HEAVY MOVABLE STRUCTURES, INC.
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AASHTO/AREMA vs. the International Design Approach

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After 125 years of movable bridge design using the AASHTO, AREMA, and CSA codes, North American design firms have had the opportunity to design several movable bridges in Europe, Scandinavia, and the United Kingdom. These experiences working in a different philosophy has allowed us to vary our designs from the North American codes and has forced us to design in a way we had not previously experienced. This has opened our minds to different ways of approaching movable bridge design.

This paper explores some of the differences in design approach using several case studies over the past 10 years. We will also touch on some unique project delivery methods used by international bridge owners.

Case Study #1: Jacques Chaban-Delmas Bridge, Bordeaux France

This bridge was designed ten years ago and several of the lessons learned designing this bridge outside of AASHTO and AREMA have resulted in discrete changes to those standards.

While the design creates a visual lightness, the 5.5-million-pound, 387-foot-long vertical lift span of the Jacques Chaban-Delmas Bridge in Bordeaux France is designed to carry four lanes of traffic, two sweeping pedestrian and bicycle paths, and two light rail tracks. The unique Design-Build process successfully drove a fierce competition resulting in five dramatic designs. Innovative techniques conforming to the Eurocode and FEM, but would not have been permitted by current North American design standards (AASHTO, AREMA, and CHBDC), are described.

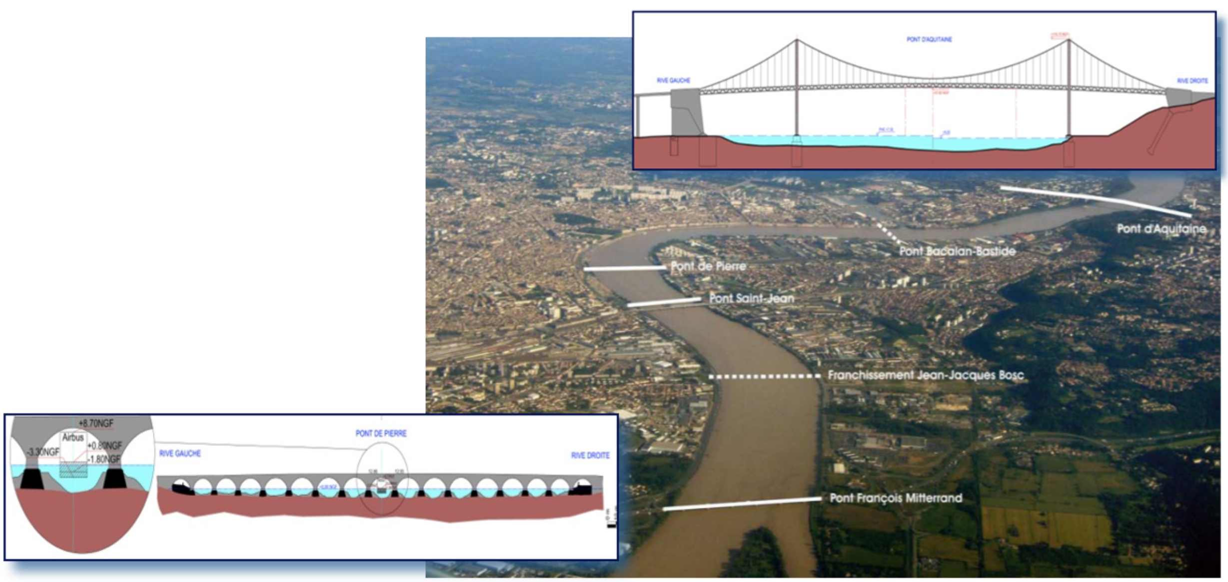


Figure 1. Project Location (Bordeaux City Center Crossing the Garonne River

1. The Selection Process

In 2002, the City of Bordeaux embarked on the challenge to host a competition for the design and construction of a new movable bridge across the River Garonne.

The city elected to use a very open Design-Build process that had very clear basic requirements:

- Provide a crossing over the River Garonne for cars, pedestrians, and bicycles, as well as, at a later date, a Tram line.
- Allow the passage of boats and, in particular, very large ships.

The technical requirements were also simply stated:

- Satisfy the Basic Project Objectives
- Meet the Eurocode
- Meet FEM
- Provide an economically viable solution
- Meet the minimum tender requirements to qualify for a $1.4 Million stipend to the unsuccessful bidders

Five separate teams were formed to pursue the project, and a hearty competition ensued. After more than two years of design and construction estimating, presentations were delivered to the City in the spring of 2005. Models of each proposed bridge are shown in Figure 2.

After much deliberation and scrutiny of technical, architectural and commercial attributes of each Proposal, the Vinci Group was determined to be the successful bidder. The group consisted of a design team of EGIS Jean Muller International, Michel Virlogeux, Lavinge Cheron Architects and Hardesty & Hanover.

Figure 2. The Five Submitted Proposals

Figure 3. The Successful Proposal

2. Description of the Bridge

The overall bridge length, including approach spans is 1421 ft. The lift span is 387 ft. in length and has a variable width that reaches 141 ft. at the center of midpoint. The lift span weighs 5.5 million pounds. In the seated position, the vertical clearance above the waterway is 42 ft., and the horizontal clearance is 348 ft. The lift span can be raised by 148 ft., along the pylons that are 262 ft. tall.

3. Unique Movable Bridge Design Features

3.1 Independent Pylons

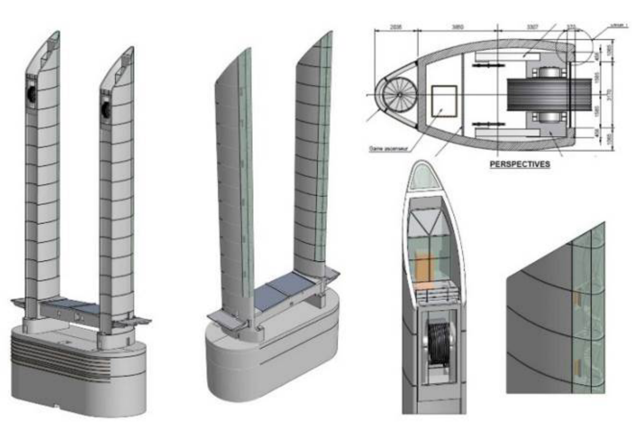


Figure 4. Four Independent Pylons

Although not unique to the movable bridge world, the use of four independent pylons on a vertical lift bridge is extremely rare in North America. Such a design necessitates the use of either a span mounted drive system, or independent drives located at the base of each pair of pylons.

The design also results in pylons that are able to deflect independently, due to the lack of a cross strut connecting the pylons. The resultant deflections can cause challenging design issues, since, while raising the lift span, the pylon flexibility can cause the need for large span guidance tolerances.

The drive system and the span guidance designs will be discuss in further detail within this paper.

3.2 Closed Loop Drive System

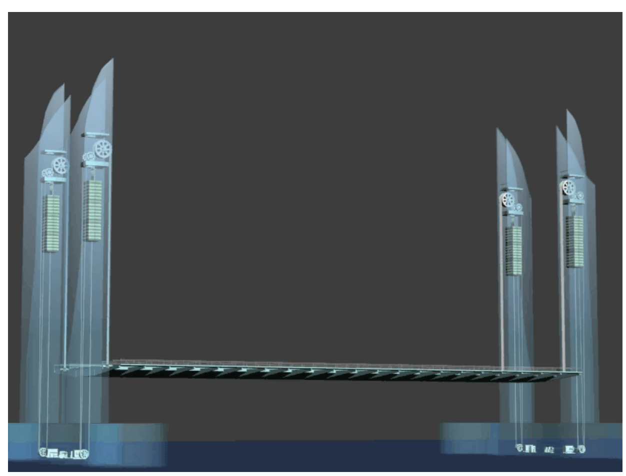


Figure 5. Closed Loop Drive System

The design team was able to justify several alternative technical concepts that were approved by the City's engineers. Since the design team was able to greatly reduce the imbalance, we were concerned that the one way rope lifting system, which entirely relies on gravity to lower the bridge, may in fact be controlling a lift span imbalance that was too light. This concern was exacerbated by the fact that when the span is fully raised, all of the weight of the massive counterweight ropes transfers to the counterweight side of the sheave. This ultimately reduces the span imbalance by 108,000 lbs. In a case of maximum wind and any other unintended force such as friction from a binding guide or bearing could cause the span to require more force to lower than gravity alone. To eliminate this concern, the team designed a two way, closed loop operating system. This system is one that connects to the bottom and top of the counterweight within the pylons assuring that the systems and utilized the machinery torque and line pull to both raise and lower the span. As described above, the drums on each back (transverse pair of pylons) are mechanically synchronized. The system uses four operating ropes per corner of the span. The operating ropes are 46mm diameter rotation resistant compacted strand wire ropes and are pretensioned to ensure that tension is maintained in the operating rope system through all operating conditions as required by the functional program.

In order to minimize the length of the drums as well as the fleet angles of the ropes, right and left hand helical grooves were used. In this manner the ropes that are being wound on the drum occupy the grooves vacated by the paying-out ropes. The uphaul ropes extend from the operating drum near its transverse center though the core of the pylon and attach to the bottom of the counterweight box at the spine plate. The downhaul ropes extend from the end of the operating drum length (symmetrically about the transverse center) and extend through the core of the pylon up to the sheave level. At the level of the sheave, each downhaul rope wraps around a 1.70 m diameter deflector sheave and terminates at the top of the counterweight.

The Diameter ratios between the operating drums/ deflector sheaves and the operating ropes is 38:1. The American Association of State Highway officials (AASHTO) standard, the American Railway Engineering and Maintenance of Way (AREMA) recommended practice and the Canadian Highway Bridge Design Code (CHBDC) require a minimum ratio of 45:1.

The anticipated impact of this deviation from North American practice would be expected to present itself is advanced wear of the ropes. The design team provided an operating rope replacement procedure along with permanently mounted winches to facilitate future operating rope replacement, if needed.
There are a number of advantages of this two-way system. First, the lift span is positively controlled at all positions. The system has the ability to drive the bridge either up or down regardless of the position of the span. This was a major advantage and helped the design team to minimize the imbalance of the span, which resulted in several significant architectural, engineering, and cost benefits.

A number of modern vertical lift bridges in Europe utilize an extremely span-heavy condition compared to US standards. The governing FEM code requires the load (the lift span) to be sufficiently heavy to maintain positive downward force through all conditions including environmental loads. This philosophy, combined with substantially higher wind design loads that are not commonly designed for in North America, led to a functional program that anticipated a span imbalance of nearly 700,000 lbs. in the seated position. This imbalance has a dramatic impact on the initial load to lift and the power requirements for the bridge, let alone the physical and special impacts of the resultant enormous operating system.

As part of the Project Study phase, the design team performed a span balance study. This study evaluated a number of span balance conditions for a one-way rope system (the system conforming directly to the functional program) and a two-way system. One primary concern of the owner was the safety of the system and the ability to ensure the bridge can be lowered from the raised position in the event of a power failure. Another primary concern was the uplift forces produced by wind on the structure in the seated position. The owner initially prohibited the use of span locks. Their initial desire was to have the span balance load that exceeds the highest possible uplift that the wing-shaped lift span would encounter while carrying vehicles and pedestrians. ***This is an important design case that is not addressed in AASHTO, AREMA or the CHBDC. Typical practice in the US is to provide for a minimal span heavy imbalance of 10-40k with the span seated, regardless of potential uplift forces.***

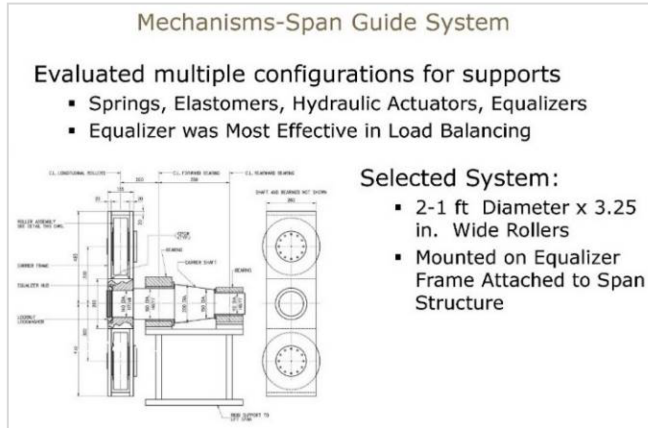


Figure 6. Mechanisms-Span Guide System

As part of the span balance study, the design team advanced the site specific wind analysis. This analysis determined the wind loads anticipated by the functional program were larger than the actual site conditions. Using this site specific data, the design team performed detailed wind analysis and modeling to determine the wind forces on the span for a number of positions of lift and conditions (nominal wind, extreme wind). The results of the span balance study were presented to the owner and the owner concurred with the design team that a seated span imbalance (span minus counterweight) of 200,000 lbs. and the use of the two-way rope system would be used for the remaining phases of the design and construction. This seated imbalance results in a span neutral balance condition at the full lift height, exclusive of environmental loads, due to the substantial counterweight rope transfer weight.

This change resulted in a reduction of the torque required to operate the bridge, lowering the system horsepower from 600HP to 175 HP, and, just as importantly, allowed the architects to greatly improve upon the slenderness of the pylons. The potential to utilize auxiliary counterweights was evaluated and it was determined through coordination with the builder than the additional cost and complexity of the auxiliary counterweight system was greater than the cost impact of the proposed balance on the machinery and power demands. In addition, the spatial constraints within the pylons made the inclusion of auxiliary counterweights a less preferable options. ***AASHTO, AREMA and the CHBDC would require auxiliary counterweights on a lift bridge of these proportions.***

3.3 Span Machine Full Load Testing

Another benefit of the two-way operating system centers on constructability. The functional program required that the machinery be load tested in the assembled condition. With the two-way system, the closed loop of the operating ropes and the counterweight could be operated independent of the span and counterweight ropes. This provides the builder flexibility in the sequence of field operations and permitted the time-intensive machinery testing to be performed exclusive of the lift span float-in.
The actual testing program that was implemented, to prove out the capacity of the operating system, was to install the full operating machinery system and connect it to the partially constructed counterweights in each pylon (see later counterweight description). The partial counterweight dead load was made equivalent to the maximum testing load and performed to the satisfaction of the City's engineers.

3.4 Counterweight Ropes

The counterweight ropes are 3-inch- (76mm-) diameter, rotation resistant, compacted strand wire ropes, fitted with open shelter sockets at each end. ***At the time of design, these wire ropes would not meet AASHTO, AREMA or the CHBDC is the counterweight rope size. In those guides/codes, the maximum rope diameter limited to 2-1/2 inches. In large part due to this bridge, AASHTO and AREMA have recently changed to allow for ropes larger than 2-12" in diameter.***

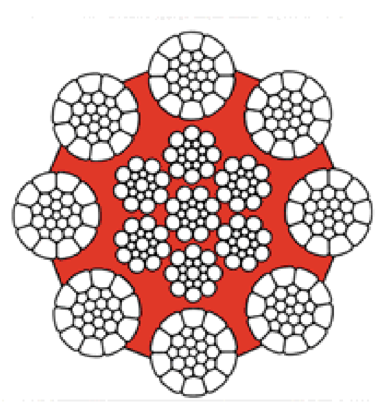
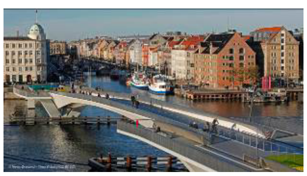


Figure 8. Main Counterweight Rope

The bridge has ten ropes per corner. The counterweight ropes drape off the counterweight sheaves and each counterweight rope is connected to the end diaphragm of the lift span through an adjustable take-up assembly. The opposite end of each counterweight rope is pinned to the counterweight anchorage plate. Due to the concentrated lifting loads the end diaphragms were stiffened and as a result act as an integral lifting girder. ***The counterweight sheave is a welded steel design with a 4.0 m pitch diameter, this D/d ratio of 52:1 meets the FEM governing code, but is significantly lower the 80:1 ratio listed by AASHTO, AREMA and the CHBDC.***

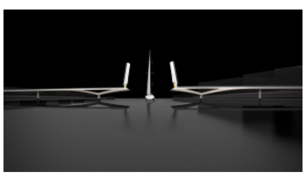
The design impacts resulting from this are significant. The benefits and disadvantages were carefully weighed. The primary impact was that the pylons could be much more slender and the visual impact to the tender design was crucial. The design team was able to use 12-ft diameter sheaves, as opposed to a minimum 20-ft diameter sheave that AASHTO and other codes would require. The primary concern was the significant bending that the wire ropes would experience as they passed over the sheaves. This was mitigated by agreeing to view the counterweight ropes as a wear component. While in the US, vertical lift bridges typically have their ropes changed after several decades, the possibility of more frequent changes was accepted. To prepare for eventual rope replacement, each pylon is equipped with a permanent hoisting system designed specifically for future rope replacements. The procedure was also prepared in great detail.

4. Noted Design Code Variations in Subsequent Movable Bridges



Inderhavnen Pedestrian/Cyclist Bridge
Copenhagen, Denmark

Unique 180m retractive pedestrian/cyclist bridge. Completed in 2015.



Waterford Sustainable Transport Bridge
Waterford, Ireland

New double-leaf bascule bridge of the River Suir for pedestrians, cyclists, and designed for carbon-free vehicle. In construction bidding phase.

Great Yarmouth Third River Crossing
Norfolk County, England

New double-leaf bascule roadway, pedestrian, and cyclist bridge. Currently in construction with estimated completion in 2024.

River Clyde Swing Bridge
Glasgow, Scotland

New double cable-stayed swing bridge for vehicular, pedestrian, and cyclist use. Currently in detailed design with estimated construction start in 2023.

4.1 Collective Design Differences in Code Requirements and Preference

- **Turned and Fitted Bolts:**
  Use of turned or fitted bolts for machinery connections. Its standard practice to use friction connections wherever possible and the use of turned bolts is frowned upon.

- **Custom Shim Packs:**
  Use of custom shims. We have had a lot of resistance to the use of shim packs and custom machined shims.

- **Planetary Gear Boxes:**
  Europeans are very comfortable using catalog planetary reducers directly driving a pinion on the output shaft which is not prohibited by AASHTO but is much less common in the US.

- **Maintenance Free Bearings:**
  Europeans seem to use bearing materials that require much less maintenance than those used in North America. For example, the wedges and span locks on Clyde use DRIE-D type bearings. At Waterford, we are using Lubrite type trunnion bearings.

- **Keys and Interference Fits:**
  The preference is to use interference fits without keys to mount gears and coupling hubs, etc. Additionally, when a key is used they think it is strange that we would also use an interference fit. There is no requirement for fits like those in AASHTO. Other design standards tend to stay away from interference fits. Machinery fabricators push back hard against our requests for high tolerances on fits.

- **Service Factors:**
  It is common to employ the FEM methodology to determine life requirements based on load spectrum and desired life. For instance, on Clyde, the reducers meet an M8 life rating. There is no requirement for bearings to have 40000 hrs L10 life and no requirement for reducers to have a 1.5 AGMA service factor.

- **Bronze Bearing Pressures:**
  There is no list of allowable bearing pressures for bronze bearings. We have typically deferred to AASHTO but it is not a requirement. The Dutch code does address this, however.

- **Machinery Brakes:**
  Other design standards generally prefer disk brakes over wheel brakes and frequently place a brake at the low speed end of a system.

- **Wire Rope Construction:**
  Other design standards do not call for a 6x19 rope anywhere. They would typically use a more modern high strength construction.

- **Pin Racks:**
  Pin racks are commonplace, even in new construction racks which is highly unusual in the US on bridges.

- **Swing Bridge Center Pivots:**
  Europeans have been using slewing bearings for years. The River Clyde Bridge is utilizing them. Europeans tend to make their bridges much more imbalanced than we typically do. This results in more relance on machinery power, It is contradictory to their much higher focus on sustainability and carbon imprint.

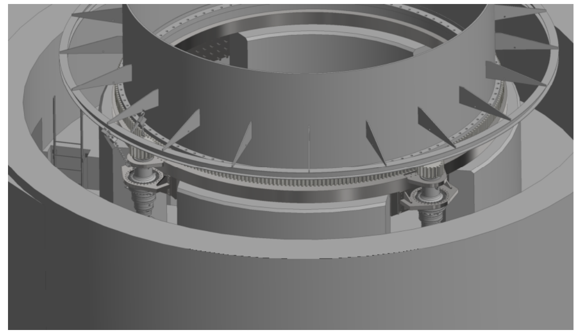


Figure 9. Typical Slewing Bearing Drive Machinery Arrangement

- **Span Design:**
  Orthotropic decks are the standard. This which greatly affects how machinery is mounted and sequence of installation.

- **Design Checking and Plan Stamps:**
  There are Category III checks on every project in the UK There seems to be 3 movable bridge firms on every project. The owners engineer, the design engineer and the Cat III checker. Essentially, the Cat 3 checker does an full independent design check.

  CE marking instead are required of being stamped by a PE. The main difference is the classification of the bridge as a machinery product. This relates to the CE marking. They ultimately look at a one of a kind moving bridge as a product that is designed for a specific purpose. In the US we look at bridges more as publicly held structures. Stand procedure is to go through a thorough process of producing a formal FMEA on every project.

- **Dedicated Span Locks:**
  The standards generally prefer to have dedicated locking systems independent of the span drive machinery to hold the bridge in position when open to vehicular traffic and fully unload the machinery when not in operation. This I believe is suggested in their Machinery Directive but we have been able to get around it in some cases. They also like to provide a method to lock a bridge in the open position for extended periods.

- **Barrier Gates:**
  They are not required to use barrier gates that could actually stop a car.

5. Conclusion

Philosophically, the European model accounts for a “smarter” user. It is not expected that someone would intentionally or accidently drive off an open bridge . Conversely from the operations side, they like systems and safety measures for each mechanism or control.. The Chaban-Delmas bridge had interlocks to the control system for every door and gate that pre-empted movement of the bridge. Best way to describe the priority is that employee/operator safety requirements are very high and user safety is lower and governed more by common sense of the user.

Our observation is that they are also willing to rely on engineering principles much more readily than in the US. We have prescriptive codes and we generally struggle to put the design problem at hand in the framework of the code requirements. In the European model, they have the code but are very ready apply engineering principles and FEM to validate the design concept. This often results in more optimized and ultimately conservative design.

Acknowledgements

Jacques Chaban-Delmas Bridge
Bordeaux, France
Owner
- La CUB-Urban Community of Bordeaux

Contractor
- Vinci Group: Design-Build Contractor
- GTM: Civil Works Construction
- NFM Technologies: Machinery supplier
- Cimolaï : Steel Structure

Design Consortium
- EGIS Jean Muller Int'l: Lead Design Consultant
- Michel Virlogeux: Bridge Designer
- Charles Lavigne: Bridge Architect (Concept Phase)
- Hardesty & Hanover: Movable Bridge Systems Designer
- Lavigne-Cheron Architects: Bridge Architect

Inderhavnen Pedestrian/Cyclist Bridge
Copenhagen, Denmark
Owner
- Copenhagen City Council

Contractor
- Valmont SM: General Contractor
- SH Group: Machinery and Controls Contractor
- H&C: Electrical Contractor
- COWI: Resident Engineering and Construction Services

Design Consortium
- Studio Bednarski: Bridge Architect
- Flint & Neill Ltd (now COWI): Bridge Structural Design
- Hardesty & Hanover: Movable Bridge Specialist / Mechanical & Electrical Design
- Spiers & Major: Project Lighting Consultant
- COWI: Design Coordination Consultant

Waterford Sustainable Transport Bridge
Waterford, Ireland
Owner
- Waterford City Council

Design Consortium
- Roughan & O'Donovan: Project Lead and Bridge Engineer
- Knight Architects: Bridge Architect
- Hardesty & Hanover: Movable Bridge Specialist / Mechanical & Electrical Design

Great Yarmouth Third River Crossing
Norfolk County, England
Owner
- Norfolk County Council

Contractor
- BAM Farrans Joint Venture

Design Leads
- Roughan & O'Donovan: Project Lead and Bridge Engineer
- Hardesty & Hanover: Movable Bridge Specialist / Mechanical & Electrical Design

River Clyde Swing Bridge, ***Glasgow, Scotland***
Owner
- Refrewshire County Council

Contractor
- Graham: General Contractor
- Hollandia Infra: Superstructure & MEICA Fabrication

Design Leads
- Hardesty & Hanover: Lead Movable Bridge Engineer
- Roughan & O'Donovan: Movable Bridge Superstructure Engineer
- Ramboll: Substructure Design