HEAVY MOVABLE STRUCTURES, INC.

**NINTH BIENNIAL SYMPOSIUM**
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# RETROFIT OF THE CHRISTA MCAULIFFE BRIDGE

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Timothy Noles & Michael Sileno
Hardesty & Hanover, LLP

# INTRODUCTION

The Christa McAuliffe Bridge, named after the school teacher/astronaut who died in the Space Shuttle Challenger accident, is located in Merrit Island, Brevard County, Florida. The bridge carries SR3 over the Canaveral Barge Canal, and is heavily used by many of the commuters who work at the Kennedy Space Center. In 1994 the existing two-lane bridge was doubled in capacity with the construction of a new adjacent parallel bridge, which carries northbound traffic. The Southbound (original) Bridge was rehabilitated and now carries southbound traffic.

The Southbound Bridge consists of a Hopkins trunnion bascule configuration, the most prevalent type of bascule span utilized in Florida from the 1950's to the mid 1990's. In the 1990's standards were written for the FDOT for their new movable bridges to eliminate some of the problems they have been encountering over the years, predominantly with their Hopkins trunnion bascule span bridges. One recommendation after review of many bascule bridges was to utilize simple trunnion designs for their new bascule spans due to the inherent problems of the Hopkins trunnions The main problem of the Hopkins trunnion arrangement is misalignment during span operation. The misalignment causes web/hub distortion, and machinery misalignment that reduces the life of the span. A simple trunnion remains aligned in all positions of travel and is the most common type of trunnion configuration utilized today due to its proven durability over many years of use. A disadvantage of the simple trunnion is the need for inboard trunnion supports that occupies space that could otherwise be used for counterweight.

The new Northbound Bridge bascule span was one of the first simple trunnion designs utilized in Florida since the standard was adopted by the FDOT. Once the bridge was placed in service some deficiencies of the structural, mechanical and electrical system became apparent to the FDOT. The FDOT was concerned about the design of the bascule span and its durability based upon the problems occurring shortly after the bridge was placed in service

When we first visited the bridge during the proposal stage of the project, we saw a design that we were familiar with, but quickly realized the lack of details we consider critical in bascule span design. These details enable the Engineer to predict behavior in extreme events so that structural behavior, i.e. stresses can be easily analyzed and quantitatively assessed. We approached the analysis with a design philosophy that is simple. This insures predictable behavior and deflection control. Reviewing movable bridge design is a difficult task due to each firm having its own design philosophy and interpretation of the Movable AASHTO Specifications. Innovative concepts to reduce materials and construction costs are frequently tried. However, movable bridge design evolved over time to address many of the failures or undesirable characteristics that have occurred over the past 100 years. We have taken a historical perspective in our review of the Christa McAuliffe Bridge bascule span with an understanding of the background behind the details of a bascule span design.

In our construction document review, site inspection, and load rating analysis of the bascule spans of the Christa McAuliffe Bridge we have observed many structural, mechanical, and electrical details that we would consider unconventional, untried, misapplied and undesirable for dependable service, safe operation and the long term durability of the span. Rehabilitation will be required to improve the existing maintenance requirements, reduce the possibility of unexpected rehabilitation or repair to structural and mechanical components, and provide safe and reliable service one would expect from a new bridge and a recently rehabilitated bridge. The original design of the bascule spans has inherent flaws that will require modifications and strengthening in order to improve maintainability and reliability. The purpose of our proposed rehabilitation is to eliminate, to the fullest extent practical, the problems which are effectively reducing the life of the structure, and improve the operation and maintenance requirements. Our recommendations are prudent measures we believe are necessary to ensure a durable structure. Some of the most prevalent deficiencies noted are:

- Failure of the Northbound Bridge rear live load anchorage
- Lack of bracing of the trunnion columns
- Numerous operational breakdowns and unreliable operating machinery
- Lack of independence of leaf control
- Poor maintenance access to the operating machinery

# Structural Retrofit

## Existing Structural Deficiencies

Due to the characteristics of bascule spans where very large dead and live loads are in motion on an inherently flexible cantilevered structure it is necessary to ensure stiffness and rigidity are provided to reduce vibrations and out of plane bending of various important structural components. Structural components of a movable span can be subject to small static stresses, but a member's actual service as a component of a moving machine or mechanism can be critical. These components are subject to deflections, distortions and oscillations arising under operation against the forces of friction, sudden braking, wind, and inertia. Secondary stresses associated with these factors become more significant under poor construction practices. In addition, a conservative design approach permits the structure to withstand the wide behavioral variations experienced between functioning as a bridge and operating as a mechanism. A prudent design would include adequate reserve capacity to account for reversing and repetitive stresses that effect the endurance limit or fatigue life of members. In addition, a practical design accounts for the possibility of an uncontrolled stop due to loss of power or an emergency stop to avoid irreversible damage.

The northbound bascule span structural design layout is the classic simple or "Chicago Trunnion" type, which is considered the most reliable and sturdiest type of bascule span. Unlike the Hopkins trunnion configuration, this arrangement ensures equal support stiffness during all positions of span travel as well as live load. It has numerous other advantages such as constant trunnion alignment, and reduction of fatigue stresses in the trunnion hub connection to the girder. The typical structural layout of a simple trunnion consists of a bascule span seated on trussed trunnion towers or girders simply supporting the trunnion on the inboard and outboard side of each bascule girder. The trunnion supports are the most important structural members of the span since they carry the entire load of the span and must resist overturning loads from wind and traffic, emergency stops from operation, and corresponding oscillations.

The heel of the bascule span is engaged in a rear live load anchorage and if necessary, forward live load bearings are utilized to shorten the cantilever of the bascule girder for live load. Stability and stiffness of these members are critical to reduce out of plane bending, oscillations, and torsional effects that will ensure the span behaves as designed.

The Christa McAuliffe Bridge new and rehabilitated bascule spans lack ignored some of the historic precedence used in the design of bascule spans, mainly the trunnion column and live load anchorage. The basic concept of a simple trunnion bascule span supported on trunnion columns with a rear live load anchorage without a forward live load bearing has been used successfully for decades throughout the country and are considered the most durable bascule span designs if properly detailed. However the Christa McAuliffe design eliminated many of the critical details historically used to ensure desirable behavior and a durable structure.

Typically the trunnion columns are designed as the rear leg of a trussed tower. The towers are braced with a transverse girder to form a frame to minimize side sway and the torsional effects from uneven distribution of live load. The longitudinal loads of the leaf are resisted axially by the truss members and the transverse girder, which effectively transfers the loads axially to the foundation. The trussed tower in conjunction with the transverse trunnion girder minimizes torsional effects and out of plane bending moments in the bascule span and trunnion columns from wind loads and asymmetrical live load distribution. The existing trunnion columns for the northbound bascule span are detailed as individual columns braced only at mid-height, allowing the columns to bend about the anchorage tie rods below the trunnions. There is little opportunity for the columns to load share due to the lack of continuity or bracing between columns. The trunnion columns behave as cantilevered beams/columns with a strut/tie rod anchored to the pier wall to resist the lateral loads. This detail to support the longitudinal loads and transverse loads are resisted in an ineffective manner. The columns are restrained a considerable length below the trunnion allowing the trunnion column tops to deflect laterally and the leaves to twist and consequently oscillate. The long-term durability is a concern for the anchor bolts. The anchor bolts used to resist the longitudinal loads are in a corrosive environment. In addition, retightening of these bolts will be required over time due to the relaxation of the bolts, which occur on high strength tensioned bolts of considerable length. The relaxation of the bolts will allow the column to deflect at its point of restraint.

On short double leaf bascule spans (120 ft or less), if possible, it is desirable to eliminate the forward live load bearing. This is accomplished by providing a bascule girder with adequate depth and stiffness for the span required (if vertical geometry constraints permit). This design eliminates the necessity of aligning the forward and rear bearings and ensuring dead and live loads at the trunnion are downward (gravity) loads. The rear live load bearing at the heel of the leaf is used as the primary live load bearing as is the case in the northbound bascule span. If forward live load bearings are used the anchorage is provided to prevent damage and premature wear to the trunnion and prevent uplift and/or overturning that could occur from overweight vehicles. This was a prudent measure utilized in the early development of double leaf bascule span design, however over time this component has been eliminated from many of the bascule spans in Florida. AASHTO does require a safety factor of 150% to resist uplift. Conservatism and redundancy in movable span design is necessary to ensure a safe and long lasting structure. The bascule span is a mechanism of large proportion which requires safety devices, redundancy and interlocks to ensure the span remains under control at all times and operates as designed to prevent irreversible damage and catastrophic failure to the superstructure and substructure.

Forward live load bearings were not utilized on the northbound bascule span and therefore the rear live load anchorage is the only live load support. Unfortunately, the bascule span does not meet deflection criteria and the anchorages are inadequate for the loads applied. Based on our analysis the installation of a forward live load bearing would reduce live load stresses in the girders and lock bars and reduce span deflection. The springs already installed in the trunnion bearing cap bolts will absorb any uplift impact that may occur. In addition the rear live load anchorage requires replacement. The rear live load anchorage was under designed and improperly erected. The members are unbraced, inadequately anchored to the foundation, out of position in reference to the bascule girders, and undersized for the load required to resist. In addition, the members exhibit fatigue sensitive welding details and oscillate because the members are effectively unbraced to the bascule pier back wall and are not properly anchored to the bascule pier floor.

### Trunnion Column Improvements

Improvements are required in the resistance of the longitudinal and transverse loads in order to minimize the twisting action and oscillations observed during the inspection. Our detail included trussing the existing columns with a diagonal strut and anchorage to the bascule pier to effectively brace the leaf longitudinally. The diagonal will also be used as the pinion bearing support. The tower will also be braced transversely with a girder in between the inboard columns as well as struts tied to the outboard columns from the bascule pier walls. Column pairs will also be tied at the bottom to ensure load sharing.

### Providing Live Load Anchorage

On the Northbound Bridge we detailed a provision for forward live load bearings as main live load support and replace the rear live load anchorage which is to be utilized as a back up support to prevent overturning and distressing the lock bars. The rear anchorage will be embedded in a new concrete anchorage and braced at the top to resist eccentric loading and dampen the impact loads.

## Mechanical/Electrical Retrofit

### Existing Mechanical/Electrical Deficiencies

The span drive operating machinery for all four leaves is a combined hydraulic motor system with enclosed gear drives to a main pinion and circular rack. The hydraulic drives are under relay logic control, with a programmable logic controller monitoring bridge operation. The operating machinery of the Northbound and Southbound Bridges are practically identical. The machinery is mounted to the concrete platform located inside each bascule pier in front of the counterweight. A (40 HP) squirrel cage electric motor drives a hydraulic fluid pump to generate flow in order to drive two (20 HP) vane type hydraulic span motors. In case of failure of the primary motor/pump, a (7 ½ HP) squirrel cage auxiliary electric motor/pump is available to operate the leaf at a reduced operating speed. The hydraulic power unit steel platform contains the electric motors, pumps, manifold, valves, fluid reservoir and electric drive cabinet to regulate the hydraulics for ramp and speed control functions. Each 20 HP hydraulic span motor is integrated with a hydraulic multi-disc brake and is coupled to the input shafts of a 13.46:1 ratio, differential gear box speed reducer. The speed reducer input rating is 30 HP at 28 RPM with a 1.0 service factor. Both output shafts of the reducer is coupled to a floating shaft, which rotates a main pinion. Each main pinion meshes with a rack mounted to the bottom flange of each bascule girder and concentric with the trunnion.

Ramping and speed control functions are provided by relay logic in the Motor Control Center (MCC) and a local Hydraulic Power Unit (HPU) on each leaf. Each HPU cabinet (one per leaf) contains three types of control cards; signal generator, ramp, and signal amplifier. One HPU Control Panel is located in the machinery room of each leaf. The HPU Control Panel controls the ramping speeds and timing for raising/lowering each leaf through control of the hydraulic system. Each HPU Control Panel runs the pump motor continuously to provide hydraulic pressure, until the HPU Control Panel shuts off after closing the bridge. The HPU Control Panel has a circuit breaker, contactor and overload relay for the main and auxiliary motors. Timer controls and relays located in the HPU Control Panel are part of the bridge logic control. Hydraulic controls are triggered by electromechanical relays located in the HPU Control Panel and the MCC.

Although the operating machinery is relatively new (less than 5 years in service) the hydraulic system is operating unsatisfactorily. Components within the hydraulic system have necessitated numerous unexpected nuisance repairs and require continual maintenance. Records indicate that during the period from February through November of 1999 there were 48 repair services required of which 24 were related to the hydraulic machinery.

Repairs required since the bridge has been maintained by the FDOT include periodic replacement of the electronic circuit control cards, which break down unexpectedly. The control cards in the HPU cabinet have failed (or burned out) for each leaves at different times. The failure of the cards can be attributed to the sensitive nature of these circuit boards. These cards are susceptible to voltage or current surges in the electrical system and from lightning strikes. In addition, due to the location of these cards inside the HPU drive cabinet; the cards are under constant vibration from vehicular traffic. This type of environment is detrimental to sensitive electronic equipment. There are several problems with the logical controls of the bridge. One major problem is the lack of individual leaf operation.

Accessing the components due to the tight constraints of the machinery platform has made maintenance and repairs extremely difficult. In order to access the HPU platform or walk across the platform from one side of the pier to the other one must walk and climb over numerous valves, piping, limit switches and electronic components which can easily be moved out of proper position, or stepped on causing span operating breakdown or damage to the component. The location of the pumps is underneath the HPU platform. This creates an extremely difficult task to access the pumps for maintenance and removal. Even replacement of the hydraulic fluid filters has proven to be difficult due to their location. The platforms are too small for a comfortable, and safe work environment, especially when the electrical cabinet doors are opened for access. A safe and comfortable working environment is critical in repairing electrical components.

Operational breakdowns have also occurred due to failure of the hydraulic valves. The valves are controlled by solenoids, which magnetically open and close the valves. The solenoids have required repair or replacement due to loose electrical connections. This too may be attributed to constant vibration of the HPU platform. In addition, some of the valve control solenoids are common to both the primary drive and the auxiliary drive preventing a completely independent auxiliary drive. This lack of redundancy prevents the auxiliary drive from operating should there be a breakdown of one of the control valves.

At the time of our initial inspection (9/98) the southwest hydraulic inboard motor was leaking hydraulic fluid. Hydraulic fluid leaks have occurred at one time or another to machinery on each leaf due to worn out seals and loose fittings. This is a continual maintenance requirement of the hydraulic machinery. Motor seals require periodic replacement (approximately every 6-7 years), however replacement of the seals require the motor to be taken out of service for a minimum of two weeks and to be shipped to Jacksonville for seal replacement (Approximately $10,000). A two-week out of service operation of the bridge is unacceptable, and therefore the need of a standby hydraulic motor would be required in order to perform this repair. Hydraulic piping connections have also required continual maintenance.

In the past, the northwest (near opposite) leaf has operated on the auxiliary hydraulic pump due to failure of the primary hydraulic pump. The pump has been taken out of service for repairs due to the failure of a transducer that is necessary to regulate flow to the motor. The reason for the breakdown of this component is unknown and may occur at the other pumps in the near future and throughout the life of the bridge. The repair requires the pump to be taken out of service and shipped to the pump manufacturer for the replacement of the transducer (Approximately $3,500). While a relatively simple and inexpensive repair, it is time consuming due to the difficulty in access and removal of the pump underneath the HPU platform and the need to ship the component to the manufacturer for the custom made part. The pump has been out of service approximately 4 months (3-4 weeks was expected) due to this repair. The auxiliary motor opens the leaf considerably slower than the primary motor. Under auxiliary power the near opposite leaf only opens approximately 10 degrees by the time the other leaves are fully open. Navigational vessels are instructed to use the south half of the channel to avoid the leaf. Eventually under auxiliary power the near opposite leaf achieves fully open status, however the time required opening the leaf to fully open and close the leaf is approximately 20 minutes. Although this duration for opening is acceptable under emergency conditions, it is unacceptable for vehicular traffic for extended periods.

Exacerbating the problem of maintenance and repairs to this operating machinery system is the complexity and inaccessibility of the hydraulic and electrical control systems. This causes extensive time and effort to troubleshoot the breakdowns and to perform manufacturer required maintenance to the components.

## Improvements to the Mechanical/Electrical System

As described above, the operating machinery hydraulic system during its short life in operation has been a continual maintenance problem and disruptive to navigational and vehicular traffic due to extended opening and closing times causing traffic delays and obstructed or delayed openings to navigational vessels. The United States Coast Guard has been dissatisfied with the operational problems with the bridge and has demanded continual updates on the status of the operational difficulties of the bascule span and when the bridge will be operating normally again. In conjunction with the maintenance problems, and in some cases the actual cause of the problem is the difficulty in accessing components for proper preventative maintenance. The operating machinery components are unreliable in their current configuration.

In our Inspection and Rehabilitation Report of September, 1998 we recommended reconfiguration of the hydraulics to improve maintenance capabilities. The recent maintenance problems and lack of dependability have understandably led Maintenance forces to become dismayed with hydraulic machinery as part of an operating system for a movable bridge. This initiated a re-evaluation of the hydraulic system and prompted an electro-mechanical alternative to provide a more reliable and less complex operating machinery. An electro-mechanical reconfiguration design will remove the complex hydraulic system, which requires more maintenance and repairs. In addition, more room on the bascule pier for better access for maintenance and a more dependable operation.

Other design constraints imposed were mostly economical. This led to reusing the existing racks and pinions as well as the differential reducer. Thus the final design requires removal of the entire hydraulic system and installation of a new wound rotor electric main span motor to turn a new primary reducer which will be coupled to the existing differential gearbox. A new primary reducer would be required prior to the existing differential reducer to decrease the input of the new motor to 28 RPM to match the nameplate allowable input speed of the existing reducer. A reduced speed auxiliary drive system would be provided in case of failure of the main electric motor. New machinery and motor brakes will also be required along with all associated couplings. In addition, new supports and modifications to the existing machinery supports will be necessary to accommodate the new machinery.

The advantage of the new gear train alternative is the salvaging of the existing differential reducer and rack and pinion which would be more cost effective than replacing the entire operating machinery system. In addition, the access to the machinery for both maintenance and inspection would be an appreciable improvement over the existing hydraulic system. An operating machinery system as described will require considerably less preventative maintenance than the existing hydraulic system.

Modification to the electrical system would require the addition of motor controllers for speed adjustment. We decided on an AC SCR (Alternating Current Silicon Controlled Rectifier) drive, similar to the motor controllers used at the S.R. 401 Bridge, controlling the wound rotor electric main span motor. A reduced horsepower auxiliary motor would be used for emergencies and will be driven with an independent AC electric starter. The PLC will be rewired to allow for independent operation of each leaf.

The new electrical system that will accompany the new operating machinery is less susceptible to damage by lightning. There are fewer mechanical components to control than with the existing hydraulic system. This correlates to a reduction in the complexity of the electrical system, which facilitates maintenance and troubleshooting.

There are other bridges maintained by District 5 personnel that incorporate AC SCR driven electric span motor systems. For this reason, maintaining and repairing the electrical system proposed will be a more familiar operation than with the existing hydraulic system. In addition, many bridges throughout the state and the country utilize this type of electrical system and are considered reliable. Thus, the motor control industry is very acquainted with this type of application of AC SCR electric motor drives and would be available for assistance during installation, maintenance and malfunctions.

One limitation that we discovered with reusing the existing differential reducer pertains to the power requirements of each leaf. According to power requirement calculations, each leaf requires 25 HP to overcome operating resistance due to wind, imbalance, inertia and friction. These calculations were performed in accordance with AASHTO Standard Specifications for Movable Bridges Article 2.5.3 Condition C. A wind pressure of 10 psf as outlined in the aforementioned article correlates to a wind speed of 67 mph. The existing reducer is rated for 30 HP with a service factor of 1.0. This combination of power rating and service factor defines a reducer capable of withstanding a momentary input power of 60 HP. The manufacturer of the existing gearbox was consulted in order to determine whether the nameplate rating of the gearbox is overly conservative and thus could be adjusted favorably. This is not the case, thus the nameplate data must remain as is (30 HP, 28 RPM, 1.0 service factor). Wound rotor motors are capable of delivering 300% of their full load motor torque (thus, a 25 HP motor may deliver up to 75 HP).

This momentary overload would over stress the existing differential reducer. Controlling the output of a 25 HP motor, in order to protect the gearbox, can be attained with adjustable electrical overload components. Based on our experience this method of control is not reliable. The desired settings required to protect the gearbox can easily be inadvertently changed. Small changes to the required settings can render the components ineffective.

A 20 HP motor without electrical overload components can deliver 60 HP momentarily. This is an acceptable maximum power input to the existing differential reducer. However, a 20 HP motor reduces the capability of the operating machinery to open the leaf in windy conditions. A reduction of span motor power from 25 HP to 20 HP corresponds to a reduction of maximum wind speed operation from 67 mph to 52 mph. We believe protecting the existing gearbox from potential overload damage is worth the reduction in the capacity of operating the bridge at winds speeds exceeding 52 mph.

The location and orientation of the existing gearbox will require vertical mounting of the new additional gearbox, main motor and auxiliary motor. This will require the centerline of motor shaft and reducer input shaft to be relatively high in elevation (approximately 8.5 ft.) from the machinery platform. This is not a favorable mounting configuration since it reduces accessibility. This was the optimum solution based on the given the constraints of cost, input of maintenance forces and the limited space on the bascule pier.