck surface. A detailed construction balance plan, is required to permit safe raising and lowering of the span. A temporary drive system may also be required with this approach. Care must be taken to prevent damage of the panels during lifting, handling, and transportation.

Pre-work meetings are recommended in advance of the above activities.

Summary

Use of concrete in movable span decks yields many advantages over steel open grid decks including improved protection of the steel framing, greater skid resistance, reduced traffic generated noise, better fatigue resistance, and consistent surface. Lightweight concrete offers advantages over normal concrete including enhanced durability and significant reduction in weight that reduces the size and cost of operating equipment and counterweight ballast. Lightweight concrete can be combined with fabricated steel grids and made composite with the steel framing to yield further reduction in weight, increase structural efficiency, enhance crack control, and provide opportunities to simplify the steel framing. Weight comparisons of different lightweight concrete deck systems reveal that Exodermic deck yields the lowest weight solution. A longitudinal deck span configuration, where the deck spans between floorbeams without stringers, offers advantages over transverse deck span configurations with stringers. Design and construction of movable spans with Exodermic deck requires special considerations, different from conventional steel bridges with composite concrete decks.