BASCULE BRIDGE LIGHTWEIGHT SOLID DECK RETROFIT RESEARCH PROJECT

DECK ALTERNATIVE SCREENING REPORT

FINAL

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Prepared for:

Florida Department of Transportation

Structures Design Office

Prepared by:

URS Corporation, Inc.
7650 West Courtney Campbell Causeway, Suite 700
Tampa, Florida 33607

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TABLE OF CONTENTS

1.0 INTRODUCTION AND EXECUTIVE SUMMARY

1.1 PROJECT NEED

The deck on the majority of bascule bridges in Florida consist of steel open grid roadway flooring, except for the portion of deck over the machinery room, which consists of concrete filled steel grid roadway flooring to protect the operating equipment below. The original decision to use steel open grid deck was primarily to reduce weight and thus reduce load on the structure and operating equipment with corresponding cost savings. At the time the majority of these bridges were constructed (from the mid 1950's through the early 1970's) steel open grid deck was considered the only available and practical lightweight deck system.

However, steel open grid deck has been problematic for a number of reasons including:

- Openings in the deck permit dirt and debris to collect on the steel framing members below. The dirt and debris retains moisture that contains chlorides from the saltwater environment, which is conducive to corrosion development. The network of steel grid bars makes cleaning of the steel framing members difficult.
- Although the deck typically includes a serrated top surface to improve skid resistance, the top surface polishes over time from contact with wheels, which eventually reduces the skid resistance, especially when wet, and reduces safety.
- The welded fabrication of the steel open grid deck includes numerous fatigue sensitive details (Category E Details per AASHTO LRFD) that are prone to fatigue development and as such the deck design is typically governed by fatigue provisions. Bridges with heavier truck traffic have commonly experienced premature fatigue cracking and localized failure of the secondary and tertiary bars that result in larger holes in the deck.
- Fabrication tolerances of both the steel open grid deck and bascule leaf steel framing have resulted in difficulties in achieving uniform bearing of the deck main bars on the supports. Excessive root openings and poor field welding practices have resulted in widespread cracking of the deck attachment welds.
- Tires in contact with the network of steel open grid bars and corresponding openings between the bars create resonant vibrations that generate noise that is considered a nuisance to residences and businesses nearby these bascule bridges.
- The relatively large openings in the deck and the slippery surfaces make crossing the bascule span on a bicycle a challenge. The bicycling community considers steel open grid deck a safety concern.

Over the past 60 years, the Florida Department of Transportation has invested considerable resources in addressing the above concerns including frequent repairs and replacement of the decks, and research and development to address the safety and functionality concerns including methods to improve skid resistance, wheel paths to reduce noise, and implementation of bicycle friendly surfaces in the shoulder areas.

The Department has recognized for many years that a deck with a solid surface solves most if not all of these issues. Most new bascule bridges in Florida, constructed since 1999, have included a lightweight solid deck with a concrete riding surface. There have been a number of deck systems classified as lightweight solid deck systems that have been used on new bascule bridges throughout the United States and abroad including:

- Conventionally Reinforced Concrete Slabs using Lightweight Concrete,
- Concrete Filled Steel Grid Deck (a.k.a. Grid Reinforced Concrete) using Lightweight Concrete,
- Exodermic Deck using Lightweight Concrete,
- Steel Orthotropic Deck.

However, because the weight of these deck systems is significantly greater than those of steel open grid deck and there are limitations in the amount of weight that can be added to an existing bascule bridge, it is not practical to use these deck systems to retrofit existing bascule bridges. Therefore these deck systems were not evaluated in this study.

1.2 DECK SELECTION FACTORS

1.2.1 General

There are a number of factors that should be considered in the selection of a lightweight solid deck system to replace steel open grid deck on typical Florida bascule bridges. These factors include:

- Costs including:
    - Deck fabrication and installation,
    - Modifications to the bascule leaf steel framing, bascule pier, flanking spans, counterweight, and trunnion assemblies required to implement the new deck system,
    - Design and construction inspection for the new deck system,
    - Future maintenance and inspection.
- Functionality and Safety including:
    - Load capacity (i.e. support of legal loads and permitted overloads),
    - Improved riding surface and skid resistance for vehicular and bicycle traffic,
    - Reduced traffic generated noise.
- Maintenance including:
    - Ease of repair and/or replacement of all or portions of the deck,
    - Need for periodic maintenance (e.g. reapplication of coatings and/or replacement of wearing surfaces).
- Service-life and Durability including:
    - Deck and/or deck component (e.g. wearing service, fasteners, etc.) service-life,
    - Resistance to corrosion, fatigue, wear, impact, fire, ultraviolet light, and chemicals,
    - Accommodation of thermal movements.
- Constructability including:
    - Disruption to traffic (e.g. overall construction duration, maintenance of traffic),

- Ability to accommodate fabrication and installation tolerances,
  - Sensitivity to environmental conditions during construction,
  - Shipping, storage and handling,
  - Specialized inspection requirements during fabrication and installation.
- Other Risks including:
  - Familiarity of the product and technology (e.g. years' experience, previous bridge installations, quantity and quality of applicable research, endorsement by bridge design community and AASHTO),
  - Availability of design tools and construction techniques,
  - Financial and technical support from supplier(s),
  - Product availability (e.g. opportunities for competitive bidding, sole source and/or patents).

1.2.2 Weight Considerations

In addition to the above factors, it is critical that the weight of a lightweight solid deck system including all associated appurtenances, wearing surfaces, and modifications to the bascule leaf required to implement the new deck, be as close as possible to that of the existing steel open grid deck that it will replace. Because a bascule leaf is typically balanced to reduce the power required to operate the bridge, weight added to the bascule leaf forward of the trunnions (i.e. forward of the pivot point) requires corresponding weight in the counterweight to yield a balanced condition. Furthermore, because the length of the counterweight is significantly shorter than the length of the bascule leaf, the weight added to the counterweight is typically two to three times the weight added forward of the trunnion.

Steel open grid deck found on most Florida bascule bridges consists of standard duty, hot dip galvanized, diagonal roadway flooring (a.k.a. 5-Inch 4-Way Decks with main and secondary bars in an orthogonal configuration, and tertiary bars in a diagonal configuration) with a unit weight of approximately 21 (pounds per square foot). The steel open grid deck used when the bridges were first constructed from the mid 1950's through the early 1970's typically consisted of painted rectangular grid decks (i.e. main, secondary and tertiary bars in an orthogonal configuration) with a unit weight of approximately 18 psf. Additional ballast was added to the counterweights when these decks were replaced. Many additional repairs and modifications have typically been performed on these bridges since they were originally constructed that has increased the weight of the bascule leaves. These repairs and modifications have typically included addition of steel reinforcing plates, replacement of structural members with new heavier members, replacement of span lock assemblies with new heavier duty equipment and access platforms, modifications to the bridge railings for safety purposes, addition of strips of concrete to the steel open grid deck in the wheel lines to reduce traffic generated noise, et al and corresponding addition of ballast to balance the span. Some attempts to offset the increased weight have been made including the use of lighter weight aluminum components, where practical.

There are a number of factors that limit the amount of weight that can be added to existing Florida bascule bridges including limited trunnion capacity, space to accommodate additional counterweight ballast, and structural capacity of the main girders.

The trunnion assemblies found on most existing Florida bascule bridges were originally designed for lighter loads and have little or no reserve capacity. As such, increased bascule leaf weight is anticipated to overload the trunnion assemblies, which will reduce the service life and/or result in premature failure of trunnion assembly components. Increasing the loads on the trunnions beyond recommended limits is not recommended because of anticipated:

- Accelerated wear of the bronze bushings,
- Increased structural deformation of the trunnion shafts and trunnion girders that affects trunnion alignment with corresponding edge loading of the shaft journals on the bearing bushings,
- Higher fatigue stresses,
- Significant vehicular and navigation traffic impacts, costs, and technical challenges to remove and replace the trunnion assemblies.

Factors that limit the amount of ballast that can be added to the counterweights on most Florida bascule bridges include:

- Limited space in the counterweight adjustment pockets,
- Limited clearance between the top of the counterweight and underside of the bascule pier or flanking span deck with the bascule leaf in the lowered position,
- Limited clearance between the underside of the counterweight and the machinery platform and operating equipment with the bascule leaf in the raised position,
- Limited space and technical challenges with mounting ballast to the rear counterweight girder,
- Limited structural capacity of the bascule leaf main girders.

There are means to offset the increase in weight of a heavier deck system by replacing other elements of the bridge with lighter components (e.g. replacement of the steel sidewalk grating, sidewalk support members, bridge railings, and curb assemblies with lighter aluminum or fiber reinforced plastic (FRP) members.) However, this strategy involves replacement of members that do not otherwise require replacement and thus adds additional work and cost, and should generally be avoided where practical. Because a portion of the existing bascule leaf deck consists of 3-inch deep concrete filled steel grid deck with a typical unit weight of approximately 50 psf, there are opportunities to reduce weight be also replacing this portion of deck with the lightweight solid deck system when the steel open grid deck is replaced. However, because the concrete filled steel grid deck is near the trunnion assemblies, there is not a significant corresponding reduction in the amount of ballast in the counterweight with this replacement.

Considering all of the above limitations and potential offsets, the maximum unit weight for lightweight solid deck system that can be accommodated is approximately 25 psf.

It may be possible to offset the increase in weight of a lightweight solid deck system by taking advantage of improved structural efficiency including greater strength, stiffness, structural continuity, and/or composite behavior of the new deck system to eliminate or reduce the number and/or size of existing stringers supporting the deck. However, this may require additional modifications to the bascule leaf steel framing system, bascule piers and/or flanking span structure that may not otherwise be required.

1.2.3 Deck Thickness Considerations

Proposed lightweight solid decks may have thicknesses that are different than the thicknesses of existing 5-3/16" deep steel open grid deck and/or 3" deep concrete filled steel grid deck found on typical existing Florida bascule bridges. The steel grid deck is typically supported directly on the rolled steel stringers and on steel spacer bars on the main girders, floorbeams and forward counterweight girder. On some Florida bascule bridges with Hopkins frame drive systems, the existing concrete filled steel grid deck is also supported directly on the rack girders.

The difference in thickness between the new lightweight solid deck system and existing steel grid deck must be addressed in the detailing of the deck support members. Lightweight solid deck systems with a thickness similar to that of the existing steel grid deck will require fewer modifications to the existing bascule leaf framing system.

Lightweight solid deck systems with a thickness greater than the existing steel open grid deck will result in a roadway surface that is higher than the existing roadway surface. Modifications required to raise the roadway surface on the bascule pier and/or flanking span deck surface to match that on the bascule leaves will be significant including:

- Adjustment of the approach span deck profile to match the raised deck on the bascule leaf by lifting the end at the bascule pier by installing a fill at the flanking beam floorbeam bearings,
- Replacement of the bascule pier sidewalk or raising of the sidewalk by pouring a new sidewalk slab on top of the existing sidewalk slab,
- Raising the bascule leaf sidewalk by replacing the sidewalk support framing, curbs, sidewalk grating, pedestrian railings, and span lock access hatches,
- Raising the control house floor and doors, flooring, floor hatches, ladders, plumbing, control desk, electrical penetrations, etc.

Because of the magnitude of the required modifications, raising the roadway surface should be avoided.

Lightweight solid deck systems with a thickness less than the existing steel open gird deck will require details that make up the difference between the top of the bascule leaf steel framing members (stringers, main girders, floorbeams and forward counterweight girder) and the underside of the deck. This can include setting the top of the stringers at a higher position. However, because it is generally not practical to modify the height of the top flange of the main girders, floorbeams and/or forward counterweight girder, it will be necessary to develop alternative details that allow for support and attachment to the top flanges at these locations or additional members that permits support of the deck that avoids support on these members.

1.2.4 Deck Attachment Considerations

Each lightweight solid deck system uses a different method for attaching the deck to the bascule leaf steel framing. A number of factors should be considered in attaching the deck to the bascule leaf steel framing including the following:

- Existing steel grid deck is typically field welded to the top of the steel stringers and spacer bars on the main girders, floorbeams and forward counterweight girder and the current bascule leaf steel framing details are geared toward these welded attachments that may not be conducive to the attachment of alternative deck systems.
- The solid deck surface may make attachment of the deck from the top side difficult or impractical and thus the details may need to include access from below.
- Details vary from bridge to bridge (e.g. riveted built-up construction or welded built-up construction of the main girders, floorbeams, and forward counterweight girder) that can affect the attachment details.
- Differences in coefficients of thermal expansion between the deck material and the steel bascule leaf framing may require the need for provisions to accommodate associated thermal movements if restraint forces are determined to be excessive.
- Tolerances in steel fabrication and erection may result in non-uniform support conditions that need to be addressed in the connections.
- Use of dissimilar metals can produce conditions conducive for galvanic corrosion and thus it may be necessary to implement measures to mitigate this concern including strategic selection of materials and separation of dissimilar metals.

1.2.5 Bascule Leaf Framing System Considerations

Although there are similarities in the structural configuration of typical Florida bascule bridges, there are also a number of variations in the configuration. The lightweight solid deck system must be able to accommodate a wide range of dimensions and possible configurations using standard details.

The steel framing system for typical Florida bascule bridges all include a framework of:

- Two (2) longitudinal main girders,
- Multiple, parallel, transverse floorbeams that span between the main girders,
- Multiple, parallel, longitudinal steel stringers located between the main girders and that span between the floorbeams,
- Steel grid deck (5-3/16” deep steel open grid deck and 3” deep concrete filled steel grid deck over the machinery room) that spans transversely, extends from outboard edge to outboard edge of main girders, and is supported on the top of rolled steel stringers, and spacer bars on the top flange of the main girders, and floorbeams,
- Transversely level roadway surface with no cross slope or crown.

However, numerous differences can exist from bridge to bridge including:

- Two (2) travel lanes with a clear roadway width of 26 feet to 32 feet between curbs and with no traffic separator, or four (4) travel lanes with a clear roadway width of 42 feet to 48 feet between curbs with a mountable traffic separator (raised median),
- Double-leaf or single-leaf configuration,
- One or two sidewalks that are either raised or at the same level behind curbs,
- Five (5) or six (6) floorbeams (including the forward counterweight girder) spaced from 15 feet to 20 feet on center,
- Varying number of stringers spaced from 4 feet to 4.5 feet on center,
- Curbs that separate the roadway from the sidewalk either located outboard the steel grid deck or attached to the top of the grid deck over the main girders.

Although the majority of older typical Florida bascule bridges do not currently include crash-tested traffic railings that separate the roadway from the sidewalk, the Department has a program to incorporate these traffic railings were practical and where warranted. In most configurations, the traffic railing would be mounted to the bascule leaf steel framing outboard the main girders and not mounted to the bascule leaf deck. However, there may be isolated conditions where it may be necessary to mount the crash-tested traffic railing to the deck including temporary traffic railings for future traffic control purposes. As such, the lightweight solid deck system must be able to accommodate mounting of a crash-tested traffic railing and to resist the vehicular impact loads transferred to the deck without damage.

Roadway drainage of the solid surface is not considered to be a concern with transversely level roadway surface. As such, the introduction of a roadway cross slope and/or crown is not recommended. The bascule span is typically located at or near the peak of the roadway vertical profile and as such the area of bridge deck that collects the stormwater is limited. The longitudinal profile grade will act to channel stormwater off of the bascule span.

1.2.6 Constructability Considerations

Most existing Florida bascule bridges are located in urban areas with relatively high volumes of vehicular traffic and over active navigation channels that require frequent bridge operation. Bascule leaf deck replacement can have significant impacts on the traveling public. The modular configuration of steel open grid deck has typically permitted rapid replacement of the deck, and associated stringers where required, with minimal disruptions to traffic, using:

- Short duration nighttime bridge closures, when traffic volumes are low, and restoration of vehicular traffic during daytime periods, or
- Phased construction with replacement of half of the deck at a time while vehicular traffic is maintained on the bridge.

Lightweight solid deck systems should be able to accommodate replacement in a similar manner with either of the above construction approaches where required to reduce traffic impacts.

Lightweight solid deck fabrication and erection tolerances (e.g. flatness, squareness, sweep, camber, length, width, thickness, etc.) should permit proper alignment and fit-up of the deck without unnecessary field modifications, construction delays, or poor final workmanship. Construction requirements should generally avoid or minimize the need for specialized shop and/or field inspection equipment and personnel, although critical deck material and physical properties should be verifiable by testing. Quality of the field installation should not be sensitive to environmental conditions. The lightweight solid deck system should have the capability to be field installed by typical bridge rehabilitation contractors.

1.2.7 Design Considerations

Design methodology used to confirm the lightweight solid deck design should be relatively simple, straightforward, and easily understood by qualified design professionals. Calculations to verify the deck design and load rating should generally be based on conservative, simple closed-form equations and not sophisticated, in-depth finite element analysis. Design methodology should be endorsed by AASHTO and included in the *AASHTO LRFD Bridge Design Specifications* for use in consistent application by the bridge design community.

It is preferred that the lightweight solid deck technology is generally familiar to the bridge design community, has a significant positive track record in similar applications, and is supported by applicable sound and reliable research and testing.

1.2.8 Financial and Technical Support Considerations

It is preferred that the lightweight solid deck system be a non-proprietary product, with opportunity for competitive bidding, and without royalty payments. Where the lightweight solid deck system is proprietary, without similar competitive products, the deck supplier should have sufficient financial support to ensure that the product is available in the future and that there is corresponding technical support.

1.2.9 Maintenance and Durability Considerations

The lightweight solid deck primary structural system should be durable with a service life with that will outlast the remaining service life of the typical Florida bascule bridges to receive the deck. Required maintenance should be minimal and the intervals between required maintenance should be consistent with other Florida bascule bridge maintenance activities (e.g. duration between steel cleaning and painting, electrical and mechanical system repairs, etc. which typically is every 10 to 15 years.) The lightweight solid deck should be capable of both localized repair (patching) on short notice using typical Department maintenance crews, and replacement of individual deck panels with advanced notice. Procurement duration should be similar to that required for steel open grid panels. Deck systems with closed voids should have means to access the interior spaces for periodic inspections (e.g. access holes for cameras.)

1.3 LIGHTWEIGHT SOLID DECK SYSTEM EVALUATION

1.3.1 Evaluated Deck Systems

In the past 15 years, new materials and technologies have developed that introduce new lightweight solid decks with weights similar to that of steel open grid deck and potential of solving the issues with steel open grid deck. This study investigates and evaluates these new deck products in detail to determine whether there is a viable lightweight solid deck to replace steel open grid decks on typical Florida bascule bridges. Alternative deck products that are investigated include:

- Sandwich Plate System (SPS) Deck by Intelligent Engineering
- Aluminum Orthotropic Deck by Sapa Group
- Fiber Reinforced Polymer (FRP) Composite Deck by ZellComp, et al.
- Ultra-high Performance Concrete (UHPC) Waffle Slab Deck by FIU/UCF.

1.3.2 Evaluation Process

The alternative lightweight solid deck systems are investigated and evaluated for the deck selection criteria described above. The investigation included thorough review of available literature, research and testing and review of in-service performance of the deck systems in similar applications. Conceptual level engineering development was performed for each of the deck systems to estimate the deck weight and corresponding span balance requirements, and required structural modifications.

A Value Engineering (VE) approach was used to provide a reasonable, quantifiable evaluation and comparison of the different alternatives. The existing steel open grid deck was used as the baseline for the evaluation and comparison. The alternative lightweight solid deck systems were scored and compared to steel open grid deck to determine whether the alternative deck system would add value, and compared with each other to determine which deck offered the most value. In the VE approach, each of the evaluation criteria is assigned an importance factor, in the form of a percentage of the overall importance that the criteria are considered in the evaluation. Each of the alternative deck systems is assigned a value of 1 to 9 for each of the criteria that represent an assessment of the capability of the deck to addresses the criteria in comparison to steel open grid deck. Steel open grid deck is assigned a baseline value of 5 for each of the criteria. Values for the alternative deck systems higher than 5 indicate that the alternative is superior to steel open grid deck for that criteria, while values lower than 5 indicate that the alternative is inferior to steel open grid deck, and values equal to 5 indicate that the alternative is generally equivalent to steel open grid deck. The values are multiplied by the importance factor (percentage) and summed to yield a total ranking.

FDOT LIGHTWEIGHT SOLID DECK RESEARCH PROJECT VALUE ENGINEERING COMPARISON OF ALTERNATIVES											
EVALUATION CRITERIA	CRITERIA IMPORT. FACTOR	DECK ALTERNATIVES									
		STEEL OPEN GRID		SPS		SAPA ALUM.		ZELLCOMP FRP		FIU UHPC	
		BASE	FACTORED	BASE	FACTORED	BASE	FACTORED	BASE	FACTORED	BASE	FACTORED
WEIGHT	(1-100)	19 psf	21 psf	22 psf	27 psf	17 psf	21 psf	16 psf	21 psf	34 psf	38 psf
COST	**20.0**										
Deck	5.0	5	25.0	3	15.0	2	10.0	4	20.0	3	15.0
Counterweight	5.0	5	25.0	3	15.0	5	25.0	5	25.0	1	5.0
Trunnion	5.0	5	25.0	3	15.0	5	25.0	5	25.0	1	5.0
Structural Mod.	2.0	5	10.0	4	8.0	4	8.0	4	8.0	4	8.0
Maintenance	2.0	5	10.0	5	10.0	5	10.0	5	10.0	7	14.0
Design	0.5	5	2.5	3	1.5	5	2.5	5	2.5	5	2.5
Inspection	0.5	5	2.5	3	1.5	5	2.5	3	1.5	5	2.5
FUNCTIONALITY AND SAFETY	**25.0**										
Load Rating	5.0	5	25.0	5	25.0	5	25.0	5	25.0	5	25.0
Rideability	5.0	5	25.0	7	35.0	9	45.0	7	35.0	9	45.0
Skid Resistance	5.0	5	25.0	9	45.0	9	45.0	9	45.0	9	45.0
Noise	5.0	5	25.0	9	45.0	7	35.0	9	45.0	9	45.0
Bicycle Safety	5.0	5	25.0	9	45.0	9	45.0	9	45.0	9	45.0
MAINTENANCE	**15.0**										
Ease of Deck Repl./Repair	7.5	5	37.5	3	22.5	5	37.5	3	22.5	3	22.5
Wearing Surface Maintenance	5.0	5	25.0	3	15.0	3	15.0	3	15.0	5	25.0
Other Maintenance (Coatings)	2.5	5	12.5	5	12.5	7	17.5	7	17.5	9	22.5
SERVICE-LIFE AND DURABILITY	**15.0**										
Deck Service Life	4.0	5	20.0	9	36.0	9	36.0	3	12.0	9	36.0
Wearing Surface Service Life	2.0	5	10.0	2	4.0	3	6.0	2	4.0	5	10.0
Corrosion Resistance	2.0	5	10.0	7	14.0	8	16.0	9	18.0	7	14.0
Fatigue Resistance	2.0	5	10.0	7	14.0	7	14.0	5	10.0	7	14.0
Wear Resistance	1.0	5	5.0	7	7.0	7	7.0	7	7.0	7	7.0
Impact Resistance	1.0	5	5.0	9	9.0	7	7.0	3	3.0	7	7.0
Thermal Expansion	1.0	5	5.0	5	5.0	3	3.0	3	3.0	5	5.0
Ultraviolet (UV) Light	1.0	5	5.0	5	5.0	5	5.0	3	3.0	5	5.0
Fire Resistance	0.5	5	2.5	5	2.5	3	1.5	1	0.5	7	3.5
Chemical Resistance	0.5	5	2.5	5	2.5	5	2.5	5	2.5	5	2.5
CONSTRUCTABILITY	**10.0**										
Maint. of Traffic/Constr. Dur.	4.0	5	20.0	3	12.0	5	20.0	5	20.0	3	12.0
Field Adjustment/Tolerances	2.0	5	10.0	5	10.0	5	10.0	5	10.0	5	10.0
Sensitivity to Envir. Cond.	2.0	5	10.0	5	10.0	5	10.0	5	10.0	5	10.0
Shipping/Storage/Handling	1.0	5	5.0	5	5.0	5	5.0	5	5.0	5	5.0
Specialized Inspection	1.0	5	5.0	3	3.0	5	5.0	3	3.0	3	3.0
OTHER RISKS	**15.0**										
Years Product Experience	3.0	5	15.0	1	3.0	3	9.0	1	3.0	1	3.0
Previous Bridge Installations	3.0	5	15.0	2	6.0	3	9.0	3	9.0	1	3.0
Available Design/Const. Tools	2.0	5	10.0	3	6.0	5	10.0	3	6.0	3	6.0
Research (Quantity, Quality)	2.0	5	10.0	5	10.0	5	10.0	5	10.0	2	4.0
Technological Uncertainty	2.0	5	10.0	3	6.0	5	10.0	3	6.0	2	4.0
Financial/Technical Support	2.0	5	10.0	5	10.0	5	10.0	3	6.0	5	10.0
Sole Source/Patented Prod.	1.0	5	5.0	1	1.0	3	3.0	3	3.0	1	1.0
TOTALS	**100.0**		**500.0**		**492.0**		**557.0**		**496.0**		**502.0**

1.3.3 Evaluation Findings

Steel Open Grid Deck has a total baseline ranking value of 500. Total ranking values for the alternative deck systems above 500 are generally considered superior to Steel Open Grid Deck and are considered to add overall value as an alternative deck on typical existing Florida bascule bridges. Total ranking values below 500 are considered inferior to Steel Open Grid Deck and are generally not considered to provide overall value. Based on this evaluation, the Aluminum Orthotropic Deck system is the only deck system to have a value that ranks well above Steel Open Grid Deck (557 vs. 500) and thus is considered to add value when replacing Steel Open Grid Deck. Ultra High Performance Concrete (UHPC) Waffle Slab Deck, SPS Deck and FRP Composite Deck systems have values that are slightly above or slightly below Steel Open Grid Deck (502, 492 and 496 respectively vs. 500). As such, these deck systems are generally considered to provide similar value to Steel Open Grid Deck. On the basis of this comparison, the Aluminum Orthotropic Deck is considered superior to the other deck systems that were evaluated, and offers the most value as an alternative deck system on typical existing Florida bascule bridges, with the least overall risks and challenges.

Aluminum Orthotropic Deck System: A friction-stir welded 5-inch deep Aluminum Orthotropic Deck, similar to the 8-inch deep Sapa R-Section Deck, but fabricated specifically to replace 5-inch deep Steel Open Grid Deck, offers a number of advantages and is recommended over the other evaluated alternative deck systems to replace Steel Open Grid Deck on typical Florida bascule bridges. This lightweight solid deck system is recommended because of the following reasons:

- The solution will address most if not all of the functionality and safety concerns of the Steel Open Grid Deck.
- It provides a nearly weight neutral solution that can be implemented on most typical existing Florida bascule bridge with minimal changes in overall weight and minimal modifications to the structure.
- The aluminum orthotropic deck is anticipated to be durable and provide a long service life with excellent resistance to corrosion and other environmental factors, and to protect the bascule leaf structural steel. The deck is conservatively designed for infinite fatigue resistance and the use of new friction-stir welding technology is anticipated to greatly improve the fatigue resistance.
- Although the deck system will have a significantly higher initial construction cost (approximately twice that required to replace the deck with Steel Open Grid Deck), the longer anticipated service life, lower maintenance costs, and reduced user impacts (i.e. reduced user delay costs and accident cost) will offset these higher initial costs.
- The deck will span transversely across stringers similar to Steel Open Grid Deck and can be fabricated in panels of similar width to typical Steel Open Grid Deck panels to facilitate replacement with short duration closures of the bridge or phased construction while traffic is maintained. Temporary short-term repair of the deck top surface is relatively simple and can be performed quickly by Department maintenance crews with the addition of a field welded aluminum plates.

- The proposed deck is generally of a robust design that conservatively meets all Strength, Service (deflection) and Fatigue Limit States in the *AASHTO LRFD Bridge Design Specifications*. Updated design specifications for the aluminum orthotropic deck, which utilize simple, conservative closed-form equations, have been ratified by AASHTO and incorporated into the latest revision of the *AASHTO LRFD Bridge Design Specifications*.
- A significant amount of research, development, testing, analysis and evaluation of the very similar 8-inch deep SAPA R-Section Aluminum Orthotropic Deck was previously performed that supports the design. The proposed 5-inch deep Aluminum Orthotropic Deck is a direct derivative of the 8-inch deep SAPA R-Section and is conservative by way of use of similar material thicknesses (top, bottom and web) but with shorter distances between panel points. There are several recent installations of similar aluminum orthotropic deck products in the United States and Europe that provide useful information.
- Aluminum is a relatively well known material with consistent and predictable material properties and quality control. Recent advancements in friction-stir welding have eliminated the previous concerns with gas metal arc (MIG) welding.
- The connection of the deck to the bascule leaf steel framing and splices between fabricated panels has been researched and there are simple, relatively cost-effective bolted details that have been identified.
- Concerns with galvanic corrosion due to dissimilar metals, and concerns with thermal movements due to the difference in coefficients of thermal expansion between aluminum and steel have been researched and simple, relatively cost-effective solutions to address these issues have been identified.
- Although the aluminum orthotropic deck system requires a thin epoxy polymer wearing surface, the significant stiffness of the deck is anticipated to improve the durability and service life of the wearing surface.

Although the proposed extrusion for the 5-inch deep Aluminum Orthotropic Deck system was not available at the onset of this research, SAPA Group, the world's largest supplier of aluminum extrusions with a significant number of manufacturing plants in North America, has shown a strong interest in developing this extrusion, and is in the process of developing the tooling for this extrusion. Because the proposed section is a direct derivative of the 8-inch deep SAPA R-Section, currently in production and being installed on bridges in the United States, implementation of the similar 5-inch deep extrusion is straightforward. The deck will use the latest advancements in friction-stir welding, similar to that used to fabricate the SAPA R-Section. The Department may want to consider limited additional independent testing of the proposed deck, and corresponding friction-stir welding, bolted connections, and wearing surface to supplement the research and development that has already been performed.

<u>UHPC Waffle Slab Deck System</u>: The UHPC Waffle Slab Deck system offers a number of positive aspects that make it a candidate to replace Steel Open Grid Deck on typical Florida Bascule Bridges including:

- The solution will address most if not all of the functionality and safety concerns of the Steel Open Grid Deck.

- It can be implemented on most typical existing Florida bascule bridges with minimal modifications to the structure and with a reasonable construction cost.
- The high strength, low permeable concrete material is generally anticipated to be durable with excellent resistance to corrosion and other environmental factors, and that will protect the bascule leaf structural steel.
- The deck will span transversely across stringers similar to Steel Open Grid Deck and can be fabricated in precast panels of similar width to typical Steel Open Grid Deck panels to facilitate replacement with phased construction while traffic is maintained.
- The concrete deck surface will provide a smooth riding surface with good skid resistance that eliminates the need for an applied thin epoxy wearing surface.

However, despite the above positive aspects, further research and development of this deck system is needed before it can be recommended for widespread implementation on typical Florida bascule bridges.

- The current configuration is significantly heavier than existing Steel Open Grid Deck (29 psf vs. 21 psf) and will add significant weight to the trunnion assemblies and bascule leaf structure. Although there may be opportunities for additional refinements to further reduce the weight, these refinements are currently theoretical and have not been validated with laboratory testing, are anticipated to result in corresponding reductions in strength and durability, and introduce tighter construction tolerances that may make construction difficult or impractical.
- UHPC is still considered somewhat experimental with no experience in a similar application on a bascule bridge.
  - o There are no design provisions or simple closed-form equations endorsed by AASHTO and included in the *AASHTO LRFD Bridge Design Specifications* needed to ensure a consistent design methodology by the bridge design community and to simplify the bridge design process.
  - o Although research continues to improve knowledge and understanding of UHPC as a bridge construction material, with corresponding consistency of material properties and quality control, most bridge contractors and construction inspection personnel working on bridge repair and rehabilitation projects in Florida are unfamiliar with the use of the material.
  - o The UHPC Waffle Slab Deck system has only been placed into service on one fixed bridge with multiple parallel prestressed concrete girders and has not been installed on a bascule bridge with a main girder, floorbeam and stringer framing system. It is not clear whether the limited laboratory testing performed adequately addresses the differences found in the structural framing configuration found in typical double-leaf bascule bridges.
  - o The long-term durability of the UHPC Waffle Slab Deck is not generally well known. Although UHPC provides increased impermeability, concrete cover to the reinforcing steel, required to achieve a lightweight solution, is limited. Construction tolerances are anticipated to further reduce the cover. Construction joints between the precast panels

and cast-in-place closure pours introduce opportunities for leakage (i.e. access of water containing chlorides to the embedded reinforcing steel and structural steel below.) Continuous deck systems on double-leaf bascule bridges are subject to tension stresses (due to cantilever support conditions of the main girders and localized negative bending of the floor system over the intermediate floorbeams) that act to open the construction joints.

- o There is limited experience with the field repair or replacement of UHPC Waffle Slab Deck. As such, it is unclear whether effective short-term localized repairs can be implemented with this deck system. Although the modular construction of the precast UHPC Waffle Slab Deck panels makes replacement of individual sections of the deck practical, the grouted haunches with welded headed stud shear connectors complicates the replacement and will slow the replacement process. It is not clear whether a damaged panel can be replaced in a short duration nighttime closure.

<u>FRP Composite Deck Systems</u>: There are a number of available FRP Composite Deck systems, each of a different design including overall deck thickness; structural configuration; manufacturing process; type, size, orientation, and number of layers of fiber reinforcing; type of resin; and associated physical properties including weight, strength, stiffness and span capability. Different FRP Composite Deck systems utilize different installation and construction practices including different deck attachment details. Despite the differences in these products, there a many similarities in the overall performance of these deck systems that permits the FRP Composite Deck to be evaluated as a single technology.

FRP Composite Deck systems offer a number of positive aspects that make them a candidate to replace Steel Open Grid Deck on typical Florida Bascule Bridges including:

- The FRP Composite Deck systems will address most if not all of the functionality and safety concerns of the Steel Open Grid Deck.
- They can provide a nearly weight neutral solution that can be implemented on most typical existing Florida bascule bridge with minimal changes in overall weight and minimal modifications to the structure with a reasonable construction cost.
- The FRP composite material is a corrosion resistant.
- FRP Composite Decks generally offer good overall capacity at the Strength Limit State.
- The deck will span transversely across stringers similar to Steel Open Grid Deck and can be fabricated in prefabricated panels of similar width to typical Steel Open Grid Deck panels to facilitate replacement with short duration closures of the bridge or phased construction while traffic is maintained.
- The modular nature of some FRP Composite Deck systems permits the replacement of individual panels should that become necessary.
- Although each available FRP Composite Deck system is considered proprietary, because each of the FRP Deck systems generally yields a similar solution, there are opportunities for competitive bidding.

However, despite the above positive aspects, further research and development of the available FRP Composite Deck systems is needed before they can be recommended for widespread implementation on typical Florida bascule bridges.

- FRP Composite Deck installations throughout the United States including those on several bascule bridges have generally exhibited durability issues and limited service life. Although FRP Composite Deck systems continue to improve as the technology evolves and more is learned about the design requirements, there are significant issues with current available designs that still need to be addressed. Some deck systems have performed better than others in specific areas of evaluation. For example, conservative designs with stronger and stiffer section properties and shorter deck spans have performed better than those with less conservative designs. Joints between deck panels and wearing surfaces continue to be primary sources of premature failure in FRP Composite Deck systems.
- Much of the research and development of FRP Composite Decks has not considered critical stresses and deformations that are unique to bascule bridges including those associated with 1) main girder cantilevered support conditions that introduces longitudinal membrane stresses in the continuous deck in conjunction with main girder flexure, and 2) floor system configuration with stringers and floorbeams that introduces tension in the continuous deck corresponding to stringer end rotations and negative bending of the deck over the intermediate floorbeams.
- Currently available FRP Composite Deck systems are proprietary and do not appear to have strong financial and technical support from a large corporation with significant resources. Although there is a significant amount of research that has been performed on FRP composites for use as bridge decks, the research for each individual deck product is generally limited.
- Currently there are no design provisions for FRP Composite Decks endorsed by AASHTO and included in the *AASHTO LRFD Bridge Design Specifications*. Although there are some recommended guidelines for designing FRP Composite Deck, offered by some manufacturers, some state transportation agencies, and FHWA, there appears to be little consistency, a wide range of assumptions used, and varying design practices used throughout the United States.
- FRP Composite Decks are somewhat flexible and are designed for larger deflection limits than currently used in Steel Open Grid Deck design. Many FRP Composite Deck suppliers recommend deflection limits of L/500 when AASHTO requires a deflection limit of L/800 for steel grid and other lightweight metal decks. (NOTE: For comparison, the deflection of the 5-inch deep Aluminum Orthotropic Deck for the same deck span meets a deflection limit of L/3000.) There are questions as to whether a deflection limit of L/500 is appropriate for bascule leaf decks. Although this deflection is not considered an issue for motorist comfort and safety, the significantly greater deflections are a concern for the performance of the thin epoxy polymer wearing surface.
- Testing has shown that the physical properties (e.g. strength and stiffness) of the FRP composite materials degrade with repeated loading. Although this degradation can be accounted for by conservatively specifying larger section properties, the degradation introduces questions regarding the long-term durability of the deck and the performance of the wearing surface over time as deflections increase with the degradation.

- Durability of FRP Composites is dependent on a number of factors including the manufacturing processes, and properties of the epoxy resin material and associated coatings that encapsulate the fiber material. Construction practices (including cutting and drilling of the FRP composite material) can reduce the durability by exposing the embedded fiber material to environmental factors. Exposure of the fiber material to chemicals, ultra-violet light, and even salt water can result in degradation. There is a wide range of manufacturing processes, materials and construction practices used in implementing the various available FRP Composite Deck products. Currently, there are no industry standards endorsed by AASHTO that define the specific manufacturing, construction, inspection and testing requirements (e.g. quality control) necessary to assure that an FRP Composite Deck product is durable and will provide the anticipated long-term service life.
- FRP composite materials are not currently well known to the bridge construction industry. The technology requires specialized shop inspection and field inspection practices that are unfamiliar to most bridge construction inspection personnel.

SPS Deck System: The SPS Deck system offers a number of positive aspects that make it a candidate to replace Steel Open Grid Deck on typical Florida Bascule Bridges including:

- The SPS Deck system will address most if not all of the functionality and safety concerns of the Steel Open Grid Deck.
- It can be implemented on most typical existing Florida bascule bridges with minimal modifications to the structure and with a reasonable construction cost.
- SPS Deck generally offers good overall capacity at the Strength Limit State.
- Although SPS Deck utilizes technology that is unfamiliar to most bridge contractors performing work on bridge repair and rehabilitation projects, the field installation generally utilizes conventional steel erection practices.

However, despite the above positive aspects, further research and development of this deck system is needed before it can be recommended for widespread implementation on typical Florida bascule bridges.

- The lightest recommended SPS Deck solution, required to meet deflection limits is significantly heavier than existing steel open grid deck and will add significant weight to the trunnion assemblies which typically have very limited or no reserve capacity. The sizing of the SPS Deck is governed by deflections and because the modulus of elasticity of the elastomer core decreases with increased temperatures, a thicker core is required in Florida where temperatures are generally higher than northern states. Significant additional modifications to the bascule leaf are required to offset the increase in weight. This includes replacement of a number of bridge components with lighter elements that do not otherwise need replacement, which adds unnecessary cost to a project.
- The lightest recommended SPS Deck is somewhat flexible and is designed for deflection limits equal to L/300 for deck span (i.e. stringer spacing) typically found on Florida bascule bridges. (NOTE: For comparison, the deflection of the 5-inch deep Aluminum Orthotropic Deck for the

same deck span meets a deflection limit of L/3000.) There are questions as to whether a deflection limit of L/300, recommended by Intelligent Engineering consistent with the deck plate of steel orthotropic bridge decks, is appropriate for bascule leaf decks when AASHTO requires a deflection limit of L/800 for steel grid and other lightweight metal decks. Although, this deflection is not considered an issue for motorist comfort and safety, the significantly greater deflections are a concern for the performance of the thin epoxy polymer wearing surface.

- In order to minimize the weight of the deck system (i.e. reduce the number of heavy perimeter and splice bars), the SPS Deck panels must be configured such that the longer dimension of the panel is parallel to the roadway centerline. Because this configuration is opposite to that of the existing steel open grid deck, the deck cannot be replaced in small sections (e.g. one floorbeam bay at a time) without adding additional panel splices, which further adds weight to a deck system that is already significantly heavier than the existing steel open grid deck.
- SPS Deck requires a significant amount of field welding to splice the panels. The fully welded panels make future rapid replacement of sections of the deck a challenge.
- Currently there are no design provisions for SPS Deck design endorsed by AASHTO and included in the *AASHTO LRFD Bridge Design Specifications*. Although there are some guidelines and available simplified tools for selecting an SPS Deck, in order to achieve the lightest possible deck, Intelligent Engineering recommends that a full non-linear finite element analysis of the deck and framing system be performed, which makes the design process more cumbersome and adds cost to the project. The need to use finite element analysis to design and analyze the deck introduces some concerns and challenges regarding future load rating and overload permitting.
- SPS Deck utilizes technology that is unfamiliar to the bridge construction industry (e.g. use of polymer core). The technology requires specialized shop inspection practices unfamiliar to most bridge construction inspection personnel.
- Although there is a significant amount of research that has been performed on SPS Deck over the last 15 years with impressive results, the limited use of SPS as a bridge deck material introduces some risk as to the long-term performance. There have been reported issues (deck failures) on more than one bridge in Canada, less than one-year after the SPS deck was placed into service. The issues associated with these failures will need to be fully investigated and the solutions to the cause of the failures developed and tested.

In the following report, each of the lightweight solid deck alternatives is described and discussed in greater detail with consideration of each of the evaluation criteria. In addition, because all of the evaluated deck systems, except for the UHPC Deck system, require an independent wearing surface, and the available wearing surfaces for each of the deck systems are similar, a separate description and discussion on alternative wearing surfaces is also included.

2.0 OVERVIEW OF EVALUATED LIGHTWEIGHT SOLID DECK SYSTEMS

In-depth evaluation was performed on the following four (4) lightweight solid deck systems:

- Sandwich Plate System (SPS) Deck by Intelligent Engineering,
- Aluminum Orthotropic Deck by Sapa Group,
- Fiber Reinforced Polymer (FRP) Composite Deck by ZellComp, et al.,
- Ultra-high Performance Concrete (UHPC) Waffle Slab Deck by FIU/UCF.

Following sections include product description, development background, and potential as a viable alternative for steel open grid decks on typical Florida bascule bridges using the various criteria listed in Introduction and Executive Summary.

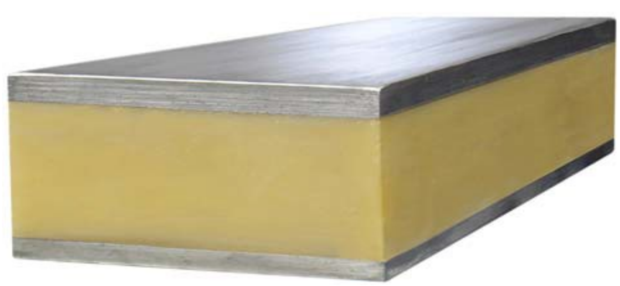
2.1 SANDWICH PLATE SYSTEM (SPS) DECK

2.1.1 Description

The Sandwich Plate System (SPS) is a proprietary and patented composite laminate plate material consisting of thin metal faceplates continuously bonded to a polyurethane elastomer core. The elastomer core transfers forces between the metal faceplates by way of shear, analogous to an I-beam when subjected to flexure with the steel plates acting as the flanges and the elastomer core as the web. The elastomer core also prevents local buckling of the metal faceplates in compression, which permits development of full yield of the metal faceplates.

SPS panels are very thin (1 to 2 inches thick) compared to traditional bridge decks. The use of these thin panels is possible through a combination of panel bending and membrane action (i.e. in-plane tension). Separation of the thin metal plates with a lightweight elastomer core more efficiently increases strength and stiffness of the plate, while minimizing the increase in weight of the plate.

The thickness of the steel plates and the elastomer core is typically customized to fit a given application and for the required strength and stiffness. SPS panels are identified by a designation such as "SPS 6-25-6". The first and last numbers indicate the steel plate thicknesses in millimeters and middle number indicates the core thickness in millimeters. An SPS bridge deck is typically constructed from a series of panel segments, connected together and to the supporting steel framing.



SPS Sample-Size Specimen

Elastomer bubbles (i.e. formed voids within the elastomer core) have been used to reduce the weight of the SPS panels. However, this technology has not been used in bridge decks where the deck plate is subject to large concentrated wheel loads.

Applications: SPS panels have been used in different highway bridge deck applications including:

- Strengthening and stiffening existing steel orthotropic decks,
- Replacement of conventional decks on existing multi-girder bridges,
- Decks for new bridges in both orthotropic deck and conventional multi-girder configurations.

Materials: For bridge applications, metal faceplates are typically fabricated from steel (e.g. ASTM A588, Grade 50W).

The elastomer formulation is proprietary, but physical properties of the formulation required for design such as modulus of elasticity, Poisson's ratio, density, etc. are published and available. The density of the elastomer is 1150 kg/m^3 (71.8 pcf).

Properties of the elastomer change with variations in temperature. The modulus of elasticity of the elastomer varies significantly with changes in temperature. As the temperature of the elastomer increases, the modulus of elasticity reduces, and deflections of the SPS deck will increase. The ultimate strength of the elastomer also varies with temperature. As temperature increases, the ultimate strength of the elastomer decreases. Poisson's ratio varies very little with changes in temperature. The elastomer also has a different modulus of elasticity in tension and compression. The shear modulus of the elastomer is load rate dependent, with faster loading rates resulting in a higher shear modulus.

Material Properties of Elastomer at Various Temperatures

	Property	mean st.dev	Temperature, °C									
			-40°C	-20°C	0°C	23°C	60°C	80°C	90°C	100°C	110°C	120°C
Tension	E (MPa)	mean	1251	1016	899	686	448	346	305	213	148	82
		st. dev.	166	67	100	10	9	18	11	18	3	22
	σ_p (MPa)	mean	48.1	40.6	33.4	21.9	15.3	11.4	10	8.3	4.6	3.7
		st. dev.	5.3	1.9	2.1	0.5	0.3	1.2	0.7	0.1	0.3	0.7
	σ_u (MPa)	mean	55.6	45.3	36.2	26.7	18.7	15.9	13.9	11.6	9.1	7.3
		st. dev.	5.5	1.4	0.6	0.5	0.4	0.9	0.7	0.3	0.3	0.3
	ε_u (%)	mean	11.9	16.9	28.2	26.0	29.5	44.0	37.4	28.0	40.7	52.2
		st. dev.	1.8	3.4	1.3	3.0	3.7	8.8	6.6	1.0	2.3	7.6
Poisson's Ratio	ν	mean	0.39	-	-	0.38	-	-	-	0.30	-	-
		st. dev.	0.01	-	-	0.00	-	-	-	0.00	-	-
Compression	E (MPa)	mean	1040	868	763	640	422	315	160	129	-	139
		st. dev.	19	61	24	12	10	32	26	9	-	25
	σ_p (MPa)	mean	68.3	50.6	38.2	27.8	15	6.5	5.7	5	-	5
		st. dev.	3.9	1.9	1.1	1.1	0.3	0.2	0.7	0.6	-	0.4
	$\sigma_{10\%\varepsilon}$ (MPa)	mean	71.6	54.1	41.6	29.9	16.4	15.5	11.8	10.5	-	7.4
		st. dev.	2.1	1.8	0.8	0.6	0.3	1.0	0.6	0.3	-	1.8
Torsion Pendulum	G (MPa)	-	518	397	326	263	188	148	126	101	74	45
	E (MPa)	$E = 2G(1+\nu)$	1409	1079	886	714	511	403	342	274	200	121

2.1.2 Product Development and Corporate Information

SPS was initially developed in the mid 1990's to provide impact resistant plating for offshore structures and ice islands working in the Canadian Beaufort Sea. SPS applications have since expanded to ship hulls and deck plates, stadium terraces, building floor systems, bridge decks, and blast walls. Currently, approximately 325,000 square feet of SPS have been fabricated and installed in different applications worldwide.

The technology was developed by Dr. Stephen Kennedy, former Professor of Civil and Environmental Engineering at Carlton University in Ontario, Canada. Dr. Kennedy is currently the Chief Technical Officer at Intelligent Engineering (IE) in Ottawa Ontario, Canada. IE was founded in 1996, and currently has offices in Canada, United Kingdom, Singapore, and Dubai. IE partner0s with Elastrogran GmbH, part of BASF, which developed the polyurethane elastomer core for the SPS. IE also provides licenses to various companies to produce the SPS product. More information regarding IE can be found at www.ie-sps.com.

2.1.3 Constructability

Fabrication: SPS panels for bridge decks are typically fabricated at a steel fabrication facility specifically licensed by IE to fabricate the panels. However, field fabrication has also been used to retrofit existing steel orthotropic decks. Steel faceplates are cut to the required size, the top and bottom faceplates separated and an airtight space created with steel perimeter bars continuously welded to the steel faceplates along the edges. Panels are not typically cambered.

Bond between the steel faceplates and elastomer is developed by intentionally roughening the interior surfaces of the steel faceplates using shot blasting or grit blasting. The bond strength varies depending on the anchor profile achieved. Steel coatings will generally reduce the bond. The bond strength is also temperature dependent with lower temperatures yielding greater bond.

A two-part liquid polyurethane elastomer is then injected into the airtight space. To prevent sagging of the top faceplate, a series of small, circular cured elastomer spacers, equal to the thickness of the elastomer core, are spaced throughout the panel. Because the elastomer experiences some expansion and high temperatures during the exothermic curing process, the SPS panels require restraining frames on top of the panels to prevent distortions and maintain flatness of the panels.

The elastomer core is extremely sensitive to moisture during the curing process, which can lead to swelling. As such, the cavity to be filled with elastomer must be dry and the humidity of the air in the cavity maintained below a specified limit, which is achieved with hot air dryers and verified with humidity and temperature measurements taken in the cavity.

The SPS panels can be made to various custom sizes, limited in size by the pumping speed and setting time of the elastomer, although multiple pours of elastomer are possible. The volume of the elastomer is limited to 1,200 liters (42.4 cubic feet), which limits a 1-1/8-inch (30 mm) core (recommended for typical existing bascule bridges in Florida) to approximately 450 square feet.

Because the panels are fabricated using structural steel, the panels can be fabricated to the same dimensional tolerances as other structural steel members. Mill tolerances in ASTM A6 and the fabrication tolerances in the AWS D1.5 Bridge Welding Code are applicable to panel fabrication.

SPS Deck System Fabrication

Specialized Inspection: SPS deck and thin epoxy polymer wearing surfaces are less common to the bridge industry and thus inspection of this construction will, at least initially, be considered specialty in nature.

Fabrication of the SPS deck will require typical steel fabrication and weld inspection. The fabricator will be required to perform quality control and submit weld procedures specifications and certifications and a quality control plan that addresses the required quality control functions to be performed. Because of the special requirements of the elastomer core and SPS panels, it may be necessary to employ personnel with specialized experience to perform quality assurance for this work. Field welding of the panel splices will require on-site involvement by welding inspectors. The contractor will be required to submit weld procedure specifications and certifications for the field welding. Quality control procedures for the wearing surface will also need to be developed.

Field Installation: The SPS panels can be fabricated of a size that can be shipped to the site by truck without special permitting. Widths of the panels are anticipated to be no more than 8 feet and lengths no longer than 40 feet, which is consistent with maximum dimensions of steel open grid deck panels. SPS panels can be stored by staking the panels on top of each other to minimize staging areas similar to steel open grid panels. SPS panels are relatively flexible and require use of lifting beams to handle and place the panels similar to steel open grid panels.

Bolting of the panels can be performed using standard turn-of-nut method or direct tension indicator washers similar to standard steel erection work. Special adapters may be required for the Skidmore device to calibrate the countersunk bolts to snug-tight condition. Tapered pins can be used to align predrilled holes in the steel members similar to typical steel erection.

The top flange of the new stringers can be match drilled with the SPS panels in the shop to improve alignment of the holes and reduce time consuming field drilling. The stringer end connections can remain blank and drilled from solid to match existing holes in the webs of the floorbeams or pre-drilled for use as a template to drill new holes in the floorbeam webs to maximize field adjustment.

The open joint between the ends of the panels and curbs or traffic railings provide clearance to accommodate tolerances in panel width. A small grouted closure pour can be provided at the counterweight to accommodate tolerances in the panel lengths. Tolerances in panel sweep and squareness can be accommodated in the root opening of the field welded joint. The flexibility of the SPS panels should be sufficient to accommodate any unanticipated small camber in the panels or tolerances in the elevation of the supporting members.

Traffic Control: Because the SPS panels are oriented having the long dimension parallel to the roadway centerline and steel open grid panels are oriented with the long direction perpendicular to the roadway centerline, and the stringers require replacement with the deck, there will be challenges in maintaining traffic on the bascule span while the deck is replaced. It may be possible to replace the deck in larger sections equal to the length of the SPS panels (one-half to one-third the length of the bascule leaf) and the full-width or half-width of the bridge, while the bridge is temporarily closed to traffic. However, it will not be practical to perform the replacement a single panel at a time or even a single floorbeam bay at a time. The use of smaller SPS panels that match the steel open grid panels will require many more splices that will significantly increase the weight of an already heavier deck system. Because panels should generally be of a dimension that can be shipped by truck, this limits the number of configurations that can be used to accommodate phased replacement of the deck.

2.1.4 Functionality and Safety

Load Capacity: An SPS deck designed to governing deflection limits will have corresponding load carrying capacity in excess of that required to support AASHTO LRFD HL-93 Live Loads. The small increase in deck weight resulting from the heavier SPS deck is not anticipated to significantly reduce the capacity of the bascule span. There are opportunities to increase the load carrying capacity of the stringers and main girders by taking advantage of the composite action between the SPS deck these members.

Rideability: SPS deck and the corresponding applied wearing surface will provide a smooth, continuous riding surface with a surface roughness comparable to asphalt or concrete pavement. Because the SPS deck is more flexible than the existing steel open grid deck, localized deflections are anticipated to increase. However, because the SPS deck will be made composite with the stringers and main girders, the overall deflections and vibrations of the bascule leaf are anticipated to decrease, which will improve the quality of the ride.

Skid Resistance: Skid resistance from the applied wearing surface will be similar to that of asphalt pavement. See Section 3 Wearing Surface Evaluation.

Noise: The vibration dampening characteristics of the elastomer core will significantly reduce noise generated by tires in contact with the deck.

Bicycle Safety: SPS deck provides a solid riding surface for the roadway and shoulders with small longitudinal open joints (less than ½” wide) located immediately adjacent to the curbs or barriers, which will greatly improve bicycle safety. Transverse deck joints between the two bascule leaves and between the bascule span and bascule pier will range from ¾” to 1½” in width, but should not be a concern for bicyclists.

2.1.5 Design and Analysis

Design Considerations: The design of SPS bridge decks is not specifically addressed in the *AASHTO LRFD Bridge Design Specifications*. Furthermore, because of the unique configuration and materials of SPS deck, it is not clear how it should be classified when implementing specific governing AASHTO design provisions and guidelines. SPS deck is comparable to steel orthotropic deck in that it utilizes continuous metal deck plate. However, SPS deck differs significantly from steel orthotropic deck in that the main structural resistance of an SPS deck is derived from the face plates and core, whereas the steel orthotropic deck derives its resistance from the deck plate and discretely spaced stiffening elements acting together as a unit. It is not clear whether the longitudinal support beams (e.g. bascule leaf stringers) can be considered as the discretely spaced stiffening elements and the SPS deck as the deck plate of a steel orthotropic deck due to the significantly wider spacing of these elements in an SPS deck solution.

Virginia Polytechnic and State University has performed research and has developed a simplified methodology to design the SPS deck. It should be recognized that the proposed design methodology, which considers a number of AASHTO provisions including loading and limit states, has not been formally reviewed and endorsed by AASHTO. Furthermore, the design methodology has not been calibrated to an established reliability index.

As the SPS deck system is a thin, flexible system, the design of SPS decks is controlled by deflections. As the design of SPS decks is not specifically addressed in the AASHTO LRFD Bridge Design Specifications, it is unclear which deflection limits are applicable to SPS deck. There are two different provisions of AASHTO Article 2.5.2.6.2 (Criteria for Deflection) that could apply.

- If SPS deck system is classified as a steel orthotropic deck with the SPS member considered the deck plate and the stringers considered as the stiffening ribs, then the provisions for orthotropic deck would be applied. These provisions include L/300 deflection limits of the deck plate, L/1000 for the stiffening ribs, and 0.1 inch maximum relative deflection between adjacent ribs from a combination live load and dynamic load allowance. These provisions also make the deflection limits mandatory. (NOTE: IE recommends and uses this less conservative assumption in their design guidelines).

- If SPS deck system is classified as "metal grid decks and other lightweight metal and concrete bridge decks", similar to steel open grid decks, then the serviceability provisions of AASHTO Article 9.5.2 apply. These provisions include L/800 deflection limits from a combination of live load and dynamic load allowance. It also makes the deflection limits mandatory. (NOTE: Researchers at Virginia Polytechnic Institute and State University use this conservative assumption).

There are several factors that must be considered in making a decision regarding the design of the deck for deflections:

- The selection of a deflection limit (i.e. L/800 vs. L/300) yields significant differences in the final SPS deck design and makes a difference whether the solution is viable or not viable (i.e. the weight of an SPS deck based on a deflection limit of L/800 will be much heavier and difficult to accommodate with existing counterweights and trunnion assemblies, while the weight of an SPS deck based on a deflection limit of L/300 will be lighter and can be accommodated).
- The effect of deflections on driver comfort is not likely to be a concern for the anticipated deck span lengths. Live load deck deflections are anticipated to be small (i.e. less than ¼") and are anticipated to remain constant over the length of the bascule span (i.e. deflections will not vary over the length of the bascule span and cause vertical accelerations that affect driver comfort). For the typical bascule span framing configuration, maximum deflections will occur directly under the wheel and deck stiffness will generally remain uniform over the length of the bascule span where the deck is supported only by the stringers and not directly supported at the floorbeams. Research indicates that vertical acceleration limits is a more appropriate means of addressing driver comfort than arbitrary deflection limits.
- Various studies regarding dynamic amplification of live loads indicates that dynamic amplification values increase with decreasing bridge stiffness. As such, dynamic load allowances specified by AASHTO may underestimate actual values on flexible decks. A conservative estimate of the dynamic load allowance is recommended for the SPS deck design if more flexible L/300 deflection limits are used.
- Excessive deflections may result in durability concerns for the wearing surface. Wearing surface durability is a well-documented concern on bridges with orthotropic decks with flexible deck plates. There are no available studies that have tested the durability of thin epoxy polymer wearing surfaces on flexible SPS decks.
- In order to reduce the weight of the SPS deck, lightweight thin wearing surfaces are required. Thin wearing surfaces do not have the ability to distribute wheel contact pressures to a larger surface area like thicker asphalt wearing surfaces used on most of the SPS deck installations. As such, wheel patch loads are likely more concentrated. However, laboratory testing of SPS decks has typically taken a conservative approach that neglects the load distribution benefit of the asphalt wearing surfaces.
- The modulus of elasticity of the elastomer core reduces with increased temperatures and temperatures in Florida are generally higher than those in northern climates where most of the SPS decks have been installed. As such, it is recommended that a conservative approach be

used in the design of the deck for deflections using modulus of elasticity values corresponding to maximum anticipated in-service temperatures in Florida.

Design Approach: Because of the inherent complexities of the materials and load-deflection characteristics of SPS, deck design has relied heavily on finite element models. IE has traditionally performed the design using a second order non-linear inelastic finite element analysis. Due to the complexity of this analysis, it is not practical for each design consultant providing bascule bridge rehabilitation design engineering services to develop the skills to properly perform this analysis. Furthermore, the budgets typical of bascule bridge rehabilitation projects are generally inadequate to cover the expenses for such analysis. A simplified analysis technique should be used by the design-consultant to conservatively estimate the size of the SPS panels (steel faceplate and elastomer core thickness) for purposes of developing the contract plans including associated modifications (e.g. steel framing, counterweight, machinery, etc.) for estimating and bidding purposes. IE can perform the in-depth finite element analysis and refine the deck during the procurement of the deck and during the panel procurement and the cost of this analysis included in the cost of the deck.

Virginia Polytechnic Institute and State University developed simple, conservative closed-form equations that can be used for the preliminary sizing of SPS deck on the basis of AASHTO LRFD Bridge Design Specifications. In developing the proposed design method all applicable AASHTO LRFD design limit states were considered (Strength I, Service I, Service II, and Fatigue). Research identified that the controlling limit state for design was Service I with the deflection limit of L/800 imposed. The closed-form equations were validated by comparison to experimental data from both field and laboratory testing and then extended to consider the design limit states within AASHTO LRFD including serviceability, strength, and fatigue. The closed-form equations were conservatively developed for simple (pinned) boundary conditions and do not consider continuity provided by deck span over multiple supports, or stiffening effects from transverse supports that yield two-way span of decks. Actual boundary conditions are between upper and lower bounds (pinned or fixed conditions).

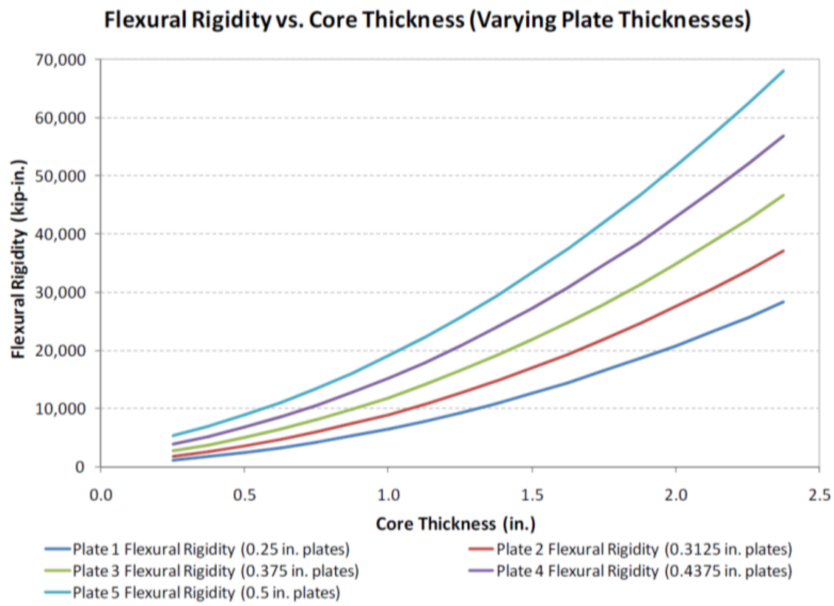
The closed-form equations were used to plot solutions in a graphical form for different deck flexural rigidities and span lengths. The closed-form equations can also be programmed into a software program (e.g. Excel Spreadsheet or MathCAD). A solution can be achieved as follows:

1) Establish a deck span “S”.
2) Determine the required flexural rigidity of the deck to meet the design criteria listed above using the following equation:

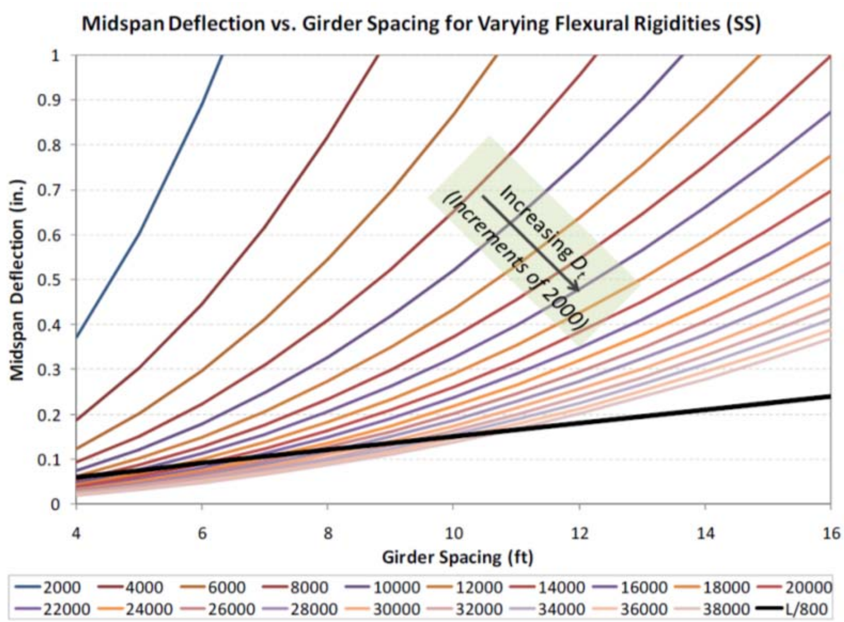
$$Req\ Flexural\ Rigidity = \left(3738 * \frac{S}{ft} - 2551\right) * kip * in$$

3) Check the provided flexural rigidity based upon the face plate thickness and the elastomer core thickness chosen. Elastomer properties should be based upon IE published data, adjusted for the maximum in-service design temperatures of the deck. The subscript “p” is for the steel face plate. The subscript “c” is for the elastomer core.

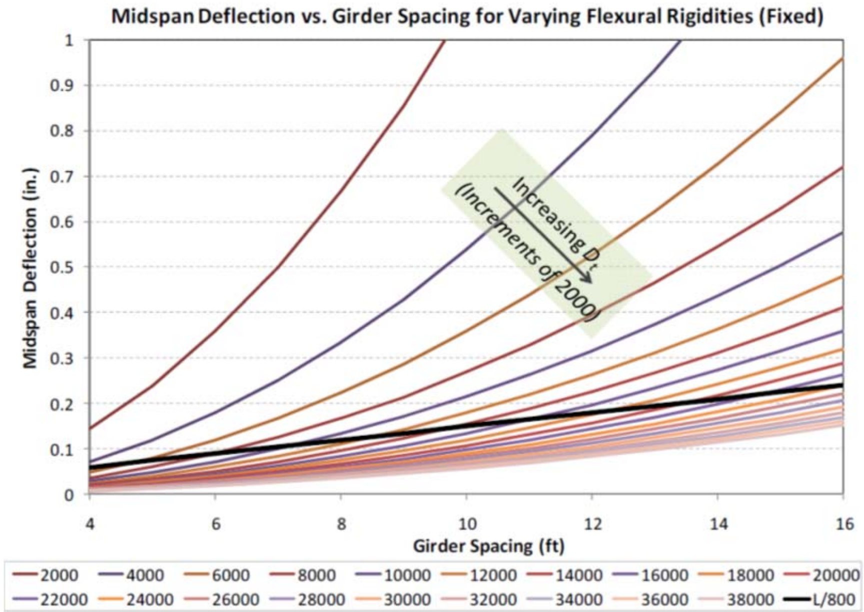
$$Prov\ Flexural\ Rigidity = \frac{2}{3}\left(E_p \frac{\left(\frac{t_c}{2}+t_p\right)^3 - \left(\frac{t_c}{2}\right)^3}{1-{\nu_p}^2} + E_c \frac{\left(\frac{t_c}{2}\right)^3 - \left(\frac{t_c}{2}\right)^3}{1-{\nu_c}^2}\right)$$



Flexural Rigidity vs. Core Thickness (Varying Plate Thicknesses)
Flexural Rigidity (kip-in.)
70,000
60,000
50,000
40,000
30,000
20,000
10,000
0
0.0
0.5
1.0
1.5
2.0
2.5
Core Thickness (in.)
Plate 1 Flexural Rigidity (0.25 in. plates)
Plate 2 Flexural Rigidity (0.3125 in. plates)
Plate 3 Flexural Rigidity (0.375 in. plates)
Plate 4 Flexural Rigidity (0.4375 in. plates)
Plate 5 Flexural Rigidity (0.5 in. plates)



Midspan Deflection vs. Girder Spacing for Varying Flexural Rigidities (SS)
Midspan Deflection (in.)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
4
6
8
10
12
14
16
Girder Spacing (ft)
Increasing Dt
(Increments of 2000)
2000
4000
6000
8000
10000
12000
14000
16000
18000
20000
22000
24000
26000
28000
30000
32000
34000
36000
38000
L/800



The conservative deflection limits and boundary conditions generally yield SPS deck solutions that are overly conservative. Although this approach is generally prudent, it yields deck designs that are heavier and that will not be viable to replace a lighter steel open grid deck on a bascule bridge. The use of more liberal deflection limits (e.g. L/300) can be addressed, if desired, by adjusting deflection values. However, as noted above, the decision to use more liberal deflection limits may have adverse consequences in the performance of the wearing surface and possibly other elements of the deck. A more accurate assessment of the effects of continuity can be addressed by interpolating between the graphs for the upper and lower boundary conditions (i.e. pinned and fixed).

IE recommends that the deck plate thickness not be less than 3/16-inch (5 mm) to ensure that fatigue of the base material does not occur during the life of the structure.

2.1.6 Durability and Service Life

Service Life: It is anticipated that a properly designed SPS deck system will provide a minimum service life that exceeds the life of a typical existing bridge (i.e. 30 to 40 years). However, because SPS is relatively new (i.e. less than 10 years of experience in bridge deck applications and slightly more than 15 years in other civil and maritime applications) there are no installations close to this age that confirm that this service life can be achieved.

Fatigue Resistance: The bond between the relatively stiff elastomer core and the thin metal faceplates eliminates the need for welded stiffener plates and the stress concentrations and fatigue sensitive details associated with these stiffeners. The continuous fillet welds between the faceplates and perimeter bars and the continuous fillet or groove welds used to splice panels together introduce fatigue sensitive details that must be considered in the design of the deck. However, these details generally have relatively high fatigue resistance that does not control the design of the deck panels (i.e. deflection limits typically control the design of the deck panels).

The fatigue category for the welded connection used in the splice detail is not specifically identified in *AASHTO LRFD Bridge Design Specifications*. However, there are details that are similar and that can be used for reference. Until more extensive testing of this joint is performed, a conservative value for the fatigue stress limit is recommended.

The bond between the elastomer and the steel has been found to be essentially fatigue insensitive unless the bond has been locally damaged from such effects as high, localized heat from welding or cutting, or freezing of water that has entered the core.

<u>Corrosion Resistance</u>: Because the SPS panels are fabricated from steel plates, the panels are susceptible to corrosion. As such, the panel exterior surfaces must be protected with steel coatings similar to other steel members. Steel coatings can consist of the same coatings used on the other bridge structural members. Metallizing the exterior steel surfaces can also be used without concerns of adverse effects to the elastomer core. The simple, flat surfaces of the SPS panel underside simplify the cleaning and painting. The use of corrosion resistant mechanically galvanized bolts, similar to those currently used for steel structures in coastal environments in Florida, also simplify the coating operations. Some caulking of joints and faying surfaces may be required in conjunction with this work.

The thin epoxy polymer, wearing surface protects the top faceplate from corrosion. However, it is important to prevent water from leaking through defects in the wearing surface and reaching the steel plate, as this can lead to corrosion. Corrosion of the top steel faceplate can result in delamination and failure of the wearing surface. As such, it is recommended that a flexible water proofing membrane be applied between the top surface SPS panels and the wearing surface.

<u>Impact Resistance</u>: SPS deck is anticipated to have good impact resistance in the event that a vehicle overturns and impacts the deck surface. SPS was specifically developed to provide impact resistant plate for offshore platforms and other maritime facilities and has been thoroughly tested to demonstrate this capability. This testing demonstrates that SPS has excellent energy absorbing properties to resist collision, ballistic projectiles and explosions.

<u>Fire Resistance</u>: SPS panels have been thoroughly tested for fire resistance in maritime (shipping) applications. Testing demonstrates that SPS has an equivalent fire rating of A60 according to the International Convention for Safety of Life at Sea (SOLAS) regulations. SPS panels are non-combustible under fire conditions. In the event of a fire, the elastomer core acts as an insulator, and protects elements on the opposite side of the SPS panel, away from the fire. However, heat from the fire will likely damage the SPS faceplates and elastomer core. In the case of a hot fire, the elastomer core exposed to the heat from the fire may transform into a gas, and vent out of the panels if there is a breach in the faceplates.

Similar to other steel members, steel loses strength and stiffness when exposed to high temperatures (i.e. greater than 1100 degrees F). Similar to other steel members, SPS panels are likely to survive short duration fires and/or fires with lower temperatures. Because the loss of strength is time-dependent, panels may provide limited structural support for loads on the deck during a fire (e.g. the vehicle on fire, emergency response vehicles and personnel). If the deck panels lose strength during these events, the steel framing below may steel provide some support to contain vehicles.

Only a substantial heat source, such as that from a roadway accident with ignited localized fuel spill, is expected to threaten the integrity of SPS deck.

<u>Thermal Expansion</u>: Because SPS panels are fabricated from steel, similar to the bascule leaf steel framing, differential thermal expansion between the panels and the steel framing will not be a concern.

The difference in coefficients of thermal expansion between the elastomer (126.9-155.6 x 10^{-6} to m/m°C for temperature range of 0 to 40 °C) and steel faceplates (11.7 x 10^{-6} m/m °C) is a potential concern and risk at normal in-service temperature ranges in Florida. The thermal contraction of the elastomer can result in loss in bond and the elastomer separating from the faceplates near the ends of long panels. Anchor bars consisting of a jagged plate attached to the faceplates within the cavity near the ends of the plate are recommended to address this concern.

<u>Chemical Resistance</u>: The elastomer core has been tested to determine the resistance to a number of chemicals including saltwater for maritime (shipping) applications. Because the elastomer is injected into an airtight cavity when the panels are fabricated, the elastomer is fully isolated from exposure to chemicals, unless there is a breach in the faceplates. Breaches at the bolted connections have been identified in some circumstances that has allowed water to enter the core.

The steel faceplates provide similar resistance to chemicals as other steel elements on the bridge. Paint coatings and wearing surface provide limited protection of the steel from chemicals and long term protection from corrosion.

<u>Ultraviolet (UV) Light Resistance</u>: Because the elastomer is injected into an airtight cavity when the panels are fabricated, the elastomer is fully isolated from UV light.

2.1.7 Maintenance

<u>Repair</u>: Damaged panels may be repaired by cutting and removing the damaged section, or by fully removing and replacing the entire panel. Local repair involves removing the damaged steel and elastomer, making sure that the elastomer is removed a sufficient distance from the steel cut line to prevent the weld heat from damaging the remaining elastomer. A new steel plate is then butt-welded to repair the hole, and new elastomer pumped into the cavity where elastomer had been removed. Because the repair involves injection of new elastomer material into the core, which involves specialty work, repairs by Department maintenance personnel are not practical. Required emergency repairs may result in closure of the bridge for extended periods until the specialty work forces can be mobilized.

<u>Periodic Maintenance</u>: The steel SPS panels will periodically require cleaning and painting at the same time and with the same paint system as the other bascule span steel members. More expensive, but longer lasting metallized coating systems can be used with the SPS panels to extend the duration between coatings.

The wearing surface on the SPS deck will require periodic (every 10 to 15 years for thin epoxy polymer wearing surface) replacement (see Section 3 Wearing Surface Evaluation).

2.1.8 Research

Design of SPS continues to evolve and significant research has been performed on SPS since its inception. From 2005 through 2012, a significant amount of research has been conducted at Virginia Polytechnic Institute and State University specifically related to the use of SPS as a bridge deck to *AASHTO LRFD Bridge Design Specifications*. Additional similar research has been performed at the University of Alberta in Canada to the *Ontario Highway Bridge Design Code*. Research has been used to verify SPS deck behavior including:

- Composite behavior between SPS deck and supporting steel girders including shear lag effects, effective width of composite deck, and efficiency of slip critical connections to achieve composite action,
- Fatigue behavior of several proposed welded and bolted connections and splice details including identification of fatigue category, S-N curves, and endurance limits,
- Ultimate strength of SPS deck panels under concentrated loads simulating wheel patch loads,
- Steel-elastomer bond behavior and required surface preparation to achieve the required bond and shear transfer,
- Fatigue of steel-elastomer bond damaged by high heat from welding,
- Confirmation of load deflection models and establishment of simplified design methodology.

Research has included a combination of finite element analysis, classical plate analysis, laboratory and field testing.

A significant amount of additional material and load testing, not directly specific to use of SPS as a bridge deck, but applicable due to similarities in other civil engineering and maritime uses, provides confidence that SPS is a durable and safe product. This testing included significant testing and evaluation of the elastomer material at different temperatures including that required to establish:

- Mechanical properties including density, tensile and compressive behavior, shear modulus, Poisson's ratio,
- Thermal properties including thermal expansion coefficient, specific heat, thermal conductivity, R-value and thermal diffusivity,
- Saltwater resistance including absorption and effect on material properties,
- Chemical resistance for numerous chemicals,
- Tensile impact toughness,
- Hardness.

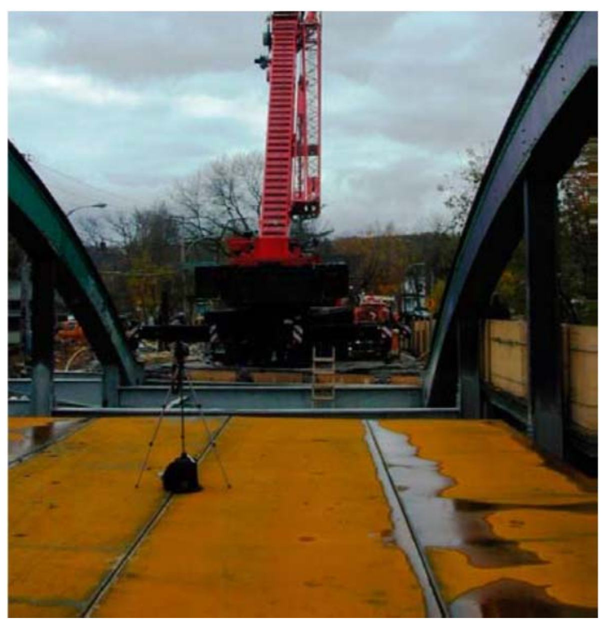
2.1.9 Recent Bridge Installations

Several highway bridges have been constructed to date using SPS deck including those described below to provide additional confidence in the performance of the deck system. Although none of the bridges constructed to date are movable bridges, IE has proposed SPS deck for several bascule bridges and has performed preliminary design including detailed finite element analysis of these bridges.

Shenley Bridge: The Shenley Bridge, built in 2003 in Saint-Martin, Quebec, Canada was the first bridge constructed using an SPS deck. The bridge is described as follows:

- Two-lane bridge, 73.8 ft span, with three steel plate girders and SPS 6.4-38-6.4 deck system (ASTM A588 Grade 50 steel).
- Designed to Canadian Highway Bridge Design Code with CL-625 design truck. IE designed the bridge using the finite element analysis (ANSYS Software was used). Deck was designed as composite with steel girders, using L/400 deck deflection limit.
- Construction performed in 14 days.
- Individual panels utilize slip-critical bolted connections to supporting structure and are spliced by field welding.
- A water-proofing membrane coating (Stirling Eliminator) was applied to the top face of the SPS below a 50 mm asphalt wearing surface.
- Guardrails were bolted to perimeter angles welded to the SPS deck.
- Composite action was confirmed by field-testing of the bridge.

Lennoxville Bridge: The Lennoxville Bridge, rehabilitated in 2005 in Lennoxville, Quebec, Canada included installation of an SPS deck on the existing stringers.

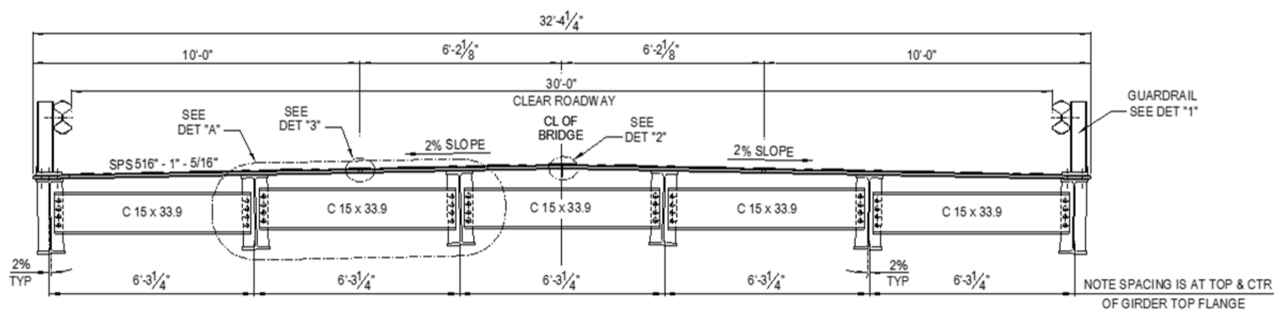


- The bridge is an historic through-truss bridge.
- Replacement of the existing concrete deck with a 60% lighter weight SPS 6-38-6 deck and asphalt wearing surface was specified to address structural deficiencies and increase the capacity of the trusses. Pedestrian walkways also consist of SPS panels supported on brackets cantilevered outboard the trusses.
- The deck was made composite with the existing steel girders.

- Deck sections are bolted together and to the supporting steel beams and the deck panels are additionally field welded.
- The entire SPS deck (16 panels) was installed in a week.

Cedar Creek Bridge: The Cedar Creek Bridge, built in 2008 in Wise County, Texas is the first bridge with an SPS deck constructed in the United States

- The bridge consists of three 150-foot spans and is 32 feet wide.
- The deck consists of an SPS 8-25-8 deck that spans transversely 6'-3 ¼" between rolled steel W27x114 beams.
- The deck is made composite with the beams by shop welding the deck to the top flange of the beams.
- Deck splices use a combination of 1" diameter ASTM A325 bolts at 4" o.c. and a continuous 7/16" field groove weld.
- The SPS deck was delivered from the shop with the girders already attached and was installed in a single weekend.



Cross Section of Cedar Creek Bridge

Dawson Bridge: The Dawson Bridge, rehabilitated in 2010 in Edmonton, Canada is the only bridge with SPS deck constructed without field welding.

- The historic bridge was built in 1912 and was originally designed to carry horse drawn wagons and electric trains.
- The 776-foot long bridge has five steel truss spans with varying span lengths and a floor system with stringers and floorbeams.
- Replacement of the existing lightweight concrete deck and timber sidewalks with a lighter weight SPS 10-25-10 deck and asphalt wearing surface was specified to address structural deficiencies and

increase the capacity of the trusses. The new deck spans transversely 6'-2" between new W18x50 stringers that range in length from 16'-8" to 17'-9". The asphalt thickness varied from 1 ½" at the shoulder to 4" at the crown.

- Project included a risk control plan for the SPS deck that consisted of:
  - Background research of available literature on SPS deck systems,
  - Site visits to existing bridges with SPS deck systems and interviews of bridge authorities,
  - Development of a new all-bolted SPS splice connection and full-scale laboratory fatigue testing of the new deck connection,
  - Enhanced quality control during fabrication and construction of the deck,
  - Monitoring of the deck during service.

Retrofit of Orthotropic Deck Bridges: The steel orthotropic decks of several long span and movable bridges have been retrofitted using SPS technology by field installing an elastomer core and new steel top faceplate on top of the existing deck plate, which became the steel bottom faceplate. This solution was used to stiffen the flexible deck plate and reduce deflections and fatigue stresses.

2.1.10 Florida Bascule Bridge Specific Solution

Deck Solution: Using the preliminary design methodology described above, the required deck solution for a typical Florida bascule span would consist of an SPS 5-30-5 deck with an overall thickness of 1½" and overall unit weight of 22 psf excluding perimeter bars, wearing surface, bolts and supplemental supports. With these additional items, the overall unit weight of the deck system is approximately 28 psf.

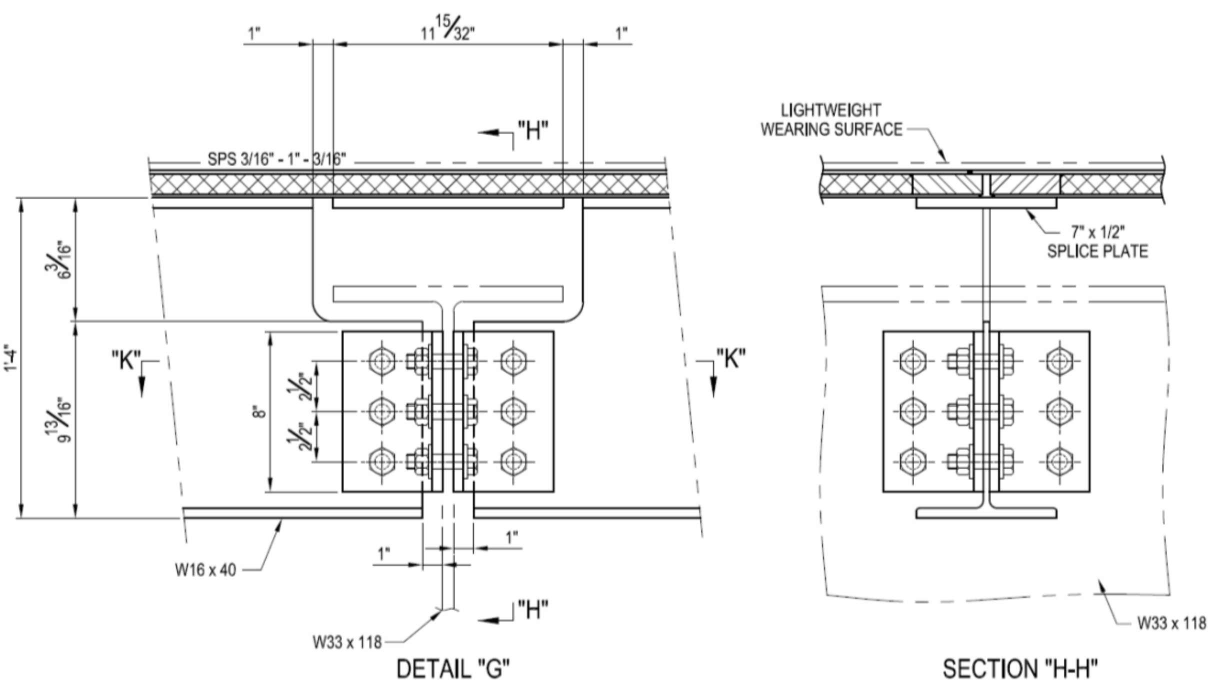
Structural Modifications: In order to accommodate the SPS deck, the following modifications to the bridge are required:

- New stringers are recommended to:
  - Facilitate shop drilling bolt holes for the deck connections, which significantly reduces the field work (i.e. match drilling the holes).
  - Provide a clean, smooth top flange that yields a more uniform bearing and faying surface.
  - Eliminate pitting from previous surface corrosion that retains moisture and is conducive to corrosion development.
  - Eliminate need to exercise care in removing the existing steel open grid deck and corresponding extensive grinding of stringer top flanges to remove residual weld and base metal, which greatly reduces construction duration.
  - Yield higher quality stringers.
  - Permit optimization of the floor system with elimination of some stringers. The new stringers can be spaced anywhere from 4'-0" to 6'-0" on center with this deck solution. The same SPS deck solution can be used for significantly varying stringer spacing because of the characteristics of the load distribution (i.e. wider stringers spacing yields greater width of SPS deck that acts to resist and distribute the load). The new rolled

steel stringers will likely be deeper than the existing stringers to accommodate the clip angle end connections to the floorbeams. It may be possible to utilize a slightly lighter stringer with more efficient section properties, that is composite with the deck, and/or that utilizes higher yield strength (i.e. Grade 50 vs. Grade 36 steel), where possible.

- The rack frames supporting the concrete filled deck (bridges with Hopkins frame drive machinery) require their top flanges be raised, which can be achieved by using bolted flange angles with longer vertical legs.
- Removal of spacer bars from the top of the existing floorbeams and main girders is not required.
- Minor modifications to the counterweight including saw cutting and grouting at the transition to the SPS deck.

Deck Connection Details: The deck will be bolted to the top flange of the new stringers. At the main girders, the deck will be bolted to new steel supports bolted to top flange. For existing riveted, built-up main girders, the new supports can utilize high strength bolts and the existing holes for the top flange rivets. The new supports can also be field welded to the top flange of the main girders; however, because the main girders are fracture critical elements, this approach introduces more risk and will require weld procedure specifications (WPSs) in accordance with AWS D1.5 Bridge Welding Code, Fracture Control requirements.

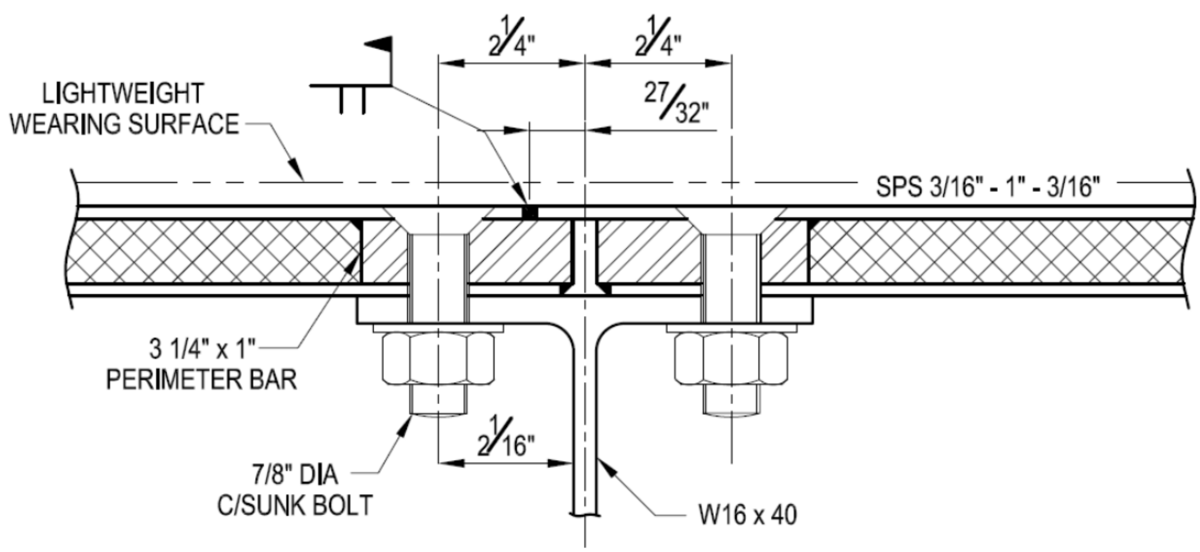


SPS Panel Deck Connection Details

The SPS deck for each leaf will extend from the front of the counterweight to the tip of the leaf (i.e. the SPS deck will replace both the steel open grid and concrete filled grid decks) and will extend the width of the roadway from curb to curb. In order to minimize the number of panel splices, which add significant weight to the deck, the SPS panels will generally by oriented with the long dimension parallel to the roadway centerline with the panels spliced over each stringer or possibly every other stringer. The panels can be made of a length where only one or two transverse splices are required. The volume of the elastomer core and/or shipping and handling generally govern the length of the panels.

Panel Splice Details: IE has developed several SPS panel splice-connection details, with the preferred and recommended detail consisting of a combination of field bolting and welding. The connection serves the dual purpose of connecting the SPS deck to the supporting steel beams and splicing the panels together to provide continuity. This connection also is used to make the deck composite with the supporting steel beams.

The bolted portion of the connection utilizes a countersunk bolt in a slip-critical connection to create a slush deck top surface that can accept a thin, lightweight wearing surface. Although, *AASHTO LRFD Bridge Design Specifications* do not recognize the use of countersunk bolts in a slip-critical connection, the bolts can be fully tensioned using turn-of-nut method, which produces pre-compression across the faying surfaces needed to resist slip.



SPS Deck Panel Splice Detail

The restraint from the bolted connection can introduce significant residual tensile stresses if welding is performed after bolting. Residual tensile stresses are additive to the tensile fatigue stresses, and may reduce fatigue life of the steel connection. As such it is recommended that the panels be bolted after welding is performed.

In some applications, this detail has permitted water to enter the elastomer cavity through poorly seated countersunk bolts. The water froze during cold winter conditions resulting in failure of the panels. Although there is a lower risk of freezing in Florida, water in the elastomer cavity presents a potential concern with corrosion.

Wearing Surface: SPS deck requires a lightweight, skid resistant wearing surface that bonds well and protects the steel top plate from corrosion. Available wearing surfaces that meet these requirements include:

- Thin epoxy polymer wearing surface with:
  - Several manufacturers with similar products that permits competitive bidding opportunities,
  - Unit weight of 3 to 4 psf for two-layer system with ¼" total thickness,
  - Good skid resistance (0.8 to 0.9 friction coefficient),
  - Shop application of large sections and field touch-up at welded joints,
  - Ability to easily replace and repair surface,
  - Significant experience in similar applications, but
  - Limited service-life (10 to 15 years) requiring period removal and reapplication.
- Hot-sprayed aluminum oxide grit (e.g. SlipNOT) with:
  - Unit weight of 0.5 to 1.0 psf,
  - Good skid resistance (0.8 to 0.9 friction coefficient),
  - Shop application, but
  - No experience as permanent roadway surface although limited experience as temporary roadway surface in small areas (i.e. used on small plates to temporarily cover holes in roadway),
  - Additional research required to verify durability and long-term skid resistance,
  - Currently no support from supplier to re-apply in field; however, this could change in the future or another technology may be developed.

(See Section 4 on Wearing Surface Evaluation for more specifics).

Weight and Span Balance Requirements: The total weight of the required SPS deck and associated perimeter bars, splice plates, bolts, main girder supports, and wearing surface is significantly heavier than the weight of the typical existing deck to be removed. A deck that is heavier than the existing steel open grid deck will also require additional counterweight ballast, equal to two to three times the net increase in weight forward of the trunnion, to balance the leaf.

Limited capacity of the trunnion assemblies, limited available space in and around the counterweights, and limited capacity of the main girders typically limit the total increase in weight that can be accommodated.

There are often opportunities to offset some of the additional weight by replacing other components with lighter components (although this unnecessarily increases the required modifications to the bridge and cost of the project) including:

- Replacement of the concrete filled portion of the deck with the proposed lightweight solid deck will reduce the overall weight of the deck. However, because this deck is located close to the trunnion, with more of the deck located back of the trunnion, the replacement does not significantly reduce the required additional counterweight ballast.

- Replacement of the stringers with lighter, more efficient sections and/or reduction in the number of stringers.
- Replacement of steel sidewalk grating with lighter aluminum sidewalk plate or planking.
- Replacement of the steel sidewalk support members and cantilevered bracket bracing members with aluminum members.
- Replacement of steel curbs and/or median with ones made from aluminum.
- Replacement of steel bridge railing with lighter crash tested aluminum railing (e.g. Edgerail).

2.1.11 Costs

Construction Costs: The cost of the SPS deck system is anticipated to be significantly higher than the cost to replace steel open grid roadway flooring (i.e. approximately two times the cost). The cost can vary due to a number of factors and depends on the modifications required to fully implement the SPS deck system. This anticipated work includes a number of items including:

- Removal and disposal of the existing steel open grid and concrete filled deck,
- Fabrication and installation of the new SPS deck panels,
- Replacement of the stringers including end connections,
- Removal of the main girder spacer bars and installation of new supports including replacement of some of the top flange rivets with high strength bolts or field welding the supports,
- Installation of the wearing surface,
- Minor modifications to the counterweight including saw cutting and grouting to accept the SPS deck,
- Addition of ballast (e.g. adjustment blocks, concrete and/or steel ballast) secured to the counterweight,
- Span balance including detailed balance calculations, and instrumentation and recording of the balanced condition before and after the work,
- Adjustment of the live loads shoes in conjunction with the deck alignment,
- Adjustment of the span locks in conjunction with the live load shoe adjustments,
- Possible modification of the top of the rack frames (bridges with Hopkins frame drive systems and where the rack frame supports the deck),
- Possible incidental work to offset the increased weight including replacement of sidewalk grating, sidewalk supports, bridge railing, curbs and/or medians with lighter members,
- Possible retrofit work to the trunnion assemblies to increase capacity including new trunnion bearing bushings with higher strength bronze material or spherical roller bearings,
- Traffic control,
- Mobilization work.

Maintenance Costs: The cost to maintain the SPS deck is anticipated to be similar to that of the steel open grid roadway flooring. Many maintenance activities will be eliminated or significantly reduced, while other maintenance activities will be added.

Reduced maintenance activities include:

- Reduction in the frequency of required cleaning and painting of the bascule leaf steel, as the solid deck better protects these elements,
- Elimination of the need to periodically repair broken steel open grid attachment welds,
- Elimination of need to periodically repair cracked secondary and tertiary grid bars,
- Elimination of the need to periodically improve skid resistance of steel open grid (e.g. scarification of top surface),
- Reduction in the future replacement of the deck.

Added maintenance activities include:

- Periodic repairs or replacement of the wearing surface (e.g. thin epoxy polymer wearing surface),
- Possible more frequent replacement of trunnion bearing bushings due to heavier loads on bearings.

Salvage Cost: The salvage value for SPS deck will be relatively low with limited scrap value for the steel in the panels. Although many of the Florida bascule bridges are of a similar configuration, it will be difficult to remove the panels from one bridge and relocated them to another bridge without damaging the panels because of the welded connection and the somewhat sensitive bond between the elastomer and the steel faceplates.

Design Cost: The design cost is anticipated to be significantly more than that for steel open grid deck due to the need to perform inelastic, non-linear, finite element analysis for each design to achieve the lightest possible weight solution. In addition, because the SPS deck details will be initially unfamiliar to the bridge design community, the cost of the plans production will also be higher, until the design community becomes more comfortable with the design and details, develops design skills and work product (plans and calculations) that can be adapted for use on multiple projects.

Inspection Cost: The inspection cost may be slightly higher than that required for replacement with steel open grid deck, at least initially, as the construction community becomes more comfortable with the quality control requirements for this new type of deck system and the unique materials. The shop fabrication and welding inspection and field bolting and welding inspection are anticipated to be slightly more than that for replacement with steel open grid deck.

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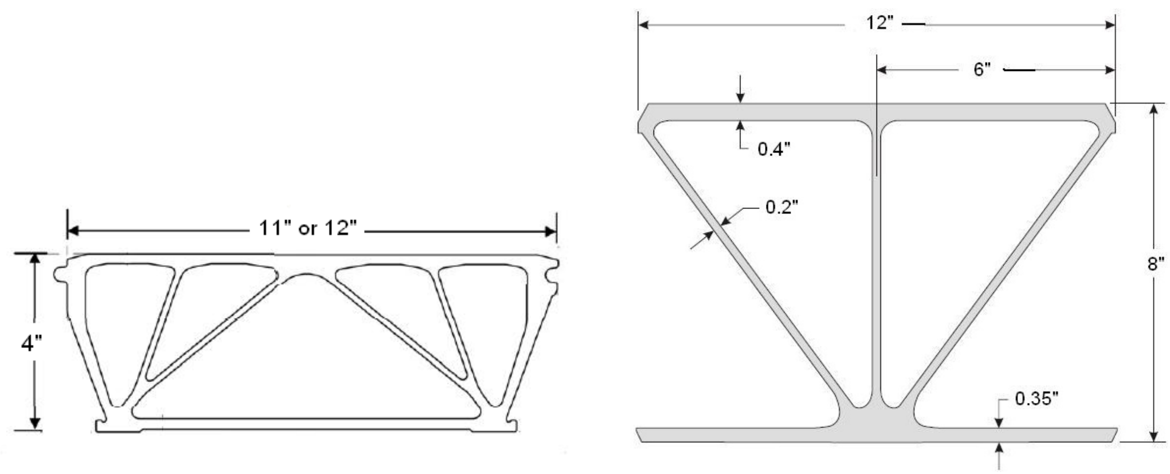
2.2 ALUMINUM ORTHOTROPIC DECK

2.2.1 Description

Aluminum alloys have much to offer for bridge deck applications, and continue to be used, primarily overseas, where their lightweight, high strength-to-weight ratio and excellent corrosion resistance satisfy service requirements. Aluminum is manufactured by an extrusion process, which permits highly customized sections that can be optimized for a given application. The lack of widespread use of aluminum, despite the structural and maintenance advantages, is primarily due to the high initial cost of the material.

Today, there is a limited number of bridge deck extrusions that have been developed and are available for use. SAPA Group currently offers two extruded aluminum orthotropic bridge deck products that have been developed and used on bridges in limited use worldwide including installations on bascule bridges:

- SAPA 100, 4-inch (100 mm) deep, 11-or 12-inch wide plank-like section, connected with adjacent section with tongue and groove connection.
- SAPA R-Shape, 8-inch deep, 12-inch wide section fabricated into wider panels by friction-stir longitudinal weld at both top and bottom flanges.



(a) (b)

Available extruded deck sections (a) Sapa 100 (b) Sapa R-shape.

<u>Material</u>: A great number of aluminum alloys might be chosen for bridge deck construction, but those most highly recommended and used currently because of their superior combination of strength, corrosion resistant, and overall ease of fabrication are alloys of the 5XXX series are used for the plate components, and the 6XXX alloys are used for the extruded shapes. Alloy 6063 is a particular favorite for the extrusions where complex and/or hollow sections are used.

Deck systems typically include a thin epoxy polymer bridge deck overlay.

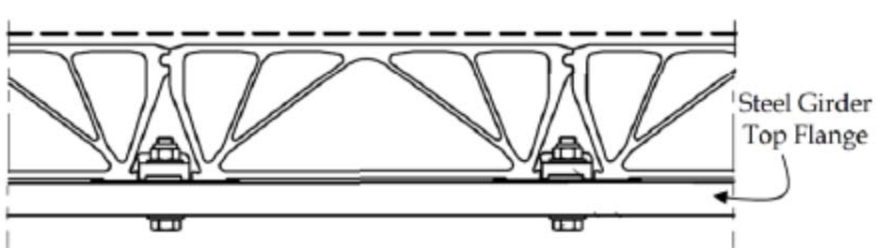
2.2.2 Product Development and Corporate Information

There is a long history (nearly 80 years) on the use of aluminum as a material for bridge structural members and bridge deck in limited use. The first practical use of aluminum in bridge applications can be traced to 1933 when the timber and steel floor system in the Smithfield Street Bridge in Pittsburgh, PA, was replaced by an aluminum deck. The change was made to reduce the dead load and increase the live load capacity. The new deck was a riveted orthotropic deck. The aluminum deck structure carried two tracks of electrified trolley cars and two lanes of motor traffic and was the major artery for traffic in Pittsburgh. The 1933 deck structure remained in service without problems for 34 years. In 1967 the deck was upgraded with a new welded aluminum orthotropic deck with increased load carrying capacity for larger, heavier trolleys and trucks. This aluminum deck remained in service for 26 years without problems until 1993 when it was replaced by a steel deck, due to short-term economics, not life-cycle cost. There were also seven highway and rail bridges in the United States and ten in Europe constructed with aluminum superstructures from the 1940's through the 1960's.

SAPA Group, the world's largest aluminum profile company, based in Sweden and with numerous manufacturing plants throughout North America, has significant experience with aluminum bridge deck technology that has evolved from 43 years of experience. SAPA currently owns patents for aluminum orthotropic bridge deck technology that has been used on 70 bridge projects in Europe since 1987 and more than 110,000 square feet of aluminum bridge deck worldwide. More information regarding SAPA can be found at www.sapagroup.com.

SAPA 100 Section: The SAPA 100, 4-inch deep extrusion is manufactured specifically for bridge deck applications and includes both 11-inch and 12-inch wide planks. The product has not been used in the United States, but SAPA reports nearly 50 installations in Europe along with a similar product, SAPA 50, 2-inch deep plank not considered in this study. The individual planks are placed on top of the support framing, side-by-side and connected to each other at the top of the planks with tongue and groove connection. The attachment of the plank to the supporting framing is by way of clamps that engage a lip at the bottom plate between the planks, which makes the bolts accessible. A thin, epoxy-polymer wearing surface is typically applied to the top of the planks.

The unit weight of planks is approximately 14 psf, excluding fasteners, wearing surface, and other appurtenances. With these additional items, the overall unit weight of the deck system is approximately 18 psf, which is very similar to the unit weight of many existing steel open grid decks.



SAPA 100 Aluminum Plank Deck System.

Elements of this deck system were tested and evaluated in 2009 as part of a Florida Department of Transportation funded research project to identify a viable alternative deck system for steel open grid deck. The study performed load testing of individual planks under simulated AASHTO vehicular loading to evaluate structural performance of the planks. The load testing was compared with finite element analysis. The research also load tested the capacity of the tongue and groove connection between the planks and the capacity of the attachment hardware. The report concluded that this deck system was a feasible alternative to steel open grid roadway flooring.

Despite the promising performance of elements of this deck system, the research did not consider a number of important factors:

- The relatively flexible Florida bascule leaf structures experience significant cantilever deflections (i.e. significant tension and corresponding elongation of the main girder top flange) both during operation and with vehicular traffic on the span. The large number of transverse tongue and groove joints between the planks will open and close under these deformations. This movement will likely result in reflective cracking of the thin epoxy polymer wearing surface at the joints. This will also permit moisture to penetrate these joints resulting in potential corrosion concerns of the steel members below.
- Although the clamp-type connection hardware performed well in laboratory static load testing, there are potential long-term serviceability concerns with this type of connection. The relatively flexible Florida bascule bridges are known to experience significant vibrations from traffic loading and there are concerns that the clamp-type connection hardware will loosen under these vibrations. Similar clamp-type hardware has been used on other aluminum products on bascule bridges including sidewalk grating and pedestrian railings and has experienced loosening of the hardware. The clamp-type connection requires tight fabrication tolerances and nearly perfect fit-up to ensure that the parts are drawn into tight contact. Small gaps can result in movements between the parts that reduce the bolt pre-load and allow the nut to loosen over a period of time from vibrations. Bolted connections that draw the faying surfaces of the two parts tightly together and that can be fully tensioned have demonstrated better performance.
- The structural analysis and design for this deck system is complex and there currently are no simplified, closed-form equations available to assist designers in estimating wheel load distribution to the planks. Without simplified equations, finite element analysis is the only practical available tool to estimate this load distribution. The use of finite element analysis to design a deck for each bascule bridge rehabilitation project that requires deck replacement adds significant engineering cost to the project and is generally not considered practical.

Although promising in many respects, SAPA 100 deck system is not ready for immediate implementation as an alternative deck system for steel open grid deck on existing bascule bridges in Florida. More research is required to verify the performance of wearing surface and clamp-type connections in this application, and a simplified, closed-form, set of engineering equations are needed to compute the wheel load distribution to the planks, before this product can be recommended. In addition, other aluminum orthotropic bridge deck products are available that address the above concerns. As such, this product has not been further evaluated in this study.

SAPA R-Section Deck: Sapa R-Section, 8-inch deep extrusions were developed and are manufactured specifically for bridge deck applications. The 12-inch wide extrusions are fabricated into wider panels by friction-stir welding the extrusions together. The deck system also includes a half-width, special extrusion that accommodates a bolted splice between panels that is flush with the top surface of the deck. Recent advancements in friction-stir welding allows for faster and more efficient fabrication of panels. Friction-stir welding also introduces significantly less heat than traditional arc welding that can weaken the base metal.

This extrusion was originally developed by Reynolds Metal Company under trade name Alumadeck. Reynolds Metal Company was later acquired by Alcoa, Inc. and then SAPA Group acquired the technology and fabrication facilities from Alcoa. This deck system is currently recognized as Sapa R-Section.

The unit weight of the extrusions is approximately 21 psf, excluding wearing surface, connection hardware, splice plates, and other appurtenances. With these additional items, the overall unit weight of the deck system is approximately 25 psf.

Friction-stir Welded Aluminum Sapa R-Section Panel.

Attachment of the SAPA R-Section extrusion to the steel framing is achieved by bolting through the bottom plate of the extrusion. Because the panels are made continuous, the interior of the panels are not directly accessible for bolting. As such, SAPA has developed a procedure to insert the bolts.

- A long aluminum angle (approximately half the length of the panel) is fabricated with the bolts secured to the horizontal leg.
- The angle with the bolts is inserted in the open end of the panels between the panel web members. The stiffness of the angle allows it to be manipulated from the end and permits the bolts to be aligned with the pre-drilled holes in the panels and supporting framing.
- The openings between the panel web members must be parallel to the framing members in order to use this procedure. The location of the supporting framing members must be located and aligned such that the bolts can be connected to the flange. It is recommended that the bolt holes in the panels and framing members be match drilled to ensure alignment.

- The head of the bolts are locked in to prevent twisting during bolt tightening by the vertical leg of the angle. Bolts are tightened by turning the nut at the underside of the top flange of the framing member.

2.2.3 Recent Bridge Installations

Virginia Department of Transportation implemented Alumadeck in two experimental bridge rehabilitation projects in 1996:

Corbin Bridge: Rehabilitation of the historic Corbin Bridge in Huntingdon, VA included replacement of the existing bridge deck with lighter weight aluminum deck to reduce dead load, preserve the historic truss structure, and increase live load capacity.

Little Buffalo Creek Bridge: Replacement of the Little Buffalo Creek Bridge on SR 58 near Clarksville, VA with a new bridge that included a lightweight aluminum deck was performed for research purposes.

- Research included load testing and structural evaluation that compared theoretical and measured static and dynamic response to vehicular loads. The research also investigated the composite behavior between girders and deck, live load distribution to the girders, and deck fatigue performance.
- The bridge consisted of a 54'-7¼" long single-span structure with four steel girders and Alumadeck bridge deck.
- The deck panels were oriented with the longer dimension parallel with the roadway centerline and made composite with the girders.

The Alumadeck performed well in both bridges and the observed behavior was close to that estimated by theoretical calculations. The researchers concluded that Alumadeck is a feasible alternative to concrete decks on fixed-span bridges, where it is crucial to reduce the weight and improve live load capacity.

(a)

(b)

Virginia DOT Alumadeck Installations: (a) Corbin Bridge, (b) Little Buffalo Creek Bridge

Alan Road Bridge: Replacement of the superstructure on the Alan Road Bridge over Farmington River near Sandisfield, MA by Massachusetts Department of Transportation in 2001, included a lightweight

SAPA R-Section bridge deck to minimize total weight of the structure, preserve the timber abutments, and permit rapid construction to minimize the duration the bridge would be out of service.

- The new superstructure (deck and girders) was fabricated off-site as a single unit, shipped by truck to the site, and installed on abutments using a single crane lift.
- The bridge is a 53’-3¾” long, single-span structure with four steel girders and 889 square-feet of SAPA R-Section aluminum deck.
- The deck panels were oriented with the longer dimension parallel with the roadway centerline and made composite with the girders.

MassDOT Sapa R-Section Installation: Alan Road Bridge over Farmington River, MA

Although the SAPA R-Section deck demonstrates tremendous promise, implementation of this deck on a typical Florida bascule bridge presents a number of challenges that makes the deck less desirable. These challenges are described below.

Significant modifications to existing Florida bascule bridges are required to accommodate a deck that is 3 inches deeper than the existing 5-inch deep steel open grid deck. In order to accommodate this deck, the roadway profile at the bascule span must be raised 3 inches which requires:

- Adjustment of the approach span deck profile to match the raised deck on the bascule leaf by lifting the end at the bascule pier by installing a 3-inch thick fill at the flanking beam floorbeam bearings,
- Replacement of the bascule pier sidewalk or raising of the sidewalk by pouring a new sidewalk slab on top of the existing sidewalk slab,
- Raising the bascule leaf sidewalk by replacing the sidewalk support framing, curbs, sidewalk grating, pedestrian railings, and span lock access hatches,
- Raising the control house floor and doors, flooring, floor hatches, ladders, plumbing, control desk, electrical penetrations, etc.

The span capability of the deck (up to 12 feet) would permit the deck to span longitudinally between floorbeams and eliminate the stringers with new floorbeams added at mid distance between existing floorbeams (i.e. at the location of the existing intermediate cantilevered brackets). The deck can also span transversely across stringers at a wider spacing.

An alternative to raising the roadway profile was also investigated, but was found to introduce too many detailing concerns. The deck will have to be modified at the main girders, floorbeams and counterweight girders with shallower extrusions (i.e. the deck thickness will have to step) with the following concerns:

- Steps in the deck thickness will introduce stress risers and numerous undesirable details.
- There does not appear to be a practical solution to accommodate the stepping of the deck thickness at both the floorbeams and main girders without introducing a significant number of small pieces and corresponding number of additional joints and splices.
- The typical deck connection details used by Sapa for this deck system will also not be practical.

The above concerns are applicable whether the deck is oriented with the extrusions parallel to the roadway centerline or perpendicular to the roadway centerline.

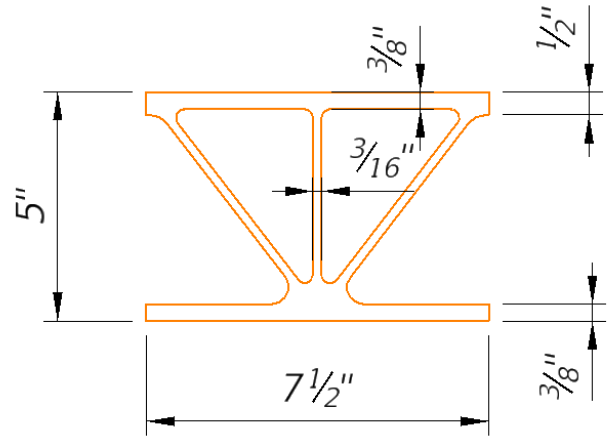
The total weight of the SAPA R-Section deck and associated splice plates, bolts, main girder supports, and wearing surface is significantly heavier than the weight of the typical existing deck to be removed. This also will require additional counterweight ballast, equal to two to three times the net increase in weight forward of the trunnion, to balance the leaf. The additional weight may also overload the trunnion assemblies, which have limited reserve capacity (see Trunnion Capacity Evaluation). There are opportunities to offset the increase in deck weight with other modifications (although this unnecessarily increases the required modifications to the bridge and cost of the project).

2.2.4 Florida Bascule Bridge Specific Solution

<u>Deck Solution</u>: In recognition of the significant advantages of aluminum orthotropic deck systems and the need for a lightweight, solid deck product that can replace steel open grid deck on Florida bascule bridges with minimal modifications, a 5-inch deep version of the SAPA R-Section, similar to the depth of the 5-3/16" deep steel open grid deck has been developed and evaluated for consideration. This product is considered a derivative of already developed aluminum orthotropic deck designs. The proposed alternative extrusion was developed, analyzed and evaluated by the research team in consultation with SAPA consultants including Randy Kissell, lead author of Chapter 7 (Aluminum Structures) of the *AASHTO LRFD Bridge Design Specifications*. Financial viability and product support has been discussed with SAPA executives.

The alternative orthotropic deck design takes advantage of previous product development for the SAPA R-Section and Alumadeck including research, testing, engineering design, and latest advancements in aluminum technology including friction-stir welding. Because the proposed deck would be nearly identical to the SAPA R-Section deck, the majority of research previously prepared specifically for the SAPA R-Section (e.g. live load distribution, strength, fatigue, deflection, and composite behavior) would still be valid for the new extrusion. Engineering calculations based on previous research for the SAPA R-Section verifies the adequacy of the proposed section. Additional testing of proposed alternative connections to the supporting steel framing may be warranted.

The alternative extrusion is depicted below.



Alternative 5-inch Deep Aluminum Orthotropic Deck Extrusion

Analysis of this alternative extrusion yielded the following results:

- The unit weight of the extrusions is approximately 17 psf, excluding wearing surface, connection hardware, splice plates, and other appurtenances. With these additional items, the overall unit weight of the deck system is approximately 21 psf.
- Deck is designed to span transversely across stringers.
- Span capability of the deck system is a maximum of 8'-9" between stringers (governed by L/800 deflection limits.)
- The deck system comfortably meets all *AASHTO LRFD Bridge Design Specifications* Strength, Service (Deflection) and Fatigue Limit States (including newly revised and adopted provisions).
- Design is generally governed by local stresses in deck top plate under wheel patch loads.
- The deck is very stiff with very small live load deflections (i.e. approximately L/3000 for stringer spacing typical for Florida bascule bridges).
- The alternative extrusion appears to be more efficient than the SAPA R-Section with lower governing top plate localized stresses, despite the use of conservative load distribution and structural support assumptions used to evaluate SAPA R-Section. The lower stresses are due to the use of the same top plate thickness as the SAPA R-Section, even though there is a shorter effective span between web members.

As discussed with SAPA, there may be opportunities to further optimize this alternative extrusion to achieve additional structural efficiency and weight reduction.

The 5-inch deep alternative extrusion maintains all of the advantages of the 8-inch deep SAPA R-Section extrusion, but eliminates the significant disadvantages including:

- The 5-inch deep profile does not require raising the bascule span roadway profile and corresponding substantial bridge modifications.
- The weight of the deck is much closer to that of the existing steel open grid deck. As such, the adjustments to the counterweight and additional load on the trunnions are minimized. The

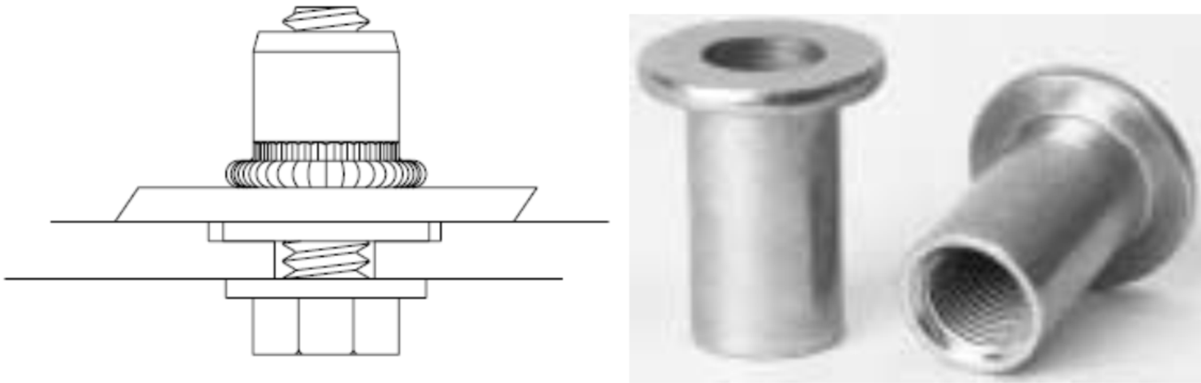
solution does not require other modifications needed to offset the increase in weight, not otherwise required.

Structural Modifications: The following modifications to the bridge are required to implement the aluminum orthotropic deck:

- Existing stringers supporting existing steel open grid deck can be reused and remain as currently configured. However, replacement of the stringers is recommended in order to:
  - Facilitate shop drilling bolt holes for the deck connections, which significantly reduces the field work (i.e. overhead match drilling these holes).
  - Provide a clean, smooth top flange that yields a more uniform bearing and faying surface.
  - Eliminate pitting from previous surface corrosion that retains moisture and is conducive to corrosion development.
  - Eliminate need to exercise care in removing the existing steel open grid deck and corresponding extensive grinding of stringer top flanges to remove residual weld and base metal, which greatly reduces construction duration.
  - Yield higher quality stringers.
  - Permits optimization of the floor system with elimination of some stringers.
- Existing stringers supporting the concrete filled steel grid deck over the machinery areas require lowering by 2 inches to address difference in height between the 3-inch existing deck and new 5-inch deck.
- The rack frames that support the concrete filled deck (bridges with Hopkins frame drive machinery) require that the top flanges be lowered by removing and reattaching the top flange, and trimming the top of the web.
- Removal of spacer bars from the top of the existing floorbeams and main girders is not required, but is recommended to eliminate unnecessary loose contact between the aluminum deck and steel framing.
- Minor modifications to the counterweight including saw cutting and grouting at the transition to the aluminum deck.

Deck Connections: The deck will be bolted to the top flange of the new stringers. At the main girders, the deck will be bolted to new steel supports bolted to top flange. For existing riveted, built-up main girders, the new supports can utilize high strength bolts and the existing holes for the top flange rivets. The new supports can also be field welded to the top flange of the main girders; however, because the main girders are fracture critical elements, this approach introduces more risk and will require weld procedure specifications (WPSs) in accordance with AWS D1.5 Bridge Welding Code, Fracture Control requirements.

An alternative deck connection detail is proposed to attach the aluminum orthotropic deck to the steel framing using a blind installed internally threaded rivet type connection, a.k.a. Rivnut. Rivnuts were originally developed and patented in the 1936 for use in the aircraft industry to connect thin elements and make blind attachments. Advancements in Rivnut technology now include high-strength and corrosion resistant materials that can accept ASTM A325 high-strength bolts. Currently, the maximum available size of high-strength rivnuts is ½-inch diameter; however, Bollhoff, the manufacturer of the Rivnuts, has indicated that a custom ¾-inch diameter can be fabricated.

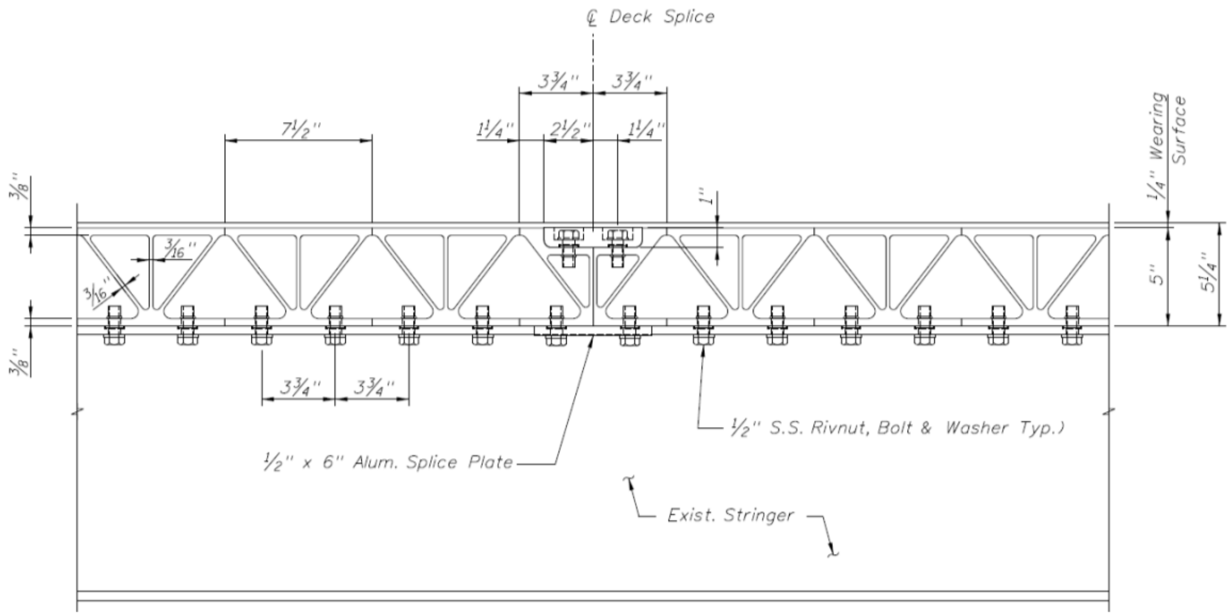


Rivnut (Internally Threaded Rivet) Connection

The deck will be conservatively treated as non-composite in sizing the supporting steel stringers, while the number and size of connection fasteners will be determined by conservatively assuming that the deck acts compositely with the stringers. Oversized holes in the steel members will be used to accommodate thermal expansion with standard sized holes used at the center of thermal movement to secure and maintain the alignment of the panels as the movement occurs and as the bridge raises and lowers. Preliminary calculations for the strength of the composite connection indicate that ½-inch diameter bolts at 3¾ inches on center (i.e. four connectors per panel opening between the members) will be adequate. Alternatively, ¾-inch diameter bolts spaced at 7½ inches on center (i.e. two connectors per panel opening between the web members) will also be adequate. Bolts throughout the panels can be omitted intermittently due to detailing issues without concern.

Panel Splice Details: The aluminum deck for each leaf will extend from the front of the counterweight to the tip of the leaf (i.e. the aluminum deck will replace both the steel open grid and concrete filled grid decks) and will extend the width of the roadway from curb to curb. The transversely spanning panels can be made in lengths up to approximately 40 feet. This will permit the panels to extend the full width of the roadway for two-lane bridges (typically 28 to 32 feet on most two-lane Florida bascule bridges) and half the width of the roadway for four-lane bridges (typically 42 to 48 feet on most four-lane Florida bascule bridges) with an open joint between the two halves below the median. The panels can be made shorter and in two halves to accommodate phased deck replacement where required to facilitate traffic control.

Panel splices utilize a special half-extrusion that is friction-stir welded to the other extrusions along the edges of each panel. When two adjacent panels are butted together, the special half-extrusions accommodate a bolted aluminum splice plate that fits in a recess in the top of the extrusions to splice the panel top plate and maintain a flush deck surface. An aluminum splice plate is used on the underside of the panels to splice the bottom plate. The use of Rivnuts, similar to the deck connection, is recommended to address the blind connection for the splice plates.



Possible Detail of 5-inch Aluminum Deck Spanned Transversely Attached to Existing Stringers

Wearing Surface: The aluminum deck requires a lightweight, skid resistant wearing surface that bonds to the aluminum top plate. Available wearing surfaces that meet these requirements include:

- Thin epoxy polymer wearing surface with:
  - Several manufacturers with similar products that permits competitive bidding opportunities,
  - Unit weight of 3 to 4 psf for two-layer system with ¼" total thickness,
  - Good skid resistance (0.8 to 0.9 friction coefficient),
  - Shop application of large sections and field touch-up at welded joints,
  - Ability to easily replace and repair surface,
  - Significant experience in similar applications, but
  - Limited service-life (10 to 15 years) requiring period removal and reapplication.
- Hot-sprayed aluminum oxide grit (e.g. SlipNOT) with:
  - Unit weight of 0.5 to 1.0 psf,
  - Good skid resistance (0.8 to 0.9 friction coefficient),
  - Shop application, but
  - No experience as permanent roadway surface although limited experience as temporary roadway surface in small areas (i.e. used on small plates to temporarily cover holes in roadway),
  - Additional research required to verify durability and long-term skid resistance,
  - Currently no support from supplier to re-apply in field; however, this could change in the future or another technology may be developed.

(See Section 3 Wearing Surface Evaluation for more specifics).

Weight and Balance Requirements: Due to small differences in the unit weight of the existing deck and new deck, the counterweight will require some adjustment. Because the weight of the new deck is very similar to the typical steel open grid deck, adjustments can likely be made by adjusting the balance blocks. Other modifications to offset the weight are not anticipated.

2.2.5 Functionality and Safety

Load Capacity: An aluminum orthotropic deck designed to governing stress limits will have corresponding load carrying capacity in excess of that required to support AASHTO LRFD HL-93 Live Loads. The unit weight of the proposed aluminum deck will be close to that of the existing steel open grid deck, and thus there will be no reduction in capacity of the bascule span members.

Rideability: The aluminum orthotropic deck and the corresponding applied wearing surface will provide a smooth, continuous riding surface with a surface roughness comparable to asphalt or concrete pavement. Because the aluminum orthotropic deck has greater stiffness than the existing steel open grid deck, deflections and vibrations will be significantly reduced, which will further improve the quality of the ride.

Skid Resistance: Skid resistance from the applied wearing surface will be similar to that of asphalt pavement. See Section 3 Wearing Surface Evaluation.

Noise: The solid surface of the aluminum orthotropic deck is anticipated to reduce noise generated by tires in contact with the deck relative to steel open grid deck. However, the hollow cells of the deck may still generate some resonance due to vibration of the deck thin web members.

Bicycle Safety: The aluminum orthotropic deck provides a solid riding surface for the roadway and shoulders with small longitudinal open joints (less than ½" wide) located immediately adjacent to the curbs or barriers, which will greatly improve bicycle safety. Transverse deck joints between the two bascule leaves and between the bascule span and bascule pier will range from ¾" to 1½" in width, but should not be a concern for bicyclists.

2.2.6 Durability and Service Life

Service Life: It is anticipated that the aluminum orthotropic deck system will provide a minimum service life that exceeds the remaining life of a typical existing bascule bridge (i.e. 30 to 40 years). Installations of aluminum deck in similar coastal environments in Europe confirm that this service life can be achieved.

Fatigue Resistance: Significant research on fatigue of aluminum orthotropic decks and conservative design practice for fatigue provides that confidence that fatigue will not be a concern. Advancements in aluminum welding technology (e.g. friction-stir welding) yields significant improvements in fatigue resistant at the welded joints, although, this increased fatigue resistance is conservatively neglected in current design practice.

Corrosion Resistance: Aluminum has been commonly been used on bascule bridges in Florida for various components including sidewalk surfaces and pedestrian railings without significant corrosion concerns, where appropriate materials and detailing practices are used. Aluminum can be subject to several types of corrosion that are either inconsequential or that can easily be mitigated.

Open Air Corrosion: Uncoated aluminum provides excellent corrosion resistance primarily because aluminum spontaneously forms a thin but effective oxide layer that prevents further oxidation. Aluminum oxide is generally impermeable and, unlike the oxide layers on many other metals, it adheres strongly to the parent metal. If damaged mechanically, aluminum oxide layer repairs itself immediately. The aluminum oxide layer is generally stable in the pH range 4 to 9, which is the expected pH in the marine environment.

The corrosion of metals in the open air depends on the duration of wetness and the composition of the surface electrolytes. The duration of wetness refers to the period during which a metal surface is sufficiently wet for corrosion to occur and it is normally considered to be the period when condensation occurs (i.e. duration when relative humidity exceeds 80% and metal surface temperatures are below the dew point temperatures) which is usually during nighttime hours. Condensation does not typically form during daylight hours and condensation from nighttime hours usually evaporates quickly after the sun rises. Surface wetness can also occur during periods of fog and splashing from waves, although the deck on most bascule bridges is usually well above the splash zone. The hollow interior of the aluminum orthotropic deck can be sealed such that there is not a significant change in humidity.

In marine environments, surface corrosion can result in superficial surface pitting, that is generally considered inconsequential. The Swedish Corrosion Institute has carried out field exposure tests in a number of environments and for numerous untreated metals. The average loss in thickness (measured by pit depth) of uncoated aluminum plate in marine environments was found to be less than 10 µm (0.01 mm) per year.

The details of the aluminum orthotropic deck, with a flat, horizontal bottom are generally such that there will be no standing water and thus the presence of an electrolyte is minimized. The thin epoxy polymer, wearing surface provides additional corrosion protection for the top surface of the deck and the high stiffness of the aluminum orthotropic deck provides greater confidence that the wearing surface will not be breached.

Galvanic Corrosion: Galvanic corrosion can occur when dissimilar metals are in metallic contact in the presence of an electrolyte (e.g. wet coastal atmosphere). In the presence of a liquid, a battery cell is created, allowing current to flow with corrosion occurring at the anodic component of the cell. The least noble metal in the combination becomes the anode and corrodes, while the more noble of the metals becomes the cathode and is protected against corrosion. In the aluminum-steel combination, aluminum is less noble than steel and thus is expected to corrode and sacrifice itself for the steel.

Although, galvanic corrosion from the direct contact of uncoated aluminum with steel is a known to occur, this issue is easily mitigated. Where dissimilar metals are used in combination, galvanic corrosion can be prevented by electrically insulating the two materials. Painting the steel is considered an adequate insulator and is a practical solution. The *Aluminum Design Manual* specifies that a steel paint system consisting of a zinc primer and intermediate and finish coats containing aluminum, as is the case for typical Florida DOT preferred coating systems, will provide adequate separation to prevent corrosion due to dissimilar metals. The *Aluminum Design Manual* also specifies that aluminized, hot-dip galvanized or electro-galvanized steel placed in contact with aluminum need not be painted.

Special care should be taken in the selection of the fasteners and/or fastener coatings to avoid galvanic corrosion. There are a number of available steel fastener materials that have been effectively used with aluminum on Florida bascule bridges (e.g. Type 316 stainless steel and hot dip galvanized bolts, nuts and washers). Stainless steel is more noble than the aluminum and thus the fasteners are not expected to corrode; however, the less noble aluminum may experience localized corrosion adjacent to the fasteners in severe conditions, although this has not been common on other aluminum materials on Florida bascule bridges. Galvanized steel fasteners contain zinc, which is less noble than aluminum and will protect the aluminum; however, the oxidation will eventually exhaust the zinc coating and the fastener will have a limited service life. Galvanic corrosion is minimized when the more noble component has a small surface area relative to the less noble component. Because the fasteners have a small surface area, compared to the aluminum deck, galvanic corrosion is less of a concern.

Crevice Corrosion: Crevice corrosion can occur in narrow, liquid-filled crevices (e.g. the joints between panels). Water on the surface adjacent to joints is drawn, through capillary action, into the crevices between the metal surfaces. Use of sealing compounds between components can prevent moisture from entering the crevices and minimize crevice corrosion. Pre-compression of the plates within the joint from proper bolt tightening will also act to seal the crevices.

<u>Impact Resistance</u>: The 3/8” minimum thickness of the top flange plate and the high stiffness of the aluminum orthotropic deck are anticipated to yield relatively good impact resistance in the event that a vehicle overturns and impacts the deck surface.

<u>Fire Resistance</u>: Similar to steel members, aluminum loses strength and stiffness when exposed to high temperatures. However, the threshold temperature where aluminum is affected by heat is lower than that of steel (400 to 600 degrees F for aluminum compared to 900 to 1100 degrees F for steel).

Similar to steel members, aluminum orthotropic deck is likely to survive short duration fires and/or fires with lower temperatures. Because the loss of strength is time-dependent, panels may provide limited structural support for loads on the deck during a fire (e.g. the vehicle on fire, emergency response vehicles and personnel). If the deck panels lose strength during these events, the steel framing below may steel provide some support to contain vehicles.

Only a substantial heat source, such as that from a roadway accident with ignited localized fuel spill, is expected to threaten the integrity of aluminum deck.

<u>Thermal Expansion</u>: The difference in coefficients of thermal expansion between aluminum and steel (12.8×10^{-6}/°F and 6.5×10^{-6}/°F respectively) and the restraining effects from bolting the deck to the steel framing and the stiffness of the steel framing must be considered in detailing the deck. In addition,

as the aluminum deck will have more direct exposure (i.e. the aluminum deck will be directly exposed to the sun, while the steel framing will be shaded by the deck) and aluminum has higher thermal conductivity (i.e. the aluminum changes temperature at a faster rate than steel), the temperature of the aluminum is anticipated to be significantly different than the temperature of the steel. Differential movements between the two materials is anticipated to be significant (i.e. differential movements will exceed 3/8" from counterweight to leaf tip and 1/8" to 1/4" from curb to curb on a typical two-lane and four-lanes Florida bascule bridges, respectively). Because of the magnitude of these differential movements, details for attaching the deck will need to accommodate the movement and prevent restraint that would develop large forces in the deck and steel framing members. More accurate assessment of the differential temperature will need to be determined during design.

The difference in thermal expansion can be addressed as follows:

- Deck panels will extend transversely the full width of the roadway, from curb to curb, for a typical two lane Florida Bascule bridge.
- Deck panels will extend transversely half the width of the roadway, with an expansion joint in the middle of the roadway, beneath the median for a typical four lane Florida bascule bridge.
- The panels will be spliced such that they are continuous within each floorbeam bay in the longitudinal direction, with intermediate expansion joints between the panels located over each of the intermediate floorbeams. Maximum thermal movements are estimated to be less than 1/32-inch within a floorbeam bay.
- Oversized holes in the steel members will be used to accommodate thermal expansion with standard sized holes used at the center of thermal movement (i.e. at the center of the floorbeam bay) to secure and maintain the alignment of the panels as the movement occurs and as the bridge raises and lowers. The panels will bear on 1/8-inch thick, high Durometer (70-90) neoprene pads
- Expansion joints between panels and at the curbs can consist of low cost, low maintenance low modulus silicone joint sealant with backer rods installed against the vertical plates at the edge of the panels or neoprene strip seals secured to the panel special end extrusions.

<u>Chemical Resistance</u>: Aluminum provides similar resistance to chemicals as steel elements on the bridge. The protective properties of the natural oxide layer, yields good resistance to many chemicals. Low or high pH values (less than 4 and more than 9) lead to the oxide layer dissolving and, consequently, rapid corrosion of the aluminum. Inorganic acids and strong alkaline solutions are thus very corrosive for aluminum. The wearing surface provides limited protection of the aluminum from chemicals.

<u>Ultraviolet (UV) Light Resistance</u>: Aluminum is not subject to degradation from UV light and there are no coatings required for the deck system that can degrade.

2.2.7 Design and Analysis

Design Considerations and Approach: Design of the aluminum orthotropic deck will be based on *AASHTO LRFD Bridge Design Specifications*. Design provisions were recently submitted by the aluminum industry to AASHTO for consideration and adoption. The deck is designed for AASHTO LRFD Strength I, Service I (deflections) and Fatigue I Limit States (infinite fatigue life). Similar to steel orthotropic decks, the deck is evaluated for three different structural systems:

- *System 1*: Global Stresses (Strength and Fatigue) in the deck due to composite action with supporting steel framing are evaluated. Although the steel framing will conservatively be designed neglecting composite behavior, it is anticipated that the deck will exhibit some composite behavior due to friction and resistance in the bearing pads between the deck and stringers or main girders. As such, the fasteners used to connect the deck to the supporting members will be evaluated for the composite action.
- *System 2*: Global Stresses (Strength, Fatigue and Deflection) in the deck due to flexure between the stringers are evaluated. Calculations for load distribution to determine flexural moments in the aluminum orthotropic deck panels are based on classical orthotropic deck theory. The load distribution equations have been corroborated by testing of SAPA R-Section panels performed by Virginia Department of Transportation.
- *System 3*: Local Stresses (Strength and Fatigue) in the deck top plate due to wheel patch loads are evaluated.

Calculations can be performed with closed-form equations using spreadsheets (e.g. Excel, MathCAD, etc.).

The design of the deck for typical stringer spacing on Florida bascule bridges is governed by System 3 local fatigue stresses. Deflections corresponding to stringer spacing found on typical Florida bascule bridges are very small (approximately L/3000). The maximum span capability (i.e. stringer spacing) of the deck is 8’-9” and is governed by allowable deflection limits (L/800).

2.2.8 Constructability

Fabrication: The aluminum orthotropic deck panels and other components (e.g. splice plates, end plates, joint plates, and other appurtenances) will be fabricated at an aluminum fabrication plant. The extruded sections will be cut to length and welded together using friction-stir welding to create panels. The panels will then be mated up to the supporting stringers and main girder support angles in an inverted assembly layout (i.e. the panels and stringers oriented upside down) to permit match drilling of the holes for the connections and splices. The Rivnuts will then be installed in to the panels. The wearing surface may also be shop applied to the panels and deck top splice plates.

Tolerances on panel length, width, camber, and flatness will generally be similar to that of steel open grid deck. Tighter tolerances on panel sweep and squareness are needed to ensure proper fit-up of the panels at the splices and because the greater lateral stiffness of the panels will not permit adjustment in the horizontal plane of the panels. The use of standard oversized holes in top flange of the stringers and main girder supports will assist in accommodating small differences between shop and field alignment.

Field Installation: The existing steel open grid and stringers will be removed. The main girder and floorbeam spacer bars will also be removed and the rack frames and counterweight girder top flanges modified as required. The new stringers and main girder support members will be installed. Final drilling of the holes in the webs of the floorbeams for the stringer connection angles will be performed after the panels are aligned to the stringer top flanges. Shims between the stringer connection angles and floorbeam webs will be provided for adjustment. Removal of the existing rivets and final drilling of the holes in the horizontal legs of the new supports at the main girder top flanges (or field welding of the supports if permitted) will be performed with the panels aligned to the supports.

Specialized Inspection: Friction-stir welding, Rivnut fasteners, and thin epoxy polymer wearing surfaces (or hot-spray applied aluminum oxide grit wearing surface if permitted) are less common to the bridge industry and thus inspection of this construction will, at least initially, be considered specialty in nature.

Fabrication of the aluminum deck will require aluminum fabrication and weld inspection. The fabricator will be required to perform quality control and submit weld procedures specifications and certifications and a quality control plan that addresses the required quality control functions to be performed. Because of the special requirements of the friction stir welding, it may be necessary to employ personnel with specialized experience to perform quality assurance for this work.

Rivnut installation and rivnut bolt tightening quality control procedures will need to be developed. Field welding of main girder supports if permitted will require on-site involvement by welding inspectors. The contractor will be required to submit weld procedure specifications and certifications for the field welding. Quality control procedures for the wearing surface will also need to be developed.

Traffic Control: Because the aluminum orthotropic deck panels will be oriented with the long dimension perpendicular to the roadway centerline similar to steel open grid panels, there is an opportunity to replace portions of the deck (i.e. one floorbeam bay at a time in lieu of the entire deck) during short duration (overnight) closures of the bridge in order to minimize traffic impacts. There are also opportunities to replace the deck in phases in order to maintain traffic on the bridge while the work is performed. The modular fabrication of the panels permits the panels to be fabricated in a size (length, width and thickness) that closely matches that of the existing steel open grid panels to be replaced. Small openings between the existing steel grid panels and the new aluminum panels due to small differences in panel dimensions can be temporarily covered with a thin plate. Joints in the panel along the roadway centerline can permit the panels to be replaced in two halves with traffic maintained on the opposite half. Details may need to be developed to accommodate bolting of temporary traffic railing to the aluminum deck panels.

2.2.9 Costs

Construction Costs: The cost of the aluminum orthotropic deck system is anticipated to be significantly higher than the cost to replace steel open grid roadway flooring (i.e. approximately two times the cost).

The cost can vary due to a number of factors and depends on the modifications required to fully implement the aluminum orthotropic deck system. This anticipated work includes a number of items including:

- Removal and disposal of the existing steel open grid and concrete filled deck,
- Fabrication and installation of the new aluminum deck panels,
- Replacement of the stringers including end connections,
- Removal of the main girder spacer bars and installation of new supports including replacement of some of the top flange rivets with high strength bolts or field welding the supports,
- Installation of the wearing surface,
- Minor modifications to the counterweight including saw cutting and grouting at the transition to the aluminum deck,
- Adjustment of balance blocks,
- Span balance including detailed balance calculations, and instrumentation and recording of the balanced condition before and after the work,
- Adjustment of the live loads shoes in conjunction with the deck alignment,
- Adjustment of the span locks in conjunction with the live load shoe adjustments,
- Possible modification of the top of the rack frames (bridges with Hopkins frame drive systems and where the rack frame supports the deck),
- Traffic control,
- Mobilization work.

Maintenance Costs: The cost to maintain the aluminum orthotropic deck is anticipated to be similar to that of the steel open grid roadway flooring. Many maintenance activities will be eliminated or significantly reduced, while other maintenance activities will be added.

Reduced maintenance activities include:

- Reduction in the frequency of required cleaning and painting of the bascule leaf steel, as the solid deck better protects these elements,
- Elimination of the need to periodically repair broken steel open grid attachment welds,
- Elimination of need to periodically repair cracked secondary and tertiary grid bars,
- Elimination of the need to periodically improve skid resistance of steel open grid (e.g. scarification of top surface),
- Reduction in the future replacement of the deck.

Added maintenance activities include:

- Periodic repairs or replacement of the wearing surface (e.g. thin epoxy polymer wearing surface).

Design Cost: The design cost is anticipated to be only slightly more than that for replacement with steel open grid deck, at least initially, as the design community becomes more comfortable with the design and details, develops design skills and work product (plans and calculations) that can be adapted for use on multiple projects. The available closed-form design equations facilitate simple design calculations.

Salvage Cost: Aluminum has a relatively high salvage cost due to the high cost of the material. Because many of the Florida bascule bridges are of a similar configuration, there is an opportunity to relocate the deck panels from one bridge and use them on another bridge or to store previously used panels for use to replace damaged panels on an individual basis.

Inspection Cost: The inspection cost may be slightly higher than that required for replacement with steel open grid deck, at least initially, as the construction community becomes more comfortable with the quality control requirements for this new type of deck system and the unique materials. The shop fabrication and welding inspection and field bolting and welding inspection are anticipated to be slightly more than that for replacement with steel open grid deck.

2.2.10 References

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2.3. FIBERGLASS REINFORCED POLYMER (FRP) COMPOSITE DECK

2.3.1 Description

Fiberglass reinforced plastic (FRP) is a composite material that has a number of characteristics that makes it a good alternative to replace steel open grid deck on bascule bridges. FRP composites can be designed to provide a wide range of mechanical properties including tensile, flexural, impact and compressive strengths. FRP composites are generally lightweight (i.e. approximately 20% of steel) with high strength-to-weight ratio and are generally resistant to creep and fatigue. FRP composites are versatile and can be fabricated in many different configurations, customized specifically for a given application (e.g. bridge decks), designed and fabricated such that the strength is oriented to meet specific configuration and loading demands, made into larger more complex structural components and systems that simplifies connections and minimizes the number of components that must be handled. The relatively low modulus of elasticity of FRP composites make them relatively flexible compared to other bridge deck materials and thus deflections generally control the design of FRP bridge decks. FRP composite materials are susceptible to degradation from ultraviolet light and chemicals; however, the materials can be formulated with additives to improve the resistance to these effects.

Material: FRP generally consists of a combination of:

- Polymer (plastic) matrix (e.g. thermoplastic or thermoset resin) such as polyester, isopolyester, vinyl ester, epoxy, or phenolic,
- Reinforcing agent (e.g. as fiberglass, carbon fiber, aramid or other reinforcing material) such that there is a sufficient aspect ratio (length to thickness) to provide a discernible reinforcing function in one or more directions.
- May also contain fillers, additives, core materials that modify and enhance the final product.

The constituent elements in a composite retain their identities (they do not dissolve or merge completely into each other) while acting in concert to yield the desired properties.

Various FRP composite bridge deck products have been developed over the last 15 years. Thickness of the various deck products have ranged from 4 to 9 inches depending on the intended application and the thickness of the existing bridge deck to be replaced. Decks are typically designed to be supported on and span transversely across longitudinally spanning girders or stringers similar to other conventional decks. The FRP composite decks are typically modular with panels joined together in the field to create a seamless final installation. The length of the panels are typically equal to the full width of the bridge and the width of individual panels are typically 8 to 10 feet wide for fabrication, shipping and handling purposes. The majority of FRP composite deck systems consist of pultruded shapes that are adhesively or mechanically bonded together in the field, and mechanically fastened to the supporting structural framing. Nearly all FRP composite decks that have been developed are multi-cell hollow sections with top and bottom faceplates and a series of web members that connect the top and bottom face plates. The configuration of the cross section and details including splices between panels and connection to the supporting structure has varied significantly among different deck products.

2.3.2 Product Development and Corporate Information

Since 1996, there have been a number of different FRP composite deck systems that have been developed, tested, and put into service throughout the United States. More than 80 vehicular bridges in the United States have been constructed or rehabilitated using FRP composite decks. FRP composite bridge decks technology continues to evolve with ongoing research and product development and enhancement. Installations to date have yielded mixed durability and performance results.

Fabrication of FRP composites typically uses one of three current manufacturing techniques:

Pultrusion: Pultrusion is a manufacturing process for producing continuous lengths of reinforced polymer structural shapes with constant cross sections. Raw materials consist of a liquid resin mixture and flexible textile reinforcing fibers. The process involves pulling the raw materials through a heated steel-forming die using a continuous pulling device. The continuous reinforcement materials are saturated with the resin mixture in a resin bath and pulled through the die. Heat from the die initiates the gelation (or hardening) of the resin. A rigid, cured profile is formed that corresponds to the shape of the die.

The advantage of pultrusion is that the manufacturing produces a well-controlled and consistent dimensional profile. Pultrusion is the most automated process, requiring little hands-on labor. Internal die segments allow open or wrap-around shapes to be designed and details such as hollow tubes and trapezoids to be produced. The disadvantage is that pultrusion produces long, narrow profiles, so deck designs employing pultrusion must consider how to combine pultruded elements to create the necessary width. Pultrusion is by far the most common method used in fabricating FRP composites for bridge deck applications.

Vacuum-Assisted Resin-Transfer Molding (VARTM): VARTM employs a soft bag over the part to seal the mold so that a vacuum can be drawn under the bag. Once vacuum is achieved, the part is pressed onto the hard tool by atmospheric pressure. Resin ports on feed tubes are then opened to permit resin to flow into the mold and infiltrate the dry fabric reinforcement.

The advantage of VARTM is rapid infusion of large parts when the procedure works. Infusion of large sections can be accomplished in minutes. Because the fiber reinforcement is compressed and locked in place by atmospheric pressure on the soft bag side, high fiber volume can be achieved. Good dimensional tolerance also is achieved because excess resin can just flow out of the vacuum ports. Because the resin flows indiscriminately under vacuum, the VARTM process requires volumetrically nearly solid sections in order to avoid forming resin-rich areas or resin pools in cavities. Also, any nonstructural materials such as foam core must be able to sustain the atmospheric pressure without crushing.

Hand Lay-up or Open Molding: The hand lay-up process is the most fundamental method of manufacturing still widely used in all industries. Fiber reinforcement is placed in position on the mold or plate and then saturated with resin. A crew then uses specialized rollers and paddles to work the resin into the fabric, fully wetting the layer. After determining that the layer is fully wetted, the crew repeats the process on succeeding layers until the lamination is complete. The component is then left to cure thoroughly, which takes from a few hours to overnight.

The advantage of hand lay-up is its low capital equipment costs and the low-to-moderate labor skill required. These factors usually make it the least expensive method for one-of-a-kind or limited production work. For complex parts, this may be the only feasible method. The disadvantage of this process is the variability in procedure and material properties due to the manual labor involved.

In addition to the above manufacturing processes, additional secondary fabrication and assembly is usually required before panels are shipped including:

- Bonding components together to make larger components and assemblies using epoxy adhesives,
- Pre-drilling holes for component and panel connections and splices for use in the field,
- Material repairs,
- Application of gel coat,
- Surface preparation of top faceplate to accept the wearing surface.

FRP composite deck components are then shipped to the site, installed on the bridge structural framing, spliced together, and secured to the structural framing.

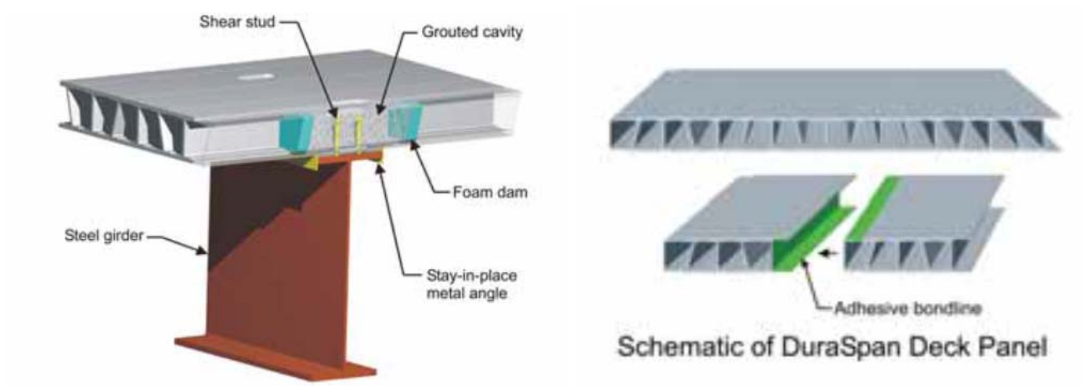
Splicing of components and panels has been performed using a number of details including both epoxy adhesive bonded, bolted, or screwed lap joints. Panels have been connected and secured to the bridge structural framing using a number of different attachments including welded headed studs attached to the steel structure and grouted keyways within the panels or through bolted connections.

2.3.3 Recent Bridge Installations

Although there are numerous available FRP composite deck products, because the support conditions, steel framing configurations, and corresponding stresses and structural deformations on bascule bridges are different than those on typical parallel, multi-girder fixed bridges, only FRP deck systems that have been installed on bascule bridges are investigated and evaluated in this study. Two (2) FRP composite bridge deck systems have been used on bascule bridges in the United States:

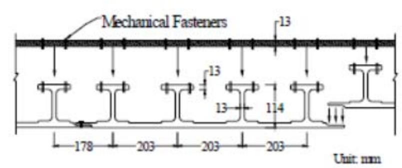
DuraSpan: The DuraSpan FRP composite deck system was manufactured by Martin Marietta Composites. The deck system consists of a series of 5-inch or 8-inch deep, rectangular, multi-cell pultruded tubular deck planks spliced together in the field using epoxy adhesive bonded lap joints to make a continuous closed deck system. The deck planks are connected to the supporting structural framing using mechanical fasteners (e.g. welded headed studs with grouted cavity within the deck).

The deck system was installed on three bascule bridges by Oregon Department of Transportation from 2001 through 2005, one bascule bridge by Multnomah County, Oregon in 2006, and one vertical-lift bridge at the Port of Long Beach, California in 2003. The deck system has also been installed on several fixed bridges. The in-service product has developed a number of maintenance and durability issues and is no longer produced and supported by Martin Marietta Composites.



DuraSpan FRP Composite Deck Panel

ZellComp: The ZellComp FRP composite bridge deck system was initially developed in 2002 and put in to production in 2005. ZellComp has 5-, 7- and 9-inch deep versions of the deck system. The deck consists of individual 32-inch wide lower pultruded sections panels each with four T-sections that resemble small wide-flanges and made integral with a bottom plate, and a separate top faceplate that is mechanically fastened to the bottom panel. The pultruded FRP composite parts are mechanically connected together in the field (in lieu of bonded epoxy adhesive joints) to create a continuous closed, multi-cell, tubular deck system. The lower pultrusion is connected to the supporting steel framing using mechanical fasteners (e.g. through bolting of the bottom plate or welded headed studs with grouted cavity within the deck). The open shape of the lower pultrusion facilitates this connection. The upper faceplate is connected to the lower pultrusion after the lower pultrusion is connected to the structural framing. The faceplate is secured to the top flanges of the pultruded wide-flange components using mechanical fasteners. Self-tapping screws were initially used to make the blind-connection from the top. Following some performance issues with this connection, improvements to this connection have been proposed utilizing rivnuts (internally threaded rivets) attached to the top flange of the wide-flanges.



a) Cross section of the deck system

b) Picture of the deck showing all components

The 5-inch deep version of the deck has been installed on one bascule span in 2011 and is in the process of being installed on a second bascule span in 2012, by Multnomah County, Oregon. The deck system has also been installed on several fixed bridges throughout the United States.

Lewis and Clark Bridge: Lewis and Clark Bridge, rehabilitated in 2001, over Lewis and Clark River on US 101 in Clatsop County, near Astoria, OR was one of two bascule bridges in the United States to first receive an FRP deck.

- Bridge is owned and maintained by Oregon Department of Transportation,
- Originally built in 1924,
- 112-foot Single-leaf Bascule Span with 20-foot deck width with stringers at 2'-9" on center,
- Steel open grid deck was replaced with DuraSpan FRP bridge deck system (manufactured by Martin Marietta composites). The deck, composed primarily of glass fibers and polyester resin, was nominally 5 inches thick and weighed approx. 15 psf,
- 77,000 lbs. of ballast required for each counterweight,
- 2-inch thick epoxy concrete wearing surface exhibited cracking within 1 year and is in very poor condition after 9 years,
- FRP composite deck and connections are sound after 9 years,
- A field visit of the bridge in December 2011 by the research team revealed that the FRP deck is in poor condition with signs of the typical cracking at the joints and adjacent failure of the wearing surface as well as random delamination and cracking throughout,
- Bridge carries an average of 3,300 vehicles per day and is posted for a load limit of 40 Tons.

Old Youngs Bay Bridge: Old Youngs Bay Bridge, rehabilitated in 2002, over Youngs Bay on US 101 in Clatsop County, near Astoria, OR was one of two bascule bridges in the United States to first receive an FRP deck.

- Bridge is owned and maintained by Oregon Department of Transportation,
- Originally built in 1921,
- 166-foot Double-leaf Bascule Span with 20-foot deck width with 5'-4" stringer spacing,
- Bridge carries an average of 5,600 vehicles per day and is posted for a load limit of 40 Tons,
- Steel open grid deck was replaced with DuraSpan FRP bridge deck system (manufactured by Martin

Marietta composites). The deck, composed primarily of glass fibers and polyester resin, was nominally 5 inches thick and weighed approximately 15 psf,

- 30,000 lbs. of ballast required for each counterweight,
- ½-inch epoxy concrete wearing surface exhibited cracking in less than 1 year and severe cracking after 4 years,
- FRP composite deck and connections failed after 5 years including punch through in a few locations and deck-stringer connections breaking apart,
- FRP composite deck was replaced with a steel open grid deck in 2010 following poor performance and premature failure of the FRP deck.

<u>Siuslaw River Bridge</u>: Siuslaw River Bridge, rehabilitated in 2005, over Siuslaw River on US 101 in Florence, OR is an historic bridge that received an FRP deck.

- Bridge is owned and maintained by Oregon Department of Transportation,
- Originally built in 1936,
- 149-foot Single-leaf Bascule Span with 27-foot deck width,
- Bridge carries an average of 20,000 vehicles per day,
- Steel open grid deck was replaced with DuraSpan FRP bridge deck system (manufactured by Martin Marietta composites). The deck, composed primarily of glass fibers and polyester resin, was nominally 5 inches thick and weighed approx. 15 psf.
- Wearing surface (URE-FAST PF-60 consisting of two-component urethane, sprayed into pre-placed crushed rock and topped with coarse sand to create a semi-rigid polymer concrete) is in good condition with minor to moderate wear after 6 years.
- Connection details show minor and localized degradation

<u>Broadway Bridge</u>: Broadway Bridge, rehabilitated in 2004 over the Willamette River, Portland, Oregon is the largest bascule bridge in the world with an FRP deck.

- Bridge is owned and maintained by Multnomah County,

- Originally built in 1913, the historic bridge has served Portland's marine (river) and vehicular traffic quite well for more than 90 years,
- 278-foot Double-leaf Rall Type Bascule Span with a 46-foot deck width, is the seventh longest bascule bridge in the world,
- Bridge carries an average of 29,400 vehicles per day,
- Steel open grid deck was replaced with DuraSpan FRP bridge deck system (manufactured by Martin Marietta composites). The deck, composed primarily of glass fibers and polyester resin, was nominally 5 inches thick and weighed approx. 15 psf,

- A portion of the DuraSpan FRP deck was removed and replaced with a ZellComp FRP deck in 2011 to accommodate a new street car.
- A field visit of the bridge and meeting with the owner in December 2011 by the research team revealed the following:
    - The First FRP deck has experienced some surface cracking and debonding of the friction course. Cracking occurred at the grouted connections. The owner believes this is due to the stiffening effect of the grout compared with the otherwise flexible FRP. Some of the surface debonding is random – at locations other than the joints.
    - The new ZellComp FRP replacement deck has developed cracks at the transverse joints between deck plates soon after being subjected to traffic. These joints have been saw cut and filled with joint sealant. To date, the friction course overlay (3/8" aggregate broadcast onto epoxy) has remained securely bonded.
    - The owner reported that ZellComp initially applied a coating with a non-slip surface on the FRP top plate to receive the wearing surface, but the wearing surface debonded under traffic. In testing various methods of surface preparation, the owner determined that a shot blasted surface improved the bond of an aggregate broadcast on epoxy.
    - The owner has decided to use rivnuts to secure the top plate to the lower pultrusion in the field and has demonstrated that the screws can be replaced if needed.

<u>Morrison Bridge</u>: Morrison Bridge, rehabilitated in 2012, over Willamette River in Portland, Oregon is the most recent bascule bridge to receive an FRP deck and will have the highest volume of traffic for a bridge with FRP deck.

- Bridge is owned and maintained by Multnomah County,
- Originally built in 1958,
- 340-foot Double-leaf Bascule Span with a 78-foot deck width,
- Bridge carries an average of 53,800 vehicles per day,

Steel open grid deck is in the process of being replaced with a ZellComp FRP bridge deck system. The deck, composed primarily of glass fibers and polyester resin, has a nominal thickness of 5 inches and weighs approximately 21 psf. ZellComp has added a glass mat across the joints in the top plates, bonded with resin in an attempt to prevent cracking of the friction course. The deck is bolted to the stringers.

Other Bridge Products: There are a number of other FRP composite bridge deck products that have been developed and others currently in development, but none of these have been installed on vehicular bascule bridges in the United States (e.g. Strongwell, Bridge Composites, FiberSpan, et al).

2.3.4 Design and Analysis

Design Considerations: Although there has been significant research and development of FRP composite deck system over the last 15 years, industry standard design and construction specifications, and guidelines are not available. As such, the use of FRP composite bridge decks is generally still considered experimental. Most of the current FRP composite deck products are proprietary, designed using product or project specific research, and manufactured using proprietary material formulations and/or fabrication methods. Most installations by bridge owners have relied upon manufacturer research, technical data, guidelines and recommendations.

The lack of industry standard design and construction specifications and guidelines is largely due to the proprietary nature and wide variety of FRP composite deck products. This is expected given that the FRP composite technology permits products (e.g. bridge decks) to be readily customized including fibers, fiber architecture, and resins to suit a specific application. The nature of manufacturers to protect the intellectual property of the proprietary product research and development is not conducive to development of standardized design and construction specifications and guidelines. As such, there is limited interchangeability between various FRP composite deck products.

The significant variety of proprietary FRP composite deck products includes significant variations in:

- Cross-sectional geometry,
- Design and performance criteria,
- Materials including the resins, reinforcing, reinforcing architecture,
- Manufacturing methods,
- Critical details including deck structure, connections between components and subsystems, and connections to the supporting bridge structure,
- Type, quantity and quality of research, analysis, testing, evaluation and peer review used to validate the deck product.

The use of performance-related specifications instead of prescriptive specifications has been problematic. Performance-related specifications are not conducive for products that require long-term (greater than five years) maintenance performance as it is not practical to enforce performance requirements long into the future. Without prescriptive specifications, product details can be easily changed without validation from through testing and evaluation.

Relevant Research: Over the last 15 years, there has been very limited interaction and no continuity or common goals between various research projects. Aside from scholarly journal articles, which typically appear long after project completion, and conference presentations, in which details are sketchy, the sharing of findings is virtually nonexistent. The ineffectual end results of these fragmented efforts over the last 15 years support these conclusions.

Most research has demonstrated that FRP composite decks have significant strength and can easily be designed and developed to resist HL-93 design live loading at the Strength Limit State in the *AASHTO LRFD Bridge Design Specifications*. However, because of the low modulus of elasticity of FRP composite materials and the flexibility of FRP composite decks, other aspects of the deck design (e.g. deflection, fatigue of connection and panel splice details, wearing surface performance) usually are more important in the deck product development. Strength and stiffness of the FRP composite depends on the type, quantity and orientation of the fiber reinforcing, and resin matrix used to form composite material.

Design Approach: Currently, there is no simplified structural analysis method (e.g. simplified closed-form equations) endorsed by AASHTO that are available to accurately compute the live load wheel distribution for FRP composite decks. However, research performed in 2007 by Virginia Polytechnic Institute and State University, that included an extensive parametric study using finite element analysis and validated by laboratory testing, yielded a proposed an equivalent strip equation:

$$W = 0.0046S^2 - 0.47S + 28, \text{ where, } S = \text{Girder Spacing (inches)}$$

It is observed that the deck relative deflections from strip method generally show good agreement with the lab measurements for the cases when lab measurements are available. The research is based on a single FRP composite bridge deck type, Strongwell FRP Deck, and thus it is not clear whether the equation is applicable to other FRP composite decks. In the absence of similar research for other FRP composite decks, it gives a simplified general approach that can be used. The research concluded that the strip method specified in *AASHTO LRFD Bridge Design Specifications* for analysis of concrete, steel grid and timber decks can also be applied to FRP composite decks in conjunction with the proposed strip width equation.

AASHTO LRFD Bridge Design Specifications do not provide equations to determine the live load distribution factor for steel beams when the deck consists of an FRP composite material. The same research above by Virginia Polytechnic Institute and State University included a parametric study to estimate live load distribution factor for this case. Both finite element analysis and laboratory testing demonstrated that the live load distribution factor equation for glued laminated timber decks on steel stringers provide a good estimate of load distribution factor for FRP composite deck on steel girders. This is likely because FRP composite decks generally have similar stiffness to laminated timber decks. The lever rule approach can also be used to conservatively estimate the live load distribution factor for FRP composite deck on steel girders. This research was performed with the conservative assumption that the FRP deck is non-composite with the steel girders.

The ZellComp 5-inch deep FRP composite deck was evaluated using the closed-from equation above for the stringer spacing found on typical Florida bascule bridges. The deck met Strength I Limit State, but calculated Service I Limit State deflections were 0.10” (L/467), which is greater than the L/800 deflection limits. Because testing of this deck system identified loosening of screws and loss of composite action between upper facesheet and the lower pultrusion, section properties conservatively consider the lower pultrusion only. Because of the issues with the facesheet fasteners, it is recommended that alternative fasteners (e.g. Rivnuts) be considered, evaluated and tested. Successful strength and fatigue testing of alternative fasteners may permit the upper faceplate to be considered as composite with the lower pultrusion with reduced calculated deflections.

There are several factors that must be considered in making a decision regarding the design of the deck for deflections:

- Although *AASHTO LRFD Bridge Design Specifications* do not specifically address the deflection limits of FRP composite decks, mandatory L/800 deflection limits for these decks have been endorsed by many researchers, bridge owners, and FHWA similar to that of steel grid and other lightweight metal decks. However, other researchers and bridge owners have endorsed less restrictive L/500 deflection limits.
- The selection of a deflection limit yields significant differences in the final FRP composite deck design and makes a difference whether the solution is viable or not viable. In order to meet L/800 deflection limits, a ZellComp deck with a depth greater than 5 inches is required using stringer spacing on typical Florida bascule bridges, which is difficult to accommodate due to the significant modifications to the bridge required to raise the roadway profile grade. Alternatively, additional stringers can be added and/or the stringers re-spaced; however, this adds weight to the bascule leaf.
- The effect of deflections on driver comfort is not likely to be a concern for the anticipated deck span lengths. Live load deck deflections are anticipated to be small (i.e. less than ¼”) and are anticipated to remain constant over the length of the bascule span (i.e. deflections will not vary over the length of the bascule span and cause vertical accelerations that affect driver comfort). For the typical bascule span framing configuration, maximum deflections will occur directly under the wheel and deck stiffness will generally remain uniform over the length of the bascule span where the deck is supported only by the stringers and not directly supported at the floorbeams. Research indicates that vertical acceleration limits is a more appropriate means of addressing driver comfort than arbitrary deflection limits.
- Various studies regarding dynamic amplification of live loads indicates that dynamic amplification values increase with decreasing deck stiffness. As such, dynamic load allowances specified by AASHTO may underestimate actual values on flexible decks. A conservative estimate of the dynamic load allowance is recommended for the FRP composite deck design if a more flexible deflection limit than L/800 is used.
- Excessive deflections may result in durability concerns for the wearing surface. Wearing surface durability is a well-documented concern on bridges with orthotropic decks with flexible deck plates. There are no specific studies that have tested the durability of thin epoxy polymer wearing surfaces on flexible FRP composite decks. However, case studies of existing FRP decks

with thin epoxy polymer overlays indicated that premature failure of the wearing surface is a wide spread problem.

- In order to reduce the weight of the FRP composite deck on a bascule span, lightweight thin wearing surfaces are required. Thin wearing surfaces do not have the ability to distribute wheel contact pressures to a larger surface area like thicker asphalt wearing surfaces used on some FRP composite deck installations. As such, wheel patch loads are likely more concentrated. Laboratory testing of FRP composite decks has typically taken a conservative approach that neglects the load distribution benefit of the asphalt wearing surfaces.
- The modulus of elasticity of the resins used in FRP composite material reduces with increased temperatures and temperatures in Florida are generally higher than those in northern climates. Research demonstrated a loss in stiffness of nearly 20% to 25% over a temperature range from 70 to 130°F. As such, it is recommended that conservative physical properties corresponding to maximum anticipated in-service temperatures be used in the design of the deck for deflections.
- Exposure of FRP composites to ultraviolet light has shown to cause degradation causing micro-cracking of the composite resins that reduce the stiffness of the deck and increases deflections.

The following additional design considerations are recommended by FHWA in the absence of provisions in *AASHTO LRFD Bridge Design Specifications*.

- To avoid long term creep, predicted strains under design load should be less than 20% of the FRP composite material minimum guaranteed ultimate strength based on coupon testing.
- An environmental durability factor of 0.65 is recommended to the material properties to account for degradation of properties over time.
- In cases where the deck is expected to fail in a manner other than tension of the laminate, a factor of safety of five should be applied.
- Because of the material's typical low modulus of elasticity, most designs will be driven by deflection limitations and not strength requirements. Although the criterion for deflection is somewhat arbitrary, it is typically be kept at 1/800 of the supporting span length.

2.3.5 Functionality and Safety

Load Capacity: An FRP composite deck designed to governing stress limits with sufficient reserve capacity to address anticipated degradation will have corresponding load carrying capacity in excess of that required to support AASHTO LRFD HL-93 Live Loads. The unit weight of the proposed FRP composite deck will be close to that of the existing steel open grid deck, and thus the weight of the deck is not anticipated to significantly reduce the capacity of bascule span members.

Rideability: The FRP composite deck and the corresponding applied wearing surface will provide a smooth, continuous riding surface with a surface roughness comparable to asphalt or concrete pavement.

Due to the relatively low modulus of elasticity of FRP composites, the decks exhibit relatively low flexural stiffness and corresponding greater deflections and vibrations that are a significant design issue.

Vibration characteristics of FRP composite decks have been shown to be significantly different from those of conventional reinforced concrete bridge decks, necessitating a further evaluation of deflection criteria for these decks. For reference, research has demonstrated that FRP composite decks generally deflect 50 to 60% more than typical concrete decks for the same deck span. Although mandatory L/800 deflection limits for these decks have generally been applied, similar to that of steel grid and other lightweight metal decks, some researchers have surmised that better economy could be achieved if this deflection limit were liberalized. This has lead researchers to suggest a number of alternative serviceability criteria including new proposed empirical formulations for calculating maximum live load acceleration response, as a function of the first bending modal frequency of the bridge, and corresponding alternative serviceability criteria that limits vertical acceleration to that consistent with human tolerance to vibrations.

Skid Resistance: Skid resistance from the applied wearing surface will be similar to that of asphalt pavement. See Section 3 Wearing Surface Evaluation.

Noise: The solid surface of the FRP composite deck is anticipated to reduce noise generated by tires in contact with the deck relative to steel open grid deck. However, the hollow cells of the deck may still generate some resonance due to vibration of the deck thin web members.

Bicycle Safety: The FRP composite deck provides a solid riding surface for the roadway and shoulders with small longitudinal open joints (less than ½" wide) located immediately adjacent to the curbs or barriers, which will greatly improve bicycle safety. Transverse deck joints between the two bascule leaves and between the bascule span and bascule pier will range from ¾" to 1½" in width, but should not be a concern for bicyclists.

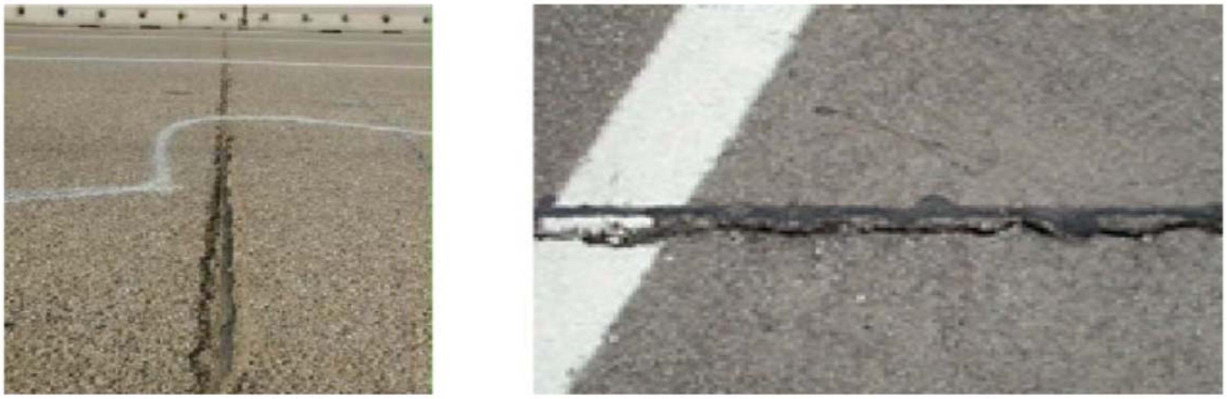
2.3.6 Durability and Service Life

Service Life: The primary concerns with FRP composite bridge decks are durability and service life. An investigation performed in 2006 reviewed the performance of the FRP composite decks of 83 bridges constructed from 1999 to 2001. Although this study did not concentrate on FRP composite decks found on bascule bridges, the issues described are symptomatic of the issues found on bascule bridges. Although the average age of these decks was less than 5 years at the time, the survey indicated that the bridges exhibited a number of concerns and problems, including issues with:

- Failure of the deck at joints between deck panels with corresponding reflective cracking in the wearing surface and water leakage through the joints to the steel framing below,
- Delamination and debonding of thin wearing surfaces,
- Non-uniform support of the deck at the haunch supports with corresponding panel movement under traffic,
- Failure of the traffic railing curbs and parapets,
- Failure at approach joints,
- Failure of deck connectors, which ranged from bolted clamp-type connectors to welded headed studs in grouted cavities in the deck,

- Delamination of the FRP composite materials and corresponding moisture ingress that makes the material susceptible to freeze-thaw.

A series of pictures below illustrate typical deficiencies.



Reflective cracking and oozed material at FRP deck-to-deck joints

Debonding at Joint and below Wear

Misalignment of Deck-to-Deck Joint

Leakage through Deck-to-Deck Joint

FRP Deck and Connection Studs Separation

Clip Type Connection Separation

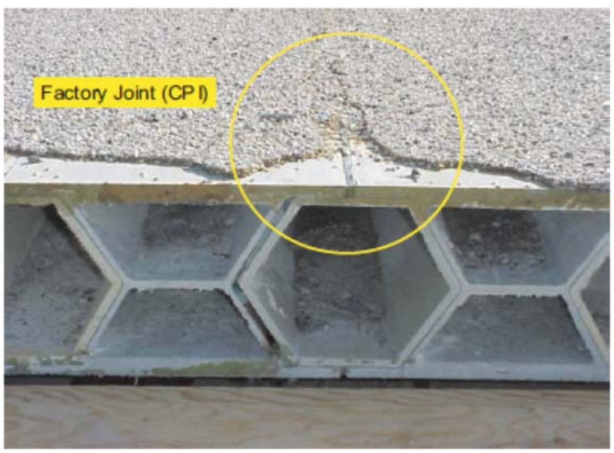
Crack in Haunch

Delamination of Wearing Surface

Wearing Durface Debonding

Buckling of Wearing Surface

Typical Steel Railing Connection



Factory Joint on Pultruded Sandwich Deck

Section of Deck with a 3-ft Diameter Bubble

Water found within core of deck after drilling

Tearing of core and faceplate buckling

Faceplate crippling

FRP Delamination (ZellComp)

Lip Separation (ZellComp Deck)

Web Buckling (ZellComp Deck)

Creep Resistance: The addition of the reinforcement to the polymer matrix increases the creep resistance (i.e. resistance to permanent deformations from sustained loads). Creep is generally not a concern for FRP composite bridge decks as the deck is not subject to large permanent loads.

Environmental Exposure: Although FRP composite materials are non-corrosive materials and deicing chemicals and saltwater will not corrode the material, exposure to these can degrade the strength and stiffness of the FRP composite material. Research demonstrated degradation of the FRP composite material from environmental exposure (30% decrease in modulus of elasticity and corresponding panel stiffness when exposed to a calcium chloride solution; 35% decrease in tensile strength when exposed to a sodium hydroxide solution). Degradation is believed to be accelerated with higher moisture and elevated temperatures.

In addition, FRP composite materials were found to degrade from weathering effects, particularly by ultraviolet (UV) light. Ultraviolet photons from the natural solar radiation cause photo-oxidative reactions that can alter the molecular chain of polymers and produce micro cracking in the polymer. Both laboratory testing and observations and testing of in-service FRP composite materials identified surface micro-cracking and chemical degradation of the epoxy and corresponding reduction in tensile strength of FRP composite materials. Laboratory testing that included exposure of fiberglass and carbon fiber reinforcing samples to UV radiation demonstrated 10% reduction in tensile strength. FRP composite materials exposed to sunshine for a period of 42 months experienced a 40% reduction in tensile strength.

FRP composite materials that will be subject to these conditions are normally fabricated with a surface layer containing a pigmented gel coat or UV inhibitor included as an additive to the composite matrix. Both methods provide protection to the underlying material by screening out UV rays and minimizing water absorption along the fiber-resin interface. The thin epoxy polymer wearing surface can also act to protect the upper faceplate from exposure. The durability of FRP composite materials in the alkaline environment and from exposure to UV light is strongly dependent on resin types and the manufacturing processes. Degradation has shown to occur if the fiber reinforcing is not properly coated and shielded by the resin matrix. Cutting and drilling of FRP composite panels can expose the fiber reinforcing. The protective benefit of the wearing surface is removed if the wearing surface is breached.

Freeze-thaw Resistance: FRP composites have low water absorption and thus are generally considered resistant to destructive expansion of freezing water. However, research has shown that freeze-thaw cycles in cold region environments can result in degradation of the FRP composite materials. Micro-cracks and voids in the polymer matrix can develop during extreme temperature changes due to differences in the coefficients of thermal expansion of fibers and resin. These cracks and voids can retain moisture that can freeze. Research conducted cyclic tests on FRP sandwich deck panels at very cold temperatures (as low as -67°F). At these very low temperatures, the stiffness of the specimen decreased 10 to 20% compared to that at room temperature and the degradation in stiffness could not be recovered. Strength reduction ranged from 10% to 30%. Freeze thaw is not anticipated to be a significant concern on most Florida bascule bridges due to the generally mild temperatures found in Florida.

Chemical Resistance: FRP composites can be formulated to provide long-term resistance to nearly every chemical and temperature environment including the destructive effects of de-icing salts and saltwater. However, these considerations have not necessarily been considered in the development of most of the FRP composite deck products. As such, the chemical resistance of these products is unclear.

Fatigue Resistance: Fatigue testing of the FRP composite deck material for cycles of 2 million to 10 million cycles has generally demonstrated good fatigue resistance. However, instances of delamination of the FRP composite material have been identified. Research also indicates that a combination of environmental exposure (e.g. UV light and saltwater) and repeated application of load can result in degradation of FRP composite physical properties including modulus of elasticity and panel stiffness. Researchers have suggested that this effect should be accounted for in the design, similar to sacrificial loss in thickness of steel members or prestress losses. Although much research has been done on the mechanical properties of FRP composites, the overall long-term durability of the material under severe environmental conditions has not been systematically evaluated.

The ZellComp FRP composite deck was specifically tested to investigate the self-tapping screw connection of the upper faceplate to the lower pultrusion. This research investigated the fatigue and failure strength of the deck and connection under cyclic loading. The testing identified significant loosening of screws and eventual fracturing of the fasteners after only 600,000 cycles that increased as the testing continued and movement of the upper faceplate that can result in corresponding cracking, delaminating and spalling of the wearing surface. It is recommended that alternative fasteners (e.g. Rivnuts) be considered, evaluated and tested.

Fire Resistance: Composites can be designed to meet fire regulations by the use of special resins and additives. Properly designed and formulated composites can offer fire performance approaching that of most metals. However, most FRP composite materials for bridge deck applications have not been developed with fire as a consideration and thus it is unclear how these materials will perform in the event of a fire.

Performance of FRP composite materials in a fire includes a number of considerations. FRP composites can burn under certain conditions. Extreme heat can degrade the FRP composite material, which shows lower heat resistance than conventional construction materials. Research of fire resistance of FRP composite structural members, which explored a number of fire scenarios with different locations above and below the bridge, predicted failure of the FRP composite materials in less than 8 minutes for a burning truck on the deck. Structural collapse was found for combined thermal and mechanical loading. As such, immediate evacuation of a bridge with an FRP deck subjected to fire is required. Other research demonstrated that even less extreme temperatures can cause problems for FRP decks including delamination between the resin and glass and thermal deformations and uplifts depending on the panel details and thermal gradients.

Relatively closely spaced stringers on a bascule span are likely to retain vehicles after the deck fails. However, fire on FRP composite deck can potentially make emergency response more problematic. Rescue efforts are likely to be hampered with the early loss in strength of the FRP composite deck.

Impact Resistance: FRP composite materials have generally shown to have some energy absorbing properties to resist collision. Although the FRP composite material glass reinforcing and resin matrix can be developed specifically to improve impact resistance, this has generally not been a primary consideration in the development of most FRP composite bridge decks. It is unclear how the deck upper faceplate and hollows tubular sections will perform under a vehicular collision.

Thermal Expansion: Response to thermal change is slightly different for FRP composite material than for concrete and steel and requires special consideration when an FRP deck is used on a concrete or steel superstructure. FRP composite material can heat up rapidly when exposed to direct sunlight. A dark wearing surface exacerbates the phenomenon. Experience has shown that a thermal gradient will occur between the top and bottom of an FRP deck when surface temperatures change fast but are not able to be conducted through the FRP immediately. This problem is especially likely to occur in early spring or late fall. The design should assume a temperature difference between the top and bottom of the deck and account for any subsequent internal thermal stresses. Since this temperature gradient can lead to an arching action as the top surface expands faster than the bottom, it may also affect the selection of bearing and anchorage details. It is important to note that thermal stresses may be as large as stresses resulting from live loads.

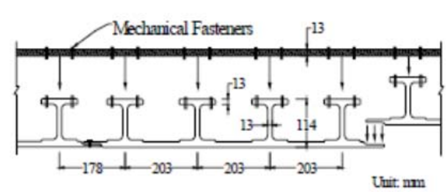
The difference in coefficients of thermal expansion between FRP composite and steel framing and the restraining effects from bolting the deck to the steel framing and the stiffness of the steel framing must be considered in detailing the deck. In addition, as the FRP composite deck will have more direct exposure (i.e. the deck will be directly exposed to the sun, while the steel framing will be shaded by the deck) the temperature of the FRP composite deck is anticipated to be significantly different than the temperature of the steel. Differential movement between the two materials is anticipated to be measurable. Because of the magnitude of these differential movements, details for attaching the deck will need to accommodate the movement and prevent restraint that would develop large forces in the deck and steel framing members. More accurate assessment of the differential temperature will need to be determined during design.

The difference in thermal expansion can be addressed as follows:

- Deck panels will extend transversely the full width of the roadway, from curb to curb, for a typical two lane Florida Bascule bridge.
- Deck panels will extend transversely half the width of the roadway, with an expansion joint in the middle of the roadway, beneath the median for a typical four lane Florida bascule bridge.
- The panels will be spliced such that they are continuous in the longitudinal direction, except for one or two intermediate expansion joints between the panels.
- Oversized holes in the steel members will be used to accommodate thermal expansion with standard sized holes used at the center of thermal movement to secure and maintain the alignment of the panels as the movement occurs and as the bridge raises and lowers.

2.3.7 Florida Bascule Bridge Specific Solution

Deck Solution: Although there have been a number of FRP composite decks that have been developed over the last 15 years, the ZellComp 5-inch deep FRP composite deck is a good candidate for use on a typical Florida bascule bridge with a depth that can be easily accommodated with minimal modifications and that has an overall unit weight similar to that of the typical steel open grid deck to be replaced. The 5-inch deep ZellComp FRP composite deck has already been installed on one bascule span and is in the process of being installed on another bascule span.



a) Cross section of the deck system

b) Picture of the deck showing all components

The deck consists of individual 32-inch wide lower pultruded panels each with four T-sections that resemble small wide-flanges and made integral with a bottom plate, and a separate pultruded top faceplate that is mechanically fastened to the lower panel. The top and bottom plates are ½-inch thick and the wide-flanges are spaced 8 inches on center.

The unit weight of the 5-inch deep ZellComp deck is 16 psf, excluding connections and wearing surface. With these other items the total unit weight is approximately 21 psf which includes a bolted connection (in lieu of a grouted connection) and 3.5 psf of wearing surface.

Panel Splices: The pultruded FRP composite parts are mechanically connected together in the field (in lieu of bonded epoxy adhesive joints) with stainless steel fasteners to create a continuous closed, multi-cell, tubular deck system. The lower pultruded panels are placed side-by-side, with a small overlap of a dapped portion of the bottom plate. There are some concerns that the extensive drilling required for the numerous small fasteners may introduce stress risers that are conducive to crack formation and that provide passage for moisture and salts to access the interior of the laminates. The use of epoxy adhesives to connect the panel components has not been tested with the ZellComp deck.

Deck Connection: The lower pultruded panel is connected to the supporting steel framing by through bolting to the stringer and floorbeam top flanges and new main girder supports (in lieu of welded headed studs with grouted cavity within the deck, which adds too much weight). The open shape of the lower pultrusion facilitates this connection. Neoprene pads are used between the steel framing and the FRP composite panels to provide a more uniform bearing surface. The upper faceplate is connected to the lower pultrusion after the lower pultrusion is connected to the structural framing. The faceplate will be secured to the top flanges of the pultruded wide-flange components using Rivnuts (internally threaded rivets) attached to the top flange of the wide-flanges in lieu of the previously used self-tapping screws that had performance concerns.

Structural Modifications: The following modifications to the bridge are required to implement the 5-inch deep ZellComp FRP composite deck:

- Existing stringers supporting existing steel open grid deck can be reused and remain as currently configured. However, replacement of the stringers would:
  - Facilitate shop drilling bolt holes for the deck connections, which significantly reduces the field work (i.e. overhead match drilling these holes).
  - Provide a clean, smooth top flange that yields a more uniform bearing and faying surface.
  - Eliminate pitting from previous surface corrosion that retains moisture and is conducive to corrosion development.
  - Eliminate need to exercise care in removing the existing steel open grid deck and corresponding extensive grinding of stringer top flanges to remove residual weld and base metal, which greatly reduces construction duration.
  - Yield higher quality stringers.
  - Permits optimization of the floor system with elimination of some stringers.

- Existing stringers supporting the concrete filled steel grid deck over the machinery areas require lowering by 2 inches to address difference in height between the 3-inch existing deck and new 5-inch deck.
- The rack frames that support the concrete filled deck (bridges with Hopkins frame drive machinery) require that the top flanges be lowered by removing and reattaching the top flange, and trimming the top of the web.
- Removal of spacer bars from the top of the existing floorbeams and main girders is not required, but is recommended to eliminate unnecessary loose contact between the FRP composite deck and steel framing.
- Minor modifications to the counterweight including saw cutting and grouting at the transition to the FRP composite deck.

<u>Wearing Surface</u>: The FRP composite deck requires a lightweight skid resistant wearing surface that bonds well to the top faceplate. Currently only the thin epoxy polymer wearing surface meets these requirements with:

- Several manufacturers with similar products that permits competitive bidding opportunities,
- Unit weight of 3 to 4 psf for two-layer system with ¼" total thickness,
- Good skid resistance (0.8 to 0.9 friction coefficient),
- Shop application of large sections and field touch-up at welded joints,
- Ability to easily replace and repair surface,
- Significant experience in similar applications, but
- Limited service-life (10 to 15 years) requiring period removal and reapplication.

(See Section 3 Wearing Surface Evaluation for more specifics).

<u>Traffic Railings</u>: No crash-testing has been performed in accordance with NCHRP 350 for traffic railings attached to the ZellComp or any other FRP composite decks to date. If a crash-tested railing attached to the deck is required, the approval will need to be on the basis of structural equivalence or crash testing will need to be performed. Research has been initiated through ongoing projects to investigate connections that will enable approved crash tested railings to be attached to the FRP decks. Limited static testing has been performed that simulates vehicular impact loads on both concrete barriers and steel rails attached to an FRP composite deck. However, this research is not in accordance with the requirements of NCHRP 350. The performance of the ZellComp FRP composite deck for vehicular impact loads applied to a traffic railing post is not clear.

<u>Weight and Balance Requirements</u>: Due to small differences in the unit weight of the existing deck and new deck, the counterweight will require some adjustment. Because the weight of the new deck is very similar to the typical steel open grid deck, adjustments can likely be made by adjusting the balance blocks. Other modifications to offset the weight are not anticipated.

2.3.8 Constructability

Fabrication: The FRP composite deck panels will be fabricated at the FRP composite manufacturing facility. The pultruded sections will be cut to length. Where the stringers are to be replaced in conjunction with the deck replacement, the panels will then be mated up to the supporting stringers and main girder support angles in an inverted assembly layout (i.e. the panels and stringers oriented upside down) to permit match drilling of the holes for the connections and splices. The Rivnuts will then be installed in to the panels. The wearing surface may also be shop applied to the panels.

Tolerances on panel length, width, camber, sweep, squareness and flatness will generally be similar to that of steel open grid deck. Flexibility of the FRP panels permits panel adjustment to address tolerances in sweep, squareness and camber. The use of standard oversize holes in top flange of the stringers and main girder supports will assist in accommodating small differences between shop and field alignment.

Field Installation: The existing steel open grid and stringers will be removed. The main girder and floorbeam spacer bars will also be removed and the rack frames and counterweight girder top flanges modified as required. The new stringers and main girder support bars will be installed. Final drilling of the holes in the webs of the floorbeams for the stringer connection angles will be performed after the panels are aligned to the stringer top flanges. Shims between the stringer connection angles and floorbeam webs will be provided for adjustment. Removal of the existing rivets and final drilling of the holes in the horizontal legs of the new supports at the main girder top flanges (or field welding of the supports if permitted) will be performed with the panels aligned to the supports.

Specialized Inspection: FRP composite materials, Rivnuts and thin epoxy polymer wearing surfaces are less common to the bridge industry and thus inspection of this construction will, at least initially, be considered specialty in nature.

The FRP composite manufacturer will be required to perform quality control and submit certifications and a quality control plan that addresses the required quality control functions to be performed. Because of the special requirements of the FRP composite fabrication, it may be necessary to employ personnel with specialized experience to perform quality assurance for this work.

Rivnut installation and Rivnut bolt tightening quality control procedures will need to be developed. Field welding of main girder supports if permitted will require on-site involvement by welding inspectors. The contractor will be required to submit weld procedure specifications and certifications for the field welding. Quality control procedures for the wearing surface will also need to be developed and employed.

Because of the complexity of the FRP composite material, potential degradation of deck strength and stiffness from environmental and loading effect that can occur without obvious visual signs, and the presence of a wearing surface that can obscure the top of the deck, specialized non-destructive examination techniques are required to periodically inspect and evaluate the deck. There are a number of available non-destructive examination methods that can be used to perform this inspection including:

- Visual Inspection,
- Tap Testing (i.e. Sounding),
- Thermal Testing,
- Acoustic Testing,
- Ultrasonic Testing,
- Radiography,
- Modal Analysis,
- Load Testing.

From NCHRP Report 564, Table below shows the various inspection methods that correlate to the types of defects they can help detect.

Technique \ Features and Anomalies	Foreign Matter	Impact Damage	Cracks	Delaminations	Disbonds	Core or Internal Elements	External Elements
Visual	X	X	X				X
Mechanical Impedance (Tap Test)		X		X	X	X	X
Thermal			X	X	X		
Ultrasonic				X	X	X	X
Acoustic Emission			X	X	X		
Radiographic	X		X			X	X
Laser Shearography and Other			X	X	X	X	

Traffic Control: Because the FRP composite deck panels will be oriented with the long dimension perpendicular to the roadway centerline similar to steel open grid panels, there is an opportunity to replace portions of the deck (i.e. one floorbeam bay at a time in lieu of the entire deck) during short duration (overnight) closures of the bridge in order to minimize traffic impacts. There are also opportunities to replace the deck in phases in order to maintain traffic on the bridge while the work is performed. The modular fabrication of the panels permits the panels to be fabricated in a size (length, width and thickness) that closely matches that of the existing steel open grid panels to be replaced. Small openings between the existing steel grid panels and the new FRP composite panels due to small differences in panel dimensions can be temporarily covered with a thin plate. Joints in the panel along the roadway centerline can permit the panels to be replaced in two halves with traffic maintained on the opposite half. Details may need to be developed to accommodate bolting of temporary traffic railing to the FRP composite deck panels, but these traffic railings will not likely be crash tested.

2.3.9 Costs

Construction Costs: The cost of the FRP composite deck system is anticipated to be significantly higher than the cost to replace steel open grid roadway flooring (i.e. approximately two times the cost). The cost can vary due to a number of factors and depends on the modifications required to fully implement the deck system. This anticipated work includes a number of items including:

- Removal and disposal of the existing steel open grid and concrete filled deck,
- Fabrication and installation of the new aluminum deck panels,
- Replacement of the stringers including end connections,
- Removal of the main girder spacer bars and installation of new supports including replacement of some of the top flange rivets with high strength bolts or field welding the supports,
- Installation of the wearing surface,
- Minor modifications to the counterweight including saw cutting and grouting at the transition to the aluminum deck,
- Adjustment of balance blocks,
- Span balance including detailed balance calculations, and instrumentation and recording of the balanced condition before and after the work,
- Adjustment of the live loads shoes in conjunction with the deck alignment,
- Adjustment of the span locks in conjunction with the live load shoe adjustments,
- Possible modification of the top of the rack frames (bridges with Hopkins frame drive systems and where the rack frame supports the deck),
- Traffic control,
- Mobilization work.

<u>Maintenance Costs</u>: The cost to maintain the FRP composite deck is anticipated to be similar to that of the steel open grid roadway flooring. Many maintenance activities will be eliminated or significantly reduced, while other maintenance activities will be added.

Reduced maintenance activities include:

- Reduction in the frequency of required cleaning and painting of the bascule leaf steel, as the solid deck better protects these elements,
- Elimination of the need to periodically repair broken steel open grid attachment welds,
- Elimination of need to periodically repair cracked secondary and tertiary grid bars,
- Elimination of the need to periodically improve skid resistance of steel open grid (e.g. scarification of top surface),
- Reduction in the future replacement of the deck.

Added maintenance activities include:

- Periodic repairs or replacement of the wearing surface (e.g. thin epoxy polymer wearing surface).

Due to great strength to weight ratio, corrosion resistance and durability of the FRP decks, savings in deck replacement and maintenance costs over a service life could be much greater than the initial cost of the entire structure. Temperature issue with reduction in stiffness can be a down side of FRP deck, which will increase maintenance of FRP deck throughout the service life of FRP deck.

The life cycle cost savings can be shown to more than offset the relatively high initial cost of the FRP materials compared to conventional material. However, long-range durability claims are viewed by the construction industry with some skepticism.

Design Cost: The design cost is anticipated to be slightly more than that for replacement with steel open grid deck, at least initially, as the design community becomes more comfortable with the design and details, develops design skills and work product (plans and calculations) that can be adapted for use on multiple projects.

Salvage Cost: The salvage value for FRP composite deck will generally be non-existent. Although many of the Florida bascule bridges are of a similar configuration, it will be difficult to remove the panels from one bridge and relocated them to another bridge without damaging the panels.

Inspection Cost: The inspection cost may be slightly higher than that required for replacement with steel open grid deck, at least initially, as the construction community becomes more comfortable with the quality control requirements for this new type of deck system and the unique materials.

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2.4 ULTRA-HIGH PERFORMANCE CONCRETE (UHPC) DECK

2.4.1 Description

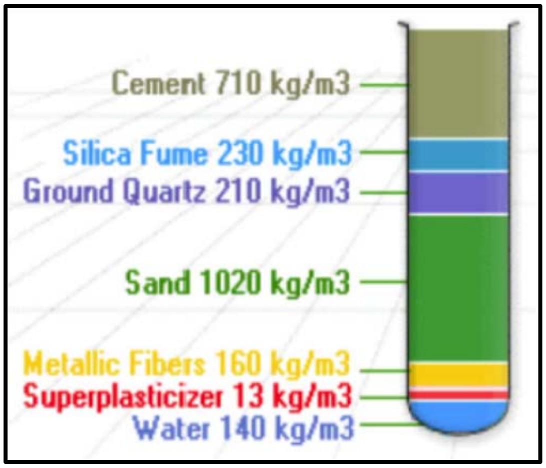
Ultra-High Performance Concrete (UHPC) is a material that has recently gained attention in the bridge industry. UHPC provides a combination of superior properties including strength, ductility, durability that permits design and construction of thinner sections and longer spans that are lighter and more efficient, while providing improved durability and impermeability against corrosion, abrasion and impact.

UHPC has potential to be used in an alternative deck design to replace steel open grid deck on Florida bascule bridges. The high concrete compressive and tensile strength allows design and construction of a lightweight waffle slab bridge deck with thin elements (slab and ribs). A UHPC waffle slab deck reinforced with MMFX rebar was previously investigated by the Florida Department of Transportation specifically for this use through a joint research project performed by Florida International University (FIU) and University of Central Florida (UCF). The researchers indicated that the proposed waffle slab will have a unit weight of 25 psf, although follow-up research yielded a unit weight of 29 psf.

Materials: A lightweight concrete waffle slab can be designed and constructed using high performance UHPC and MMFX reinforcing materials.

UHPC: UHPC is formulated from a proprietary material made by Lafarge North America under the trademark Ductal and consists of steel fiber reinforced concrete with an optimized gradation of fine powders and a very low water/cement ratio (less than 0.25). Two of the primary sources for these enhancements are the finely graded and tightly packed nature of the concrete constituent materials and the steel fibers which knit the material together after cracking has occurred. The constituent materials making up UHPC are cement, silica fume (microsilica), ground quartz, fine sand, steel fibers, water, superplasticizer, and accelerator admixture. UHPC only includes fine aggregates. The exclusion of coarse aggregate yields a material with discontinuous pore structure that reduces liquid ingress and significantly lower permeability. UHPC has good long-term creep and shrinkage behavior, excellent resistance to chloride ion penetration, and the ability to hold up well under freeze-thaw testing.

Testing of UHPC material has typically demonstrated compressive strengths of 18 to 28 ksi, and corresponding tensile strengths of 1.3 to 2.1 ksi, depending on the curing method used. The material has the capability to sustain deformations and resist flexural and tensile stresses, even after initial cracking. UHPC also typically utilizes more effective curing methods than those traditionally used to achieve the superior properties.



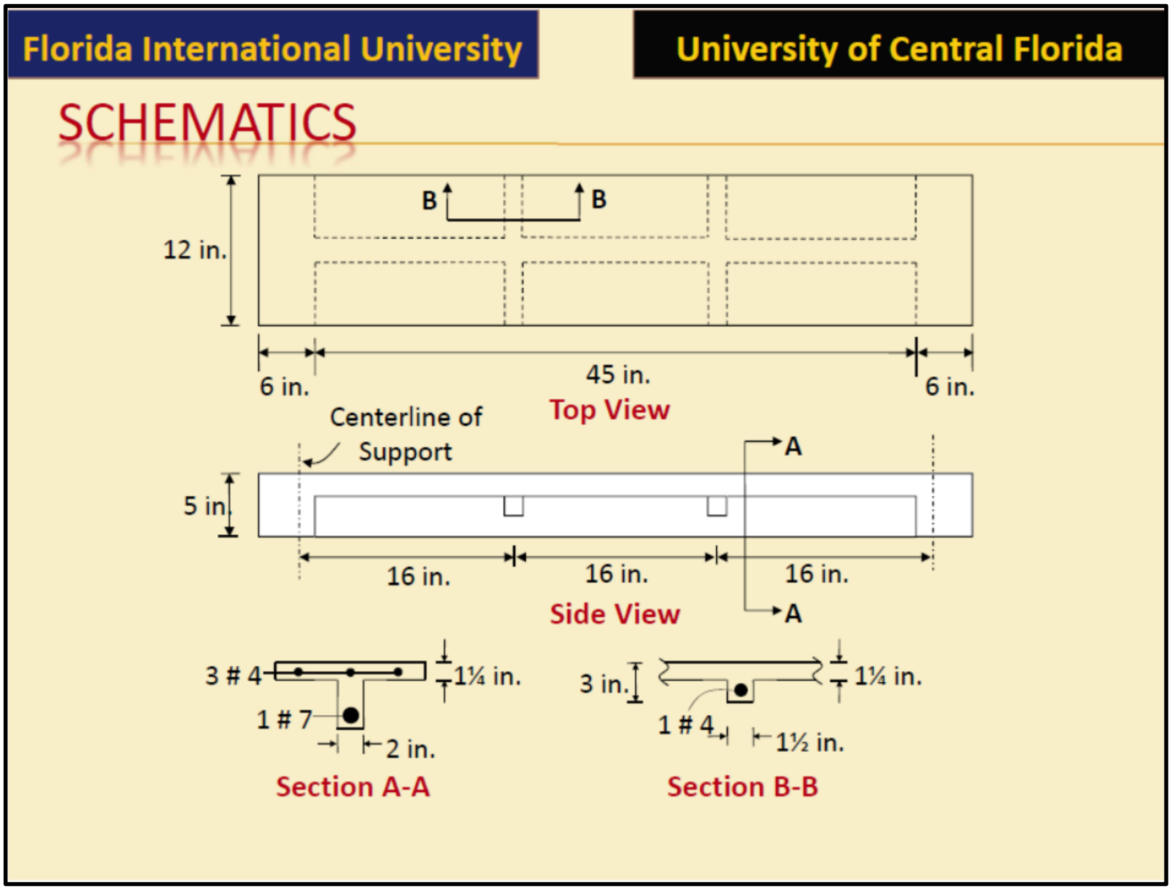
Composition of UHPC Mix

MMFX Reinforcing Steel: MMFX Technologies Corporation manufactures high-strength and corrosion-resistant reinforcing steel for concrete structures. The MMFX2 reinforcing bars, which have a material specification conforming to ASTM A1035 (Standard Specification for Deformed and Plain, Low-carbon, Chromium, Steel Bars for Concrete Reinforcement), are available in Grade 100 or Grade 120, and in all standard rebar sizes (No. 3 thru No. 11). The use of MMFX reinforcing steel is primarily due to the limited clear cover to the reinforcing steel that could be achieved with thin concrete elements (i.e. 1¼" thick top slab with No. 4 Bars, 2" thick primary ribs with No. 7 bars, and 1½" thick secondary ribs with No. 4 bars), which will not be sufficient for standard ASTM A615 Grade 60 reinforcing. Because of the corrosion-resistant material and elimination of coarse aggregate a minimum concrete cover of ½" was determined to be acceptable. The higher Grade 100 or 120 MMFX bars also yielded smaller size reinforcing bars than required using Grade 60 reinforcing, which allowed the thickness of the members to be minimized.

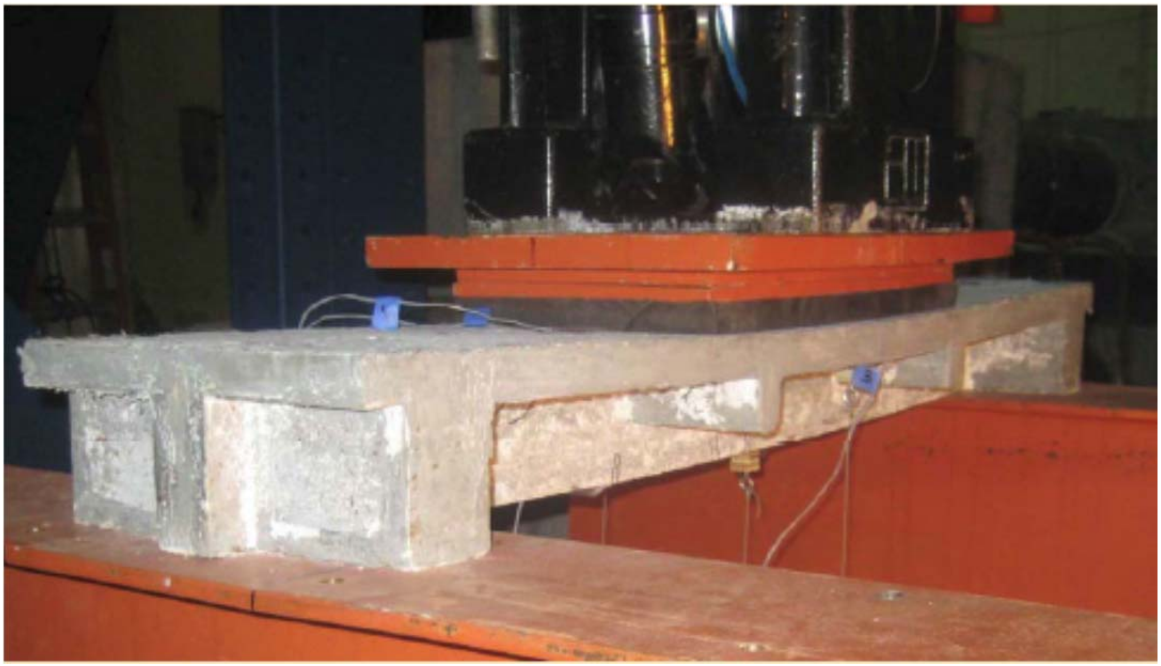
MMFX has been used in a number of locations throughout the United States and Florida. MMFX was used for the bridge deck reinforcement of the Jensen Beach Causeway Bridge in Martin County, Florida for the Florida Department of Transportation.

<u>Waffle Slab Configuration</u>: Refer to Figure 2, which shows the Florida International University (FIU) test panel schematic, and Figure 3, which shows the test panel being loaded to failure in the FIU research lab.

<u>Applications</u>: UHPC waffle deck slabs have not previously been used on a movable bridge.



Waffle Slab Schematics



Waffle Slab Load Testing

2.4.2 Product Development and Corporate Information

UHPC research is ongoing in an effort to better understand the full capabilities of the material, apply it to bridge construction, and utilize shapes that optimize both cost and strength. UHPC research in the United States is ongoing by the Federal Highway Administration (FHWA) at the Turner-Fairbank Highway Research Center in McLean, Virginia. A number of universities have contributed to the research of UHPC.

The structural behavior of this material is becoming more predictable as a result of the continuing research and testing. However, because the research is new and ongoing, design and construction specifications using UHPC have not been developed and published. Some of the structural applications for UHPC related to bridge construction that have already been researched and tested include prestressed girders, two-way ribbed (waffle) deck slab, and pourable deck joints.

As this is a relatively new material, there has only been limited use in the United States. The first bridge in the United States using UHPC as the main superstructure material was constructed in Wapello County, Iowa in 2006. The superstructure for this single span bridge includes UHPC modified Iowa Bulb-Tess prestressed Girders. The Cat Point Creek Bridge in Richmond County, Virginia was the second bridge in the U.S. to take advantage of UHPC. This ten-span bridge was constructed with UHPC in precast prestressed Bulb-Tee girders and opened to traffic in 2008. The Jakway Park Bridge in Buchanan County, Iowa used UHPC in new Pi-girders, and opened to traffic in November 2008.

UHPC has been used more extensively in Europe, Australia, and Asia. Ductal Lafarge is one of the leading suppliers of UHPC, both in the United States and internationally.

Research has also investigated use of UHPC in two-way ribbed (waffle) slabs. Ductal provided assistance the to the FIU/UCF research team for the waffle slab testing.

2.4.3 Recent Bridge Installations

UHPC waffle slab deck research, sponsored by FHWA, under the Innovative Bridge Research and Deployment (IBRD) program and the Iowa Highway Research Board (IHRB), has included a trial deck implementation on a bridge in Iowa. The world’s first bridge (and only constructed to date) with a UHPC waffle slab deck is the Little Cedar Creek Bridge in Ottumwa, Wapello County, Iowa constructed in 2011. The bridge is described as follows:

- Two-lane, 60 feet long x 33 feet wide single span bridge,
- Fourteen (14) precast UHPC, two-way ribbed (waffle), modular deck panels that measure 16 feet long x 8 feet wide x 8 inches deep, with a 2½-inch thick top slab, 5½-inch deep x 3-inch to 4-inch wide tapered ribs spaced at 2 feet on center in each direction,
- Composite with five (5) UHPC Iowa Type B precast, prestressed beams spaced at 7’-4” on center,
- Cast-in-place UHPC closure pours between panels, and haunches to attach panels to beams,
- Precast panels constructed inverted by Coreslab Structures, Inc., Omaha, Nebraska.

Laboratory testing was performed on two (2) waffle slab deck panels included the following load tests:

- Service load testing at center of panel (21 kips) and at panel transverse joint (28 kips)
- Fatigue testing at center of panel (21 kips, 1 million cycles) and at panel transverse joint (28 kips, 1 million cycles)
- Ultimate load at center of panel (48 kips) and at transverse joint (40 kips)
- Punching shear at center of panel (155 kips)
- Skid resistance

2.4.4 Florida Bascule Bridge Specific Solution

Deck Solution: Because the 8-inch deep UHPC waffle slab deck system used on the Little Cedar Creek Bridge was much heavier than could be accommodated on a typical Florida bascule bridge, a lighter, thinner version of the UHPC waffle slab deck system was developed, tested and evaluated. This new UHPC waffle slab deck system consisted of the following:

- Precast UHPC, two-way ribbed (waffle), modular deck panels that measure 5 inches deep, with a 1¼-inch thick top slab with MMFX No. 4 Bars at 4 inches on center transversely, 3¾-inch deep x 2-inch wide transverse (main) ribs spaced at 12 inches on center with one (1) MMFX No. 7 bar, and 1¾-inch deep x 1½-inch wide longitudinal (secondary) ribs at 16 inches on center with one (1) MMFX No. 4 Bar,
- Transverse span across existing steel stringers and main girders spaced at 4 to 4.5 feet on center,
- Composite with stringers, floorbeams, and main girders by way welded headed stud shear connectors and grouted closure pour and/or pockets.

Preliminary calculation of the weight of the deck was performed using the above UHPC mix design and waffle slab configuration including the weight of the embedded reinforcing steel and required haunches at the supports and joints between panels corresponding to the steel framing arrangement for a typical Florida bascule bridge. Cast-in-place concrete haunches at the supports were assumed to utilize a lightweight concrete with a unit weight of 120 pcf to reduce the weight of this material. The thicker concrete section of the haunch permits the use of a lower strength material (i.e. compressive strength of 5.5 ksi) for the haunch concrete. This calculation yielded a deck unit weight of 36 psf.

Subsequent refinement and optimization of the UHPC waffle slab configuration, including use of tapered ribs and reduced panel haunch dimensions yielded a reduction in the estimated weight to 29 psf.

Structural Modifications: The following modifications to the bridge are required to implement the UHPC waffle slab deck:

- Existing stringers supporting existing steel open grid deck can be reused and remain as currently configured. However, replacement of the stringers would:
    - Eliminate pitting from previous surface corrosion that retains moisture and is conducive to corrosion development.
    - Eliminate need to exercise care in removing the existing steel open grid deck and corresponding extensive grinding of stringer top flanges to remove residual weld and base metal, which greatly reduces construction duration.
    - Yield higher quality stringers.
    - Permits optimization of the floor system with elimination of some stringers.
- Addition of welded headed studs to top of stringers, floorbeams and main girders to achieve composite behavior.
- Existing stringers supporting the concrete filled steel grid deck over the machinery areas require lowering by 2 inches to address difference in height between the 3-inch existing deck and new 5-inch deck.
- The rack frames that support the concrete filled deck (bridges with Hopkins frame drive machinery) require that the top flanges be lowered by removing and reattaching the top flange, and trimming the top of the web.
- Removal of spacer bars from the top of the existing floorbeams and main girders.

Deck Connection and Panel Splices: The precast deck panels are spliced and attached to the bascule leaf steel framing by way of cast-in-place closure pours. Welded headed studs are installed in the top of the stringers, floorbeams, and main girders to achieve composite behavior. The studs are located in the closure pours and/or pockets in the deck panels. In order to reduce weight, the closure pour concrete is to consist with lightweight concrete. Because the haunches and closure pours are full-depth (5 inches thick) lower strength (5.5 ksi concrete) can be used for this material.

Traffic Railings: No crash-testing has been performed in accordance with NCHRP 350 for traffic railings attached to the UHPC waffle slab deck to date. If a crash-tested railing attached to the deck is required, the approval will need to be on the basis of structural equivalence or crash testing will need to be performed.

Weight and Span Balance Requirements: The total weight of the UHPC waffle slab deck including associated panel colure pours and connections is significantly heavier than the weight of the typical existing deck to be removed. A deck that is heavier than the existing steel open grid deck will also require additional counterweight ballast, equal to two to three times the net increase in weight forward of the trunnion, to balance the leaf.

Limited capacity of the trunnion assemblies, limited available space in and around the counterweights, and limited capacity of the main girders typically limit the total increase in weight that can be accommodated.

There are often opportunities to offset some of the additional weight by replacing other components with lighter components (although this unnecessarily increases the required modifications to the bridge and cost of the project) including:

- Replacement of the concrete filled portion of the deck with the proposed lightweight solid deck will reduce the overall weight of the deck. However, because this deck is located close to the trunnion, with more of the deck located back of the trunnion, the replacement does not significantly reduce the required additional counterweight ballast.
- Replacement of the stringers with lighter, more efficient sections and/or reduction in the number of stringers.
- Replacement of steel sidewalk grating with lighter aluminum sidewalk plate or planking.
- Replacement of the steel sidewalk support members and cantilevered bracket bracing members with aluminum members.
- Replacement of steel curbs and/or median with ones made from aluminum.
- Replacement of steel bridge railing with lighter crash tested aluminum railing (e.g. Edgerail).

There may be opportunities for additional refinement and optimization to reduce weight including elimination, re-spacing, and/or resizing of stringers, and re-spacing and/or resizing of transverse and longitudinal ribs. However, these refinements have not been validated by engineering and testing.

2.4.5 Functionality and Safety

Load Capacity: A UHPC deck designed to governing stress limits will have corresponding load carrying capacity in excess of that required to support AASHTO LRFD HL-93 Live Loads. The small increase in deck weight resulting from the heavier UHPC deck is not anticipated to significantly reduce the capacity of bascule span members. There are opportunities to increase the load carrying capacity the stringers, floorbeams, and main girders by taking advantage of composite action between the UHPC deck and these members.

Rideability: The UHPC deck surface will be profiled (i.e. planed) after construction to provide a smooth, continuous riding surface with a surface roughness comparable to typical concrete pavement. Because the UHPC deck has greater stiffness than the existing steel open grid deck and the deck will act compositely with the stringers and main girders, deflections and vibrations will be significantly reduced, which will further improve the quality of the ride.

Skid Resistance: Skid resistance from the applied wearing surface will be similar to that of concrete pavement.

Noise: The solid surface and the vibration dampening characteristics of the UHPC deck will significantly reduce noise generated by tires in contact with the deck relative to steel open grid deck.

Bicycle Safety: The UHPC deck provides a solid riding surface for the roadway and shoulders with small longitudinal open joints (less than ½" wide) located immediately adjacent to the curbs or barriers, which will greatly improve bicycle safety. Transverse deck joints between the two bascule leaves and between the bascule span and bascule pier will range from ¾" to 1½" in width, but should not be a concern for bicyclists.

2.4.6 Durability and Service Life

Service Life: The high strength, low permeable UHPC material is generally anticipated to provide a long service life. However, because UHPC waffle slab deck is relatively new (i.e. less than 10 years' experience in bridge deck applications) there are no installations that confirm that this service life can be achieved.

Fatigue Resistance: Although fatigue testing has been performed on UHPC waffle slab decks, with positive results, the testing performed to date has been on decks with more substantial dimensions (i.e. greater overall slab depth, top slab thickness, rib dimensions, etc.) than those proposed for the UHPC waffle slab deck for use on a typical Florida bascule bridge. As such, it is not clear whether a deck with less substantial elements will provide similar fatigue resistance.

Corrosion Resistance: The exclusion of coarse aggregate yields a material with discontinuous pore structure that reduces liquid ingress and significantly lower permeability. UHPC has good long-term creep and shrinkage behavior, excellent resistance to chloride ion penetration, and the ability to hold up well under freeze-thaw testing.

Although UHPC material provides increased impermeability, concrete cover to the reinforcing steel, required to achieve a lightweight solution, is much less than typical concrete cover used in other concrete bridge decks (less than 1/2 inch vs. 2 inches). Construction tolerances are anticipated to further reduce the cover. Construction joints between the precast panels and cast-in-place closure pours introduce opportunities for leakage (i.e. access of water containing chlorides to the embedded reinforcing steel and structural steel below.) Continuous deck systems on double-leaf bascule bridges are subject to tension stresses (due to cantilever support conditions of the main girders and localized negative bending of the floor system over the intermediate floorbeams) that act to open the construction joints. Because of the limited cover and opportunities for leakage, use of corrosion resistant reinforcing steel (e.g. MMFX, stainless steel or hot dip galvanized reinforcing steel) is recommended.

Impact Resistance: No impact testing has been performed on the UHPC waffle slab deck. As such, the impact resistance (i.e. resistance to punching from concentrated impact force) of the relatively thin (1-1/4-inch thick) top slab is not clear.

Fire Resistance: With typical reinforced concrete structures, the concrete provides limited insulation of the reinforcing steel. Reinforcing steel loses strength and stiffness when exposed to high temperatures (900 to 1100 degrees F). Because the concrete cover of a UHPC waffle slab deck is minimal, the concrete provides little protection of the reinforcing steel.

Similar to steel members, UHPC deck is likely to survive short duration fires and/or fires with lower temperatures. Because the loss of strength is time-dependent, panels may provide limited structural support for loads on the deck during a fire (e.g. the vehicle on fire, emergency response vehicles and personnel). If the deck panels lose strength during these events, the steel framing below may steel provide some support to contain vehicles.

Only a substantial heat source, such as that from a roadway accident with ignited localized fuel spill, is expected to threaten the integrity of UHPC deck.

Thermal Expansion: The coefficients of thermal expansion of UHPC concrete and steel are similar. As such differential thermal movement between the deck and bascule leaf steel framing will not be a concern.

Chemical Resistance: UHPC material provides excellent resistance to most chemicals.

Ultraviolet (UV) Light Resistance: UHPC material is not subject to degradation from UV light and there are no coatings required for the deck system that can degrade.

2.4.7 Maintenance

Repair: There is limited experience with the field repair or replacement of UHPC Waffle Slab Deck. As such, it is unclear whether effective short-term localized repairs can be implemented with this deck system. Theoretically, UHPC material can be repaired (e.g. patching of spalls) similar to conventional concrete. However, the relatively thin deck elements of the proposed UHPC waffle slab deck introduce potential questions as to the effectiveness of the repairs.

Although the modular construction of the precast UHPC Waffle Slab Deck panels makes replacement of individual sections of the deck practical, the grouted haunches with welded headed stud shear connectors complicates the replacement and will slow the replacement process. It is not clear whether a damaged panel can be replaced in a short duration nighttime closure.

Periodic Maintenance: Similar to other concrete elements, the UHPC waffle slab deck does not require periodic maintenance to ensure the long-term service life of the material.

2.4.8 Design

The design methodology of the UHPC waffle slab deck system uses simple closed-form equations based on conventional reinforced concrete design methodology. The validity of this approach is based on limited testing. However, this approach has generally shown to be conservative.

Currently, the design provisions are not endorsed by AASHTO and there are no design provisions in the AASHTO LRFD Bridge Design Specifications for UHPC or waffle slab deck systems.

2.4.9 Research

Laboratory testing was performed by Iowa State University on two (2) waffle slab deck panels for the Little Cedar Creek Bridge including the following tests:

- Service load testing at center of panel (21 kips) and at panel transverse joint (28 kips)
- Fatigue testing at center of panel (21 kips, 1 million cycles) and at panel transverse joint (28 kips, 1 million cycles),
- Ultimate load at center of panel (48 kips) and at transverse joint (40 kips),
- Punching shear at center of panel (155 kips),
- Skid resistance.

Florida International University (FIU) performed laboratory tests on the Florida bascule bridge specific UHPC waffle slab deck sections including the following:

- Ultimate load testing of four (4) individual component strips (i.e. T-beam with single rib and corresponding 12-inch wide deck slab) with three (3) different rebar anchorage details in a simple span configuration supported on steel beams spaced at 4 feet on center with single load,
- Ultimate load testing of four (4) individual component strips (i.e. T-beam with single rib and corresponding 12-inch wide deck slab) with in a two span configuration supported on steel beams spaced at 4 feet on center with two loads,
- Ultimate load testing of three (3) 36-inch wide panels (i.e. three (3) transverse ribs and corresponding deck slab and longitudinal ribs) in a two span configuration supported on steel beams spaced at 4 feet on center with two loads.

2.4.10 Constructability

Fabrication: The precast UHPC waffle slab deck panels will be fabricated at a precast manufacturing facility licensed to use the proprietary Ductal UHPC material. Because of the limited concrete cover with the thin elements, much stricter control of the reinforcing steel and concrete form dimensions will be required. Panels will be fabricated in the inverted position to achieve high quality riding surface. Specialized panel curing methods will be implemented as required to meet the specified physical properties. Panels will need to be weighed after fabrication for use in balance calculations before shipment.

Field Installation: Because of the use of precast panels with limited available cover and the need to have strict control on the weight of the deck, special care will be needed in field alignment of panels. Panels will utilize temporary leveling bolts to support and align the panels. Additional forming around at the stringer, floorbeam, and main girder haunches, and panel joints will be required. Lightweight concrete closure pour concrete will be placed and cured.

Traffic Control: Because the UHPC waffle slab deck panels will be oriented with the long dimension perpendicular to the roadway centerline similar to steel open grid panels, there is an opportunity to replace portions of the deck (i.e. one floorbeam bay at a time in lieu of the entire deck). The tight tolerances required with the deck field installation operations are anticipated to add time to the field installation operations. As such, this construction may not be conducive to short duration overnight closures, when considering all work involved. However, there are opportunities to replace the deck in phases in order to maintain traffic on the bridge while the work is performed. The modular fabrication of the panels permits the panels to be fabricated in a size (length, width and thickness) that closely matches that of the existing steel open grid panels to be replaced. Small openings between the existing steel grid panels and the UHPC waffle slab deck panels due to small differences in panel dimensions can be temporarily covered with a thin plate. Closure joints in the panel along the roadway centerline can permit the panels to be replaced in two halves with traffic maintained on the opposite half. Details may need to be developed to accommodate bolting of temporary traffic railing to the UHPC waffle slab deck panels.

Specialized Inspection: The use of proprietary UHPC material is less common to the bridge industry and considered specialty in nature.

2.4.11 Costs

Construction Costs: The cost of the UHPC waffle slab deck system is anticipated to be significantly higher than the cost to replace steel open grid roadway flooring (i.e. approximately two times the cost). Because UHPC is a proprietary material, the material is available from a sole source. The cost can vary due to a number of factors and depends on the modifications required to fully implement the UHPC waffle slab deck system. This anticipated work includes a number of items including:

- Removal and disposal of the existing steel open grid and concrete filled deck,
- Fabrication and installation of the new precast UHPC waffle deck slab panels,
- Field installation of the welded headed studs and haunch forms to stringers, floorbeams, and main girders,
- Removal of the main girder and floorbeam spacer bars,
- Addition of ballast (e.g. adjustment blocks, concrete and/or steel ballast) secured to the counterweight,
- Span balance including detailed balance calculations, and instrumentation and recording of the balanced condition before and after the work,
- Adjustment of the live loads shoes in conjunction with the deck alignment,
- Adjustment of the span locks in conjunction with the live load shoe adjustments,

- Modification of the top of the rack frames (bridges with Hopkins frame drive systems and where the rack frame supports the deck),
- Possible incidental work to offset the increased weight including replacement of sidewalk grating, sidewalk supports, bridge railing, curbs and/or medians with lighter members,
- Possible retrofit work to the trunnion assemblies to increase capacity including new trunnion bearing bushings with higher strength bronze material or spherical roller bearings,
- Traffic control,
- Mobilization work.

Maintenance Costs: The cost to maintain the UHPC waffle slab deck is anticipated to be minimal. Many bascule leaf maintenance activities will be eliminated or significantly reduced.

Reduced maintenance activities include:

- Reduction in the frequency of required cleaning and painting of the bascule leaf steel, as the solid deck better protects these elements,
- Elimination of the need to periodically repair broken steel open grid attachment welds,
- Elimination of need to periodically repair cracked secondary and tertiary grid bars,
- Elimination of the need to periodically improve skid resistance of steel open grid (e.g. scarification of top surface),
- Reduction in the future replacement of the deck.

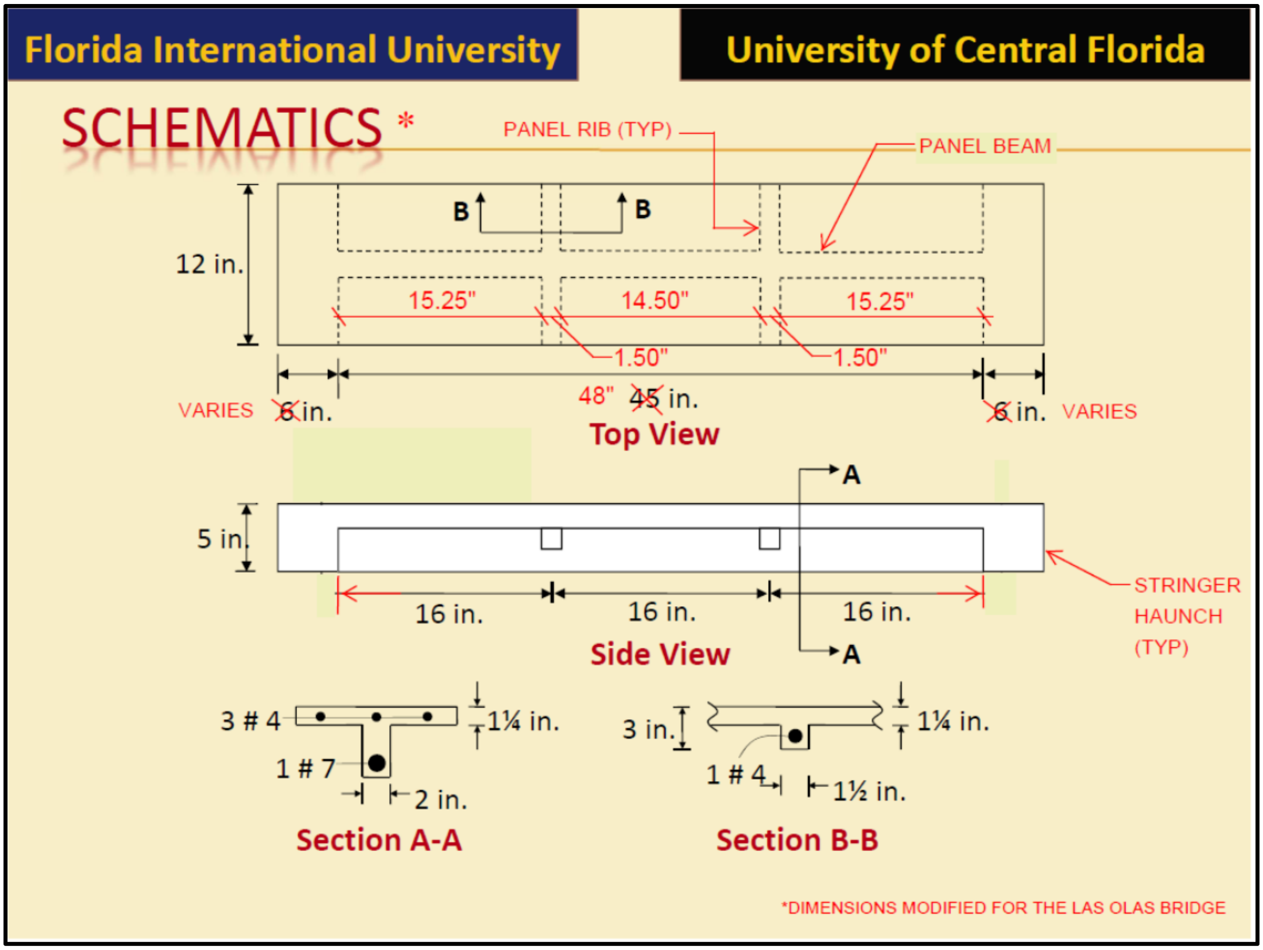
Added maintenance activities include:

- Possible more frequent replacement of trunnion bearing bushings due to heavier loads on bearings.

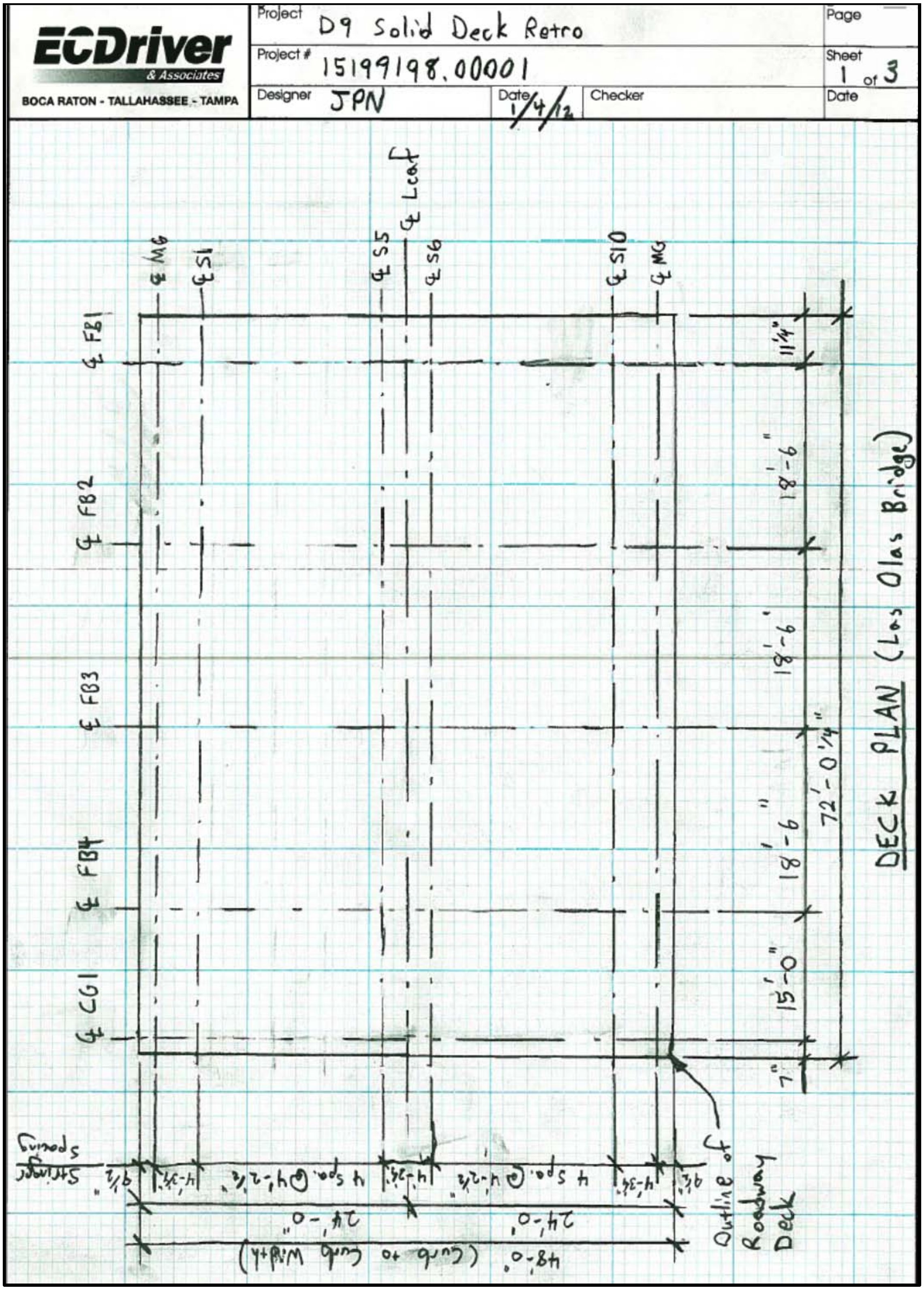
Salvage Cost: There is no anticipated salvage value for UHPC waffle slab deck.

Design Cost: The design cost is anticipated to be slightly more than that for steel open grid deck. Because this deck system will be initially unfamiliar to the bridge design community, the cost of the plans production will also be higher, until the design community becomes more comfortable with the design and details, develops design skills and work product (plans and calculations) that can be adapted for use on multiple projects.

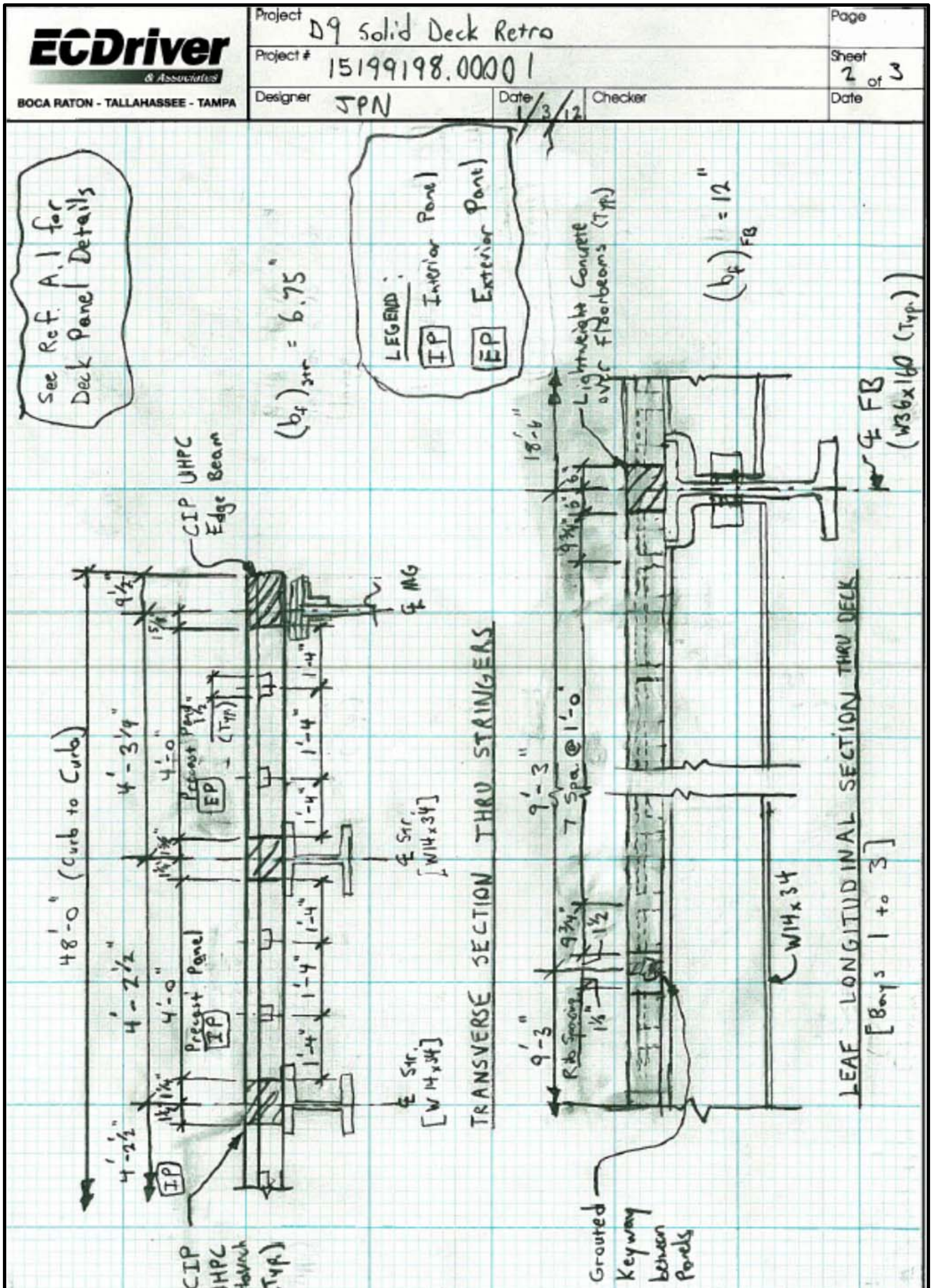
Inspection Cost: The inspection cost may be slightly higher than that required for replacement with steel open grid deck, at least initially, as the construction community becomes more comfortable with the quality control requirements for this new type of deck system and the unique materials.



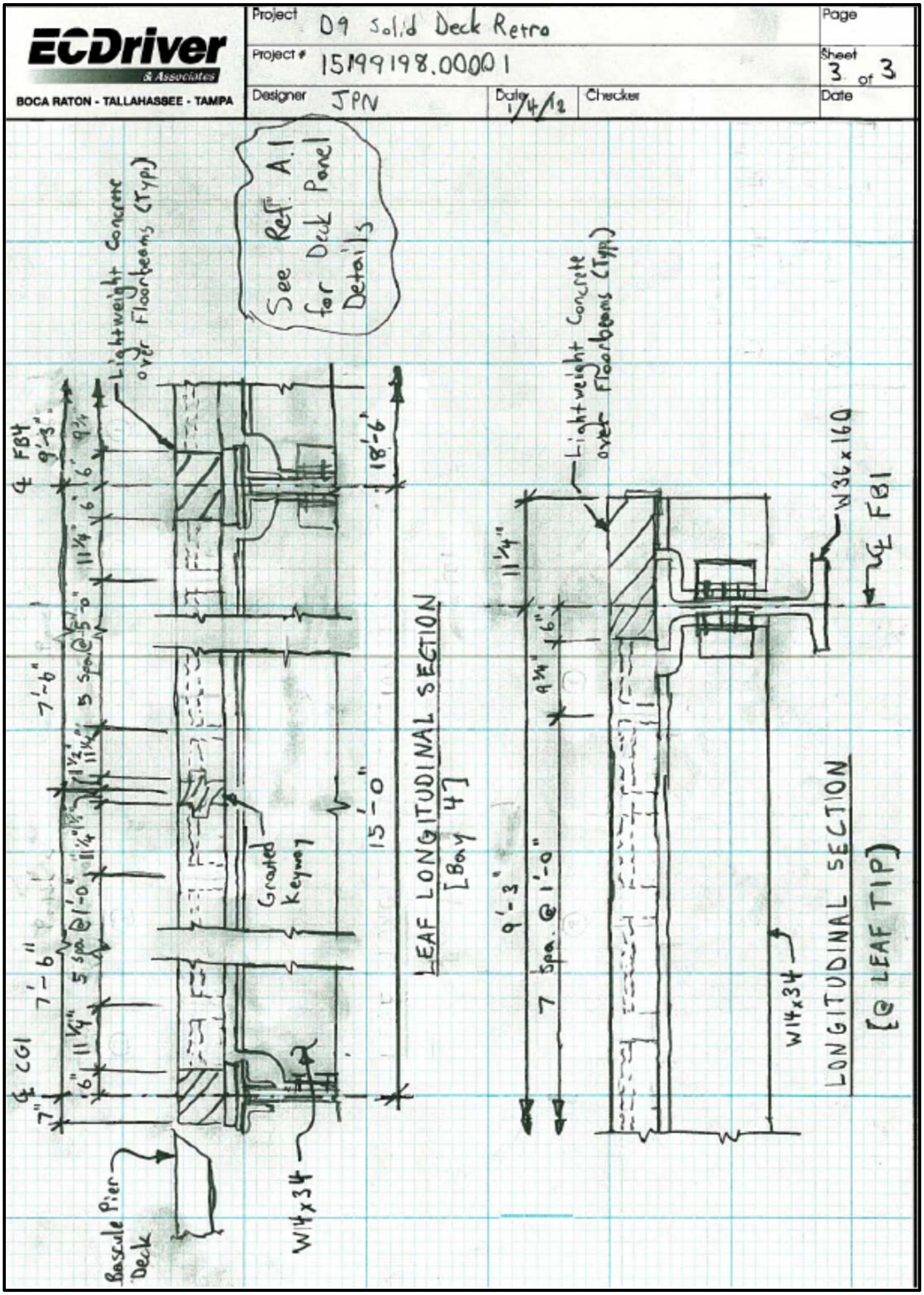
Waffle Slab Panel Schematic (Modified for Typical Florida Bascule Leaf)



UHPC Waffle Slab Details for Typical Florida Bascule Bridge (1 of 3)



UHPC Waffle Slab Details for Typical Florida Bascule Leaf (2 of 3)



UHPC Waffle Slab Details for Typical Florida Bascule Leaf (3 of 3)

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3.0 WEARING SURFACE EVALUATION

3.1 INTRODUCTION

All of the alternative lightweight solid deck systems proposed to replace the steel open grid require the use of a lightweight, skid-resistant roadway wearing surface. As there are a number of available products that meet this requirement, an evaluation of the wearing surfaces is warranted.

The lightweight solid deck alternatives under investigation include the Sandwich Plate System (SPS) developed by Intelligent Engineering, aluminum orthotropic deck system developed by Sapa, and Fiber Reinforced Polymer (FRP) deck system such as that developed by ZellComp. It was determined that ultra-high performance concrete (UHPC) waffle deck slab was too heavy to be considered a viable lightweight deck alternative, and as a result, will not be considered as one of the substrate materials for the deck overlays.

The primary function of the wearing surface is to provide a safe riding surface for vehicles crossing the bridge by providing a slip-resistant surface. The top surface of each of the proposed alternative deck systems are not inherently skid resistant surfaces. In addition, the wearing surfaces should:

- Minimize the weight added to the bridge,
- Provide a relatively smooth and uniform riding surface,
- Bond well to the substrate and provide sufficient flexibility to accommodate movement of the deck and bascule leaf structure without cracking under:
    - Expected loading conditions including wheel loads, traction and braking, thermal restraint forces,
    - Expected deformations including flexure of the deck from wheel loads and in-plane deformation of the deck from overall deflection of the bascule leaf steel framing and thermal expansion and contraction,
- Maintain integrity at the joints,
- Protect the bridge deck top surface from a wide variety of environmental conditions including exposure to typical chemicals deposited on the road including chlorides from the coastal environment and exposure to ultraviolet light,
- Resist polishing, abrasion, and wear from traffic and maintain the skid resistance,
- Provide impact resistance such as that from a vehicular collision or metal objects dropped or dragged from a moving vehicle),
- Provide a relatively long service life,
- Accommodate economical repair or replacement,
- Have the capability of either shop or field application,
- Have a history of use in similar applications.

There are a number of applied wearing surfaces that have been used on bridge decks including hot mix bituminous asphalt, polymer concrete (e.g. latex modified concrete), and thin polymer overlays. This report will not consider asphalt or polymer concrete overlays due to the required thick application of these materials and the corresponding weight. In addition, hot mix bituminous asphalt has a concern with developing an adequate bond to the proposed substrates and polymer concrete generally lacks the flexibility to accommodate the anticipated deformations without cracking. Hot spray applied metal overlays have been used in pedestrian and bicycle applications but do not have a history of use in roadway applications. However, as this type of overlay meets many of the evaluation criteria it will be included in the evaluation.

Examples of wearing surface failures

The method of applying the overlay to the bridge deck will vary, depending on the type of overlay selected, and will be summarized for each of deck overlay products evaluated in this report. The field performance of the various overlay products has been documented in some cases in various research projects, and will be discussed later in greater detail to determine what possible maintenance issues may arise for each of the products when they are put into service.

After the unsuccessful use of hot mix bituminous asphalt and polymer concrete overlays on two bascule bridges with that were retrofitted with FRP composite decks, the Oregon Department of Transportation prepared an evaluation of four thin polymer overlays in 2005. This evaluation considered and ranked the tensile strength, flexibility, bond strength, and wear resistance of these thin polymers.

3.2 ALTERNATIVE WEARING SURFACES

Initial screening of wearing surface overlays for the above evaluation criteria yielded two primary types of products that have merit including: thin polymer overlays and hot-spray applied metal overlays. Further evaluation of the proposed wearing surface overlays included review of manufacturer product data sheets and research papers.

3.3 THIN POLYMER OVERLAY WEARING SURFACES

Thin polymer bridge deck overlays have limited use in the United States for 25 years and there are a number of available products from different manufacturers that are available, each with slightly material and physical properties and corresponding advantages and disadvantages.

Thin polymer overlays generally consist of a combination of polymer resin binder and stone aggregate, which together form a single layer. The polymer overlay is usually applied in multiple layers (two or three) using a “broom and seed” application method. Two-layer overlays are typically range from 1/4” to 3/8” thick. Common resin binders for a thin polymer overlays consist of epoxy, modified epoxy (which includes epoxy urethane and polysulfide epoxy), or methyl methacrylate (MMA). More research has been conducted on epoxy or modified epoxy resin products and there are a greater number of epoxy resin products than MMA.

Thin polymer overlay products have been effectively applied to concrete, steel, aluminum and FRP, bridge decks and are generally recommended by SPS, Sapa and ZellComp for use on their deck systems. These products are generally expected to last a minimum of 15 years when properly applied per manufacturer specifications. The average installed cost of the overlays is $15 to $20 per square foot of deck area.

The products evaluated in this report are generally a sample of the thin polymer overlay products currently available. Their inclusion with this report does not imply that their products are superior to the others that have been excluded. The products shown in this report were evaluated primarily based on documented previous use and research. Products reviewed include:

- Transpo T-48: A polysulfide epoxy based polymer concrete overlay manufactured by Transpo Industries, Inc.
- FLEXOGRID Mark-163: A urethane modified epoxy polymer concrete overlay manufactured by POLY-CARB, Inc. (a subsidiary of the Dow Chemical Company).
- Traficguard EP35: An epoxy-based concrete overlay system manufactured by BASF.

(NOTE: The research performed by Oregon DOT concluded that a product using a urethane modified epoxy polymer (URE-FAST PF-60 manufactured by URE-FAST Industries, Ontario, Canada) yielded the best combination of properties).

All three products can be applied using a broom-and-seed method in multiple layers, or using single application slurry method. The epoxy resin is typically fast curing with typical cure times of 1.5 to 3.5 hours, depending on the ambient temperature, which is advantageous for traffic control purposes where the roadway can be closed for only short durations (e.g. overnight closures). The overlay is not overly sensitive to environmental conditions with a permissible ambient temperature at the time of application typically between 50 and 100°F. The overlay can typically be applied to a finished thickness of 1/4" to 1/2”. However, in order to minimize the added weight to the bascule span, it is recommended that a maximum finished thickness of 1/4” be used, which corresponds to a unit weight of 3 to 4 pounds per square foot.

Steel, aluminum and FRP composite surface to receive the overlays must be cleaned and shot or grit blasted to the requirements of SSPC-SP10, with a minimum 4 mil (0.2 mm) anchor profile. If flash rust appears, the surface must be cleaned and blasted again.

The coarse aggregate provides the skid-resistance and wear resistance. The coarse aggregates typically consist of clean, dry (less than 0.2% moisture content), sharp, angular, sound, non-friable, abrasion resistant, broken stone (e.g. silica (quartz) with Mohs scale hardness of 7 or basalt with Mohs scale hardness of 6) aggregate may be used. The coarse aggregate is typically small (100% passing a #4 Size sieve) and to a specified gradation.

The epoxy resins contain chemicals that can be considered hazardous (e.g. produce noxious fumes) and thus require care in handling per documented material-safety data sheets. Aggregates can include fines that produce dust that can be an irritant.

The coarse aggregate is combined with the epoxy resin by broadcasting it onto already placed layer of the epoxy resin with one of two methods:

Broom-and-seed Method: Usually associated with epoxy polymers, in this method, the mixed epoxy resin is typically spread onto the substrate with a notched squeegee at a prescribed application rate and in a continuous operation by applying the subsequent mixes immediately behind the preceding mixes. The aggregate is typically broadcast immediately onto the already placed epoxy resin to complete saturation until a dry surface is re-established. Additional layers are applied in a similar manner, but typically within no more than 24 hours of the preceding layer. This method of application is susceptible to contamination between applications from moisture, dust and debris if the structure must be opened to traffic between layer applications. Anything trapped in the overlay between layers could result in premature overlay failure. Multi-layer overlay systems also exhibit some level of porosity which may cause premature failure on either concrete or steel substrates.

Slurry Method: Usually associated with polysulfide epoxy polymers and MMA, slurry overlay systems are made up of specially formulated resins having excellent physical properties and a uniquely formulated slurry powder component that allows the overlays to be installed in thicknesses of 3/8" to 1/2" in a single application. This results in an overlay with virtually zero porosity preventing the egress of moisture, chlorides, salt and other corrosion-inducing substances. This process includes the application of a primer coat on the surface using the same resin as the slurry component. Immediately after the primer is installed the overlay slurry can be applied to the surface. The slurry is a mixture of the epoxy resin and the prepackaged slurry powder component that is spread over the surface using gauge rakes, preset to a specified thickness which will result in the specified overlay thickness to meet the project requirements. The slurry is formulated so that it self-levels within minutes after the gauge raking is completed resulting in a smooth uniform surface. Once the slurry has leveled the surface is then covered with the coarse broadcast aggregate. A seal coat is recommended with MMA to lock down the aggregate.

The wearing surface is usually applied in the field, but can also be applied in a shop controlled environment. Field application permits a continuously applied wearing surface with minimal cold joints.

Shop application yields discontinuities in the wearing surface with small areas of field patching at the bolted panel splices.

These products have been tested to meet a number of physical properties per various ASTM standards including compressive strength, flexural strength, flexural modulus of elasticity, wet skid resistance, tensile adhesion, tensile elongation, hardness, thermal compatibility, water absorption, chloride permeability, abrasion, viscosity, gel time and pot life. The overlays are generally impervious and prevent ingress of moisture, chlorides, salts and other corrosion inducing substances, are compatible with concrete, steel, aluminum and FRP composites, exhibit relatively good elasticity, are resistant to wear, have good bond with properly prepared and sound substrates, and are resistant to UV light. The products have been used on concrete, steel and aluminum orthotropic, and FRP composite bridge decks.

3.4 HOT SPRAY APPLIED METAL OVERLAYS

Hot-spray applied metal overlays have been used in limited applications within the bridge industry. There are only a few products and suppliers (e.g. Slip-NOT supplied by W.S. Molnar Company, and Mebac supplied by Harsco Industrial). Although these products have received widespread as slip-resistant surfaces in pedestrian-bicycle applications, these products have only been used in limited application in roadway applications (e.g. SlipNOT has been applied to plates used to temporarily cover holes in the roadway or bridge decks). The hot-spray applied metal overlay products in this report represent a sample of the products currently available in the market, and their inclusion with this report does not imply that their products are superior to the others that have been excluded. Other metal coating products that may have merit for bridge wearing surfaces include Carbinite (manufactured by Carbinite Metal Coatings), and ALGRIP metal safety flooring (manufactured by Ross Technology Corporation). Similar to SlipNOT and Mebac, the latter two products do not advertise as having been previously used as a bridge wearing surface, but have properties that make them similarly viable for similar use. For this report, the evaluation of hot-spray applied metal overlays is based on the SlipNOT product.

These products typically consist of aluminum oxide or steel grit hot-spray applied to metal substrates (steel or aluminum). Currently, application of the surface coating is performed only at the surface coating supplier's manufacturing facility to pre-fabricated components. Field application and repair of the surface coating is not currently available.

For SPS deck, the surface application may need to be applied to the top faceplate, prior to injecting the elastomer core, to prevent damage to the core caused by heat from the hot-spray application. It is not clear what surface temperature will cause damage to the elastomer core. Testing for this specific application has not been performed. The pre-fabricated SPS deck panels or top faceplate will need to be shipped to the surface coating supplier and returned to the SPS deck manufacturing facility for completion of the panel fabrication.

For aluminum orthotropic deck, the deck panels will need to be shipped to the surface coating supplier after fabrication.

The hot-spray applied metal overlay cannot be applied to an FRP composite due to the effect that the high heat from the hot-spray application would have on the material.

SlipNOT, manufactured by SlipNOT Metal Safety Flooring (a division of the W.S. Molnar Company) is available in three different grades, with each grade varying in the coarseness of the metal aggregate. The product is applied to the substrate using a patented process which applies a plasma stream deposition of molten metal to a metal substrate creating a surface that has a bond strength of at least 4,000 psi and has a surface hardness of between 55 – 63 on the Rockwell "C" scale. The SlipNOT metal surface can be steel, stainless steel, or aluminum, and is advertised as being applicable to either steel or aluminum substrates. Grade 1 is a fine surface with a peak to valley surface depth of 0.010" to 0.012", is used in light duty applications, and is available for all surface types. Grade 2 is a medium surface with an average peak to valley surface depth of 0.020" to 0.025", and is the maximum coarseness available for aluminum and stainless steel surfaces. Grade 3 is a coarse surface with an average peak to valley surface depth of 0.032" to 0.038", is used for heavy-duty application such as vehicular traffic, and is only offered as a steel surface. It is recommended by the manufacturer that this product be hot dipped galvanized as well. The galvanized steel, Grade 3 option appears to be the best option for typical Florida bascule bridges.

SlipNOT has been used in limited temporary roadway applications on bridges such as the Ridgely Avenue Bridge over Weems Creek in Annapolis, Maryland. Temporary steel plates with SlipNOT were installed on the bridge to temporarily widen the bridge deck to accommodate traffic control during bridge construction. The steel plates were removed after a couple of years of use, and installed at another site. The successful use of this product in a temporary application indicates that use in a permanent application may be practical. Additional testing to demonstrate the long-term durability and frictional resistance of the wearing surface is warranted, in recognition that the surfaces currently must be applied in the shop (i.e. the deck panels would need to be removed from the bridge and sent to the shop for re-coating if there is a significant loss in slip-resistance or other concerns with the wearing surface.

SlipNOT Road Plate on the Ridgely Avenue Bridge, Annapolis, MD

3.5 DECK OVERLAY PROPERTIES

The various properties functional, safety and durability properties for the thin epoxy polymer overlays and hot-spray applied metal coatings are described below.

Unit Weight: The unit weight of the wearing surface will have a significant effect on the bascule span balance and overall weight of the bascule span.

Thin Epoxy Polymer Overlay: A two-layer, thin polymer epoxy overlay with a thickness of 1/4" (which is the minimum recommended thickness using a two-layer application) typically yields a unit weight of 3 to 4 psf. A three-layer overlay with a thickness of 3/8" (which is the minimum recommended thickness using a three-layer application) typically yields a unit weight of 5 to 6 psf. The two-layer overlay is recommended in order to reduce weight. However, a three-layer system will typically have greater durability and a longer service life.

Hot Spray Applied Metal Overlay: A hot-spray applied metal coating (e.g. SlipNOT) will typically yield a unit weight of 0.5 to 1.5 psf, depending on the surface texture (Grade 1: Fine, Grade 2: Medium, Grade 3: Coarse).

Skid Resistance: The skid resistance of a roadway surface is an important factor in vehicle safety as it affects both stopping (braking) distance and lateral grip. The skid resistance of the wearing surface should preferably be similar to the skid resistance of typical asphalt and concrete pavements in both wet and dry conditions.

Skid resistance is tested on roadway pavement using a variety of standard tests that measure the friction between the rubber tire of a vehicle and the pavement surface. Typical tests include ASTM E1911 ("Standard Test Method for Measuring Paved Surface Frictional Properties Using the Dynamic Friction Tester), ASTM E2157 ("Standard Test Method for Measuring Pavement Macrotexture Properties Using the Circular Track Meter"), ASTM E2340 ("Standard Test Method for Measuring the Skid Resistance of Pavements and Other Trafficked Surfaces Using a Continuous Reading, Fixed-Slip Technique"), and ASTM E274 ("Standard Test Method for Skid Resistance of Paved Surfaces Using a Full-Scale Tire"). The Florida Department of Transportation typically has used ASTM E274 to test the skid resistance of steel grid decks in previous research.

Thin Epoxy Polymer Overlay: The initial skid resistance friction number (FN) of typical thin polymer epoxy overlay products tested per ASTM E274 for wet conditions is 40 to 55 (i.e. coefficient of friction of 0.40 to 0.55). The skid resistance of epoxy polymer overlays is known to reduce somewhat over time as the wearing surface is abraded and polishes.

Hot Spray Applied Metal Overlay: Skid resistance of vehicle tires on hot-spray applied metal coated surfaces has not been tested to date. The specified minimum slip resistance typically is a coefficient of friction of 0.60. Measured coefficients of friction typically exceed 0.85 (wet and dry) but can vary slightly depending on the surface grade, material and test performed.

Service Life: The expected service life of the wearing surfaces is as follows:

Thin Epoxy Polymer Overlay: A properly specified and installed thin epoxy polymer wearing surface is generally expected to provide a service life of 15 years before removal and replacement is required.

Hot Spray Applied Metal Overlay: The service life of a hot-spray applied metal overlay as a roadway wearing surface is not clear as testing has not been performed to demonstrate the wear resistance and long-term loss in skid resistance of the surface. It is anticipated that the wear resistance will dictate the service life of this wearing surface. Because there currently is no available field application of the coating and panels must be removed to the coating supplier shop for re-coating, a long service life for the wearing surface is needed to justify its use.

Wear Resistance: The ability of the wearing surface to resist wear, abrasion and polishing from vehicular traffic is important to the safety and durability of the wearing surface.

Thin Epoxy Polymer Overlay: The coarse aggregate provides the largest contribution to skid-resistance and wear resistance. The coarse aggregates that are relatively hard, angular, sound, non-friable and abrasion resistant (e.g. silica (quartz) with Mohs scale hardness of 7 or basalt with Mohs scale hardness of 6) exhibit good wear resistance. Higher quality coarse aggregates will generally provide greater wear resistance and greater durability. A three-layer system will have greater durability than a two-layer system because it takes a longer time for the thicker overlay to become worn to the layer of the substrate. The coarse aggregates are typically tested for absorption, abrasion resistance and soundness. Aggregates used in epoxy overlays have a low absorption since moisture in the overlay can cause a loss of adhesion between the epoxy and the aggregate and premature deterioration of the aggregate; a high abrasion resistance so that the overlay can provide a high skid resistance over its life; and a high soundness to resist deterioration when subjected to cycles of freezing and thawing.

Hot Spray Applied Metal Overlay: Wear resistance of vehicle tires on hot-spray applied metal coated surfaces has not been tested to date. The file hard surface coating (Rockwell C Scale Hardness of 55 to 63) is anticipated to yield good wear resistance.

Bond Strength: The strength of the bond between the wearing surface and the substrate is important to ensure that the wearing surface does not delaminate and spall under the flexural deformations.

Thin Epoxy Polymer Overlay: Typical bond (adhesive) strength between thin epoxy polymer overlay and the substrates is between 250 and 500 psi. The bond strength is dependent on the surface preparation (SSPC-SP10 surface finish for metal substrates) and anchor profile (shot or grit blast to minimum 4 mil (0.2 mm) surface roughness).

Hot Spray Applied Metal Overlay: Typical bond (adhesive) strength between hot-spray applied metal coatings and steel substrates is greater than 4000 psi (except aluminum surface on aluminum substrates which is greater than 2000 psi).

Ultraviolet Light Resistance: The wearing surface will be directly exposed to sunlight and corresponding ultraviolet (UV) radiation that is known to cause degradation of many materials.

Thin Epoxy Polymer Overlay: The epoxy polymer resins of thin epoxy polymer wearing surfaces have been specifically formulated and tested to demonstrate to resist degradation from exposure to UV radiation. The coarse aggregates are generally inert and do not degrade from exposure to UV radiation.

Hot Spray Applied Metal Overlay: The metals in the wearing surface of hot-spray applied metal overlays do not degrade from exposure to UV radiation.

<u>Chemical Resistance and Corrosion</u>:

Thin Epoxy Polymer Overlay: The dense epoxy polymer resin binders are generally impermeable and thus penetration of chemicals including chlorides from saltwater to the metal substrate provided that the wearing surface is not breached.

Hot Spray Applied Metal Overlay: The applied metal coating may or may not fully coat the substrate and thus does not prevent chemicals including chlorides from saltwater from accessing the substrate. The coating itself does not protect from rust and corrosion; however aluminum, stainless steel and galvanized steel products are generally corrosion resistant. Galvanized of steel coatings is recommended to prevent corrosion of the steel substrate.

<u>Tensile (Flexural) Strength</u>: Good flexural strength and flexibility of the wearing surface is needed to prevent development of cracking.

Thin Epoxy Polymer Overlay: The epoxy polymer resins are typically formulated with good physical properties and can accommodate some flexural deformations without cracking. Physical properties range significantly from product to product with some products providing greater strength and flexibility than others.

Hot Spray Applied Metal Overlay: The hot-spray applied metal coating does not significantly affect the tensile (flexural) strength and stiffness of the metal substrates and because the coating is metallic it is highly flexible.

<u>Maintenance</u>: Future maintenance, repair and replacement of the wearing surface must be considered in the selection of the type of surface to be used.

Thin Epoxy Polymer Overlay: Complete repairs and localized repairs to thin epoxy polymer wearing surfaces can be performed using the same material and application procedure used to originally apply the material including surface preparation. In making repairs, all unsound material surrounding the area to be repaired should be removed using mechanical means (e.g. scrapers and chippers).

Hot Spray Applied Metal Overlay: Field repair of hot-spray applied metal coatings using the same technology as the original supplier is not currently available. Panels must be removed and shipped back to the coating supplier shop for repair or replacement. It is not clear whether it is practical to remove the existing coating from the substrate or whether a new coating can be applied over the existing coating or whether the deck panel must be replaced in the event of loss of skid resistance, or other unacceptable deficiency.

Field repairs of the substrate can be performed with the hot-spray applied coating remaining intact. The coating can be sheared, flame or torch cut or otherwise fabricated without harming the surface. Since the coating is an all-metal surface it can be welded, either directly or from the opposite side, without the need of grinding or other surface preparation using the same standard metal welding rods. The coating can also be drilled, countersunk and formed.

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