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Closed-Loop Hydraulic Cylinder Drive for UK Bascule Bridge

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Introduction

The Herring Bridge is a new double-leaf trunnion bascule bridge spanning the River Yare in Great Yarmouth, England. The Norfolk County Council (NCC) project was delivered through a design-build process. The £121 M project opened for public use on February 1, 2024. A key innovative feature of the bridge is the closed-loop hydraulic cylinder drive developed for this project to offer advantages over traditional open-loop hydraulic cylinder systems for movable bridge in terms of power consumption, cost, and motion control. This paper discusses the project design criteria that was a combination of AASHTO and Eurocodes, as well as the design development and design features. The focus of this paper is on aspects of design criteria that differ between movable bridge design code in Europe and the United States, in particular those regarding wind loading on the movable span, and hydraulic cylinder drive features uncommon in the United States.

Project Background

Great Yarmouth is a seaside and port town located in Norwich County, England. The Great Yarmouth urban area has a population of about 70,000 people. The town is located at the mouth of the River Yare, one of the main waterways providing access to the Norfolk Broads, a network of navigable waters that are a destination for pleasure craft. The River Yare divides Great Yarmouth in two, with the town center, seafront, industrial areas, and outer harbor located on a narrow, 4 km long, peninsula (South Denes) between the river and the sea, isolated from the rest of the town.

Figure 1 – New Herring Bridge, Great Yarmouth, UK, viewed from the northeast

Great Yarmouth is relatively isolated with limited rail and highway connections. Despite this, Great Yarmouth, it is an active tourist destination attracting over 1 million visitors each year.
The port at Great Yarmouth is one of England's premier offshore support ports. It is an established general cargo port due in part to it being the closest North Sea crossing to continental Europe. The deep-water outer harbor at the mouth of the River Yare serves southern North Sea oil and gas fields and offshore wind farms. The port provides modern facilities for the large offshore vessels and facilities supporting offshore operations and maintenance within the river port. Overall, the port handles a wide range of cargoes including aggregates, cement, grain, fertilizers, forest products, and dry and liquid bulks.

Project Need

The River Yare bisects the port area of Great Yarmouth. There are no crossings south of the Haven Bridge, located approximately 4 km north of the river outfall into the North Sea. This forces port traffic to pass through the town center, an area that is often congested. As a consequence, investment and redevelopment is discouraged. The new Herring Bridge is located approximately 1.6 km south of the Haven Bridge and provides a means to bypass the town center and a shorter route to roadways connecting to the south. According to the NCC's project website, the Herring Bridge is needed to deliver the following objectives:

a) To support Great Yarmouth as a center for both offshore renewable energy and the offshore oil and gas industry, enabling the delivery of renewable energy Nationally Significant Infrastructure Projects (NSIPs) and enhancing the port's role as an international gateway
b) To improve access and strategic connectivity between Great Yarmouth port and the national road network thereby supporting and promoting economic and employment growth (particularly in the Enterprise Zone)
c) To support the regeneration of Great Yarmouth, including the town center and seafront, helping the visitor and retail economy
d) To improve regional and local access by enhancing the resilience of the local road network, reducing congestion and improving journey time reliability
e) To improve safety and to reduce road casualties and accidents, in part by reducing heavy traffic from unsuitable routes within the town center. To improve access to and from the Great Yarmouth peninsula for pedestrians, cyclists and buses, encouraging more sustainable modes of transport and reduce community severance
f) To protect and enhance the environment by reducing emissions of greenhouse gases and minimizing the environmental impact of the Proposed Scheme.

Design Criteria

The project owner, NCC, established the type (double-leaf bascule) and location of the proposed new bridge over the River Yare. NCC, along with their supporting consultants, also established the general and specific requirements for the project and published these with the advertisement for the project. Elements of those requirements applicable to this paper are presented below.

Governing Specifications

The project mechanical design specifications are as follows:

- BS 2573 Rules for the design of Cranes, Parts 1 (structures) and 2 (mechanisms)
- The Machinery Directive 2006/42/EC and referenced standards
- NEN 6786-1: 2017, Requirements for the Design of Movable Parts of Structures – Part 1: Movable Bridges (Dutch Code) – applied only to wind actions on the movable span
- AASHTO LRFD Movable Highway Bridge Design Specifications 2nd Edition 2007, with Interims through 2018.4.1 (AASHTO Movable)

Operational & Maintainability Requirements

Operational Requirements were established by the owner to include:

- Full rotation of bascule leaf (open or close) – 90 seconds or less
- Maximum operating wind speed – 20.1m/s, 10-minute average
- Ability to operate the bridge with a hydraulic cylinder removed for service or replacement, allowing for a slower speed and lower operating wind
- Multiple pumps/motors for redundancy
- Double seal system for hydraulic cylinder clevis bearings

Design Service Life of Major Elements

The project criteria established minimum service life for mechanical and hydraulic component and systems as follows:

- Bridge structure = 120 years
- Mechanical components and systems = 60 years
- Replaceable mechanical components = 25 years
- Major hydraulic components = 50 years
- Minor hydraulic components = 15 years
- Hydraulic hoses = 5 years
- Electrical and control systems = 15 years

Application of the Dutch Code to Movable Bridge Operating Wind Loads

Unlike the AASHTO LRFD Movable Highway Bridge Design Specifications, 2nd edition, NEN 6786-1 applies a rational site-specific approach to determining the design wind loading for movable bridges. The primary components of the Dutch Code's approach and the values[1] for the Herring Bridge are:

- Basic wind velocity Vb.0 at the bridge location (wind zone) – 20.1m/s (10min-average)
- Type of Waterway/Hours per year that the bridge need not open due to high winds –
    - Main waterway with vertical clearance (closed position) less than 6.00m
    - 12 hours per year, bridge non-operable due to high winds

To apply the above criteria the Dutch Code provides a table for selecting the design wind velocity, V_{m10}. For this site V_{m10} is 13.4m/s (30mph). A notable difference in design wind between codes is in the basis of wind velocity. The Dutch Code uses 10-minute average wind velocity. AASHTO Movable uses 1-minute average wind velocity and bases the wind pressure for operation on a 50mph wind. For comparison of these values, we can approximate the equivalents using the Durst Curve[2]. From this data the estimated 1-minute peak wind velocity in a 10-minute period can be obtained by applying a factor of 1.17. The estimated 3-second gust in a 10-minute period can be obtained by applying a factor of 1.43. Following this approach the 20.1m/s, V_{10} is equivalent to a V_{60} (1-min average) of 23.5m/s (52.6mph) and V_{m10} (13.4m/s) is equivalent to V_{m60} of 15.7m/s (35.1mph).

The project required a permanent holding device that can be engaged in the event a leaf is to be secured in the open position for maintenance. For this condition, the wind velocity is determined based on a 15-year return period. For this site the design holding device wind is 15.5m/s (34.7mph).

[1] See Table 3-10 of NEN 6786-1: 2017 Requirements for the Design of Movable Parts of Structures – Part 1: Movable Bridges

[2] ASCE 7-05, Figure C6-4

Other factors applied in calculating wind pressure per the Dutch Code that are similar to those applied in the AASHTO LRFD Bridge Design Specifications, 9th Edition, 2020, the specifications that apply to fixed bridges, and the site-specific wind design procedure in the 3rd Edition of the AASHTO Movable, include height above ground level, wind shape factor[3] (drag coefficient), and roughness length (ground surface roughness). In addition, the Dutch Code includes a 1.05 factor for imprecision of measured wind speed, a 0.95 dimension factor, and a 1.15 dynamic factor. Additionally, for hydraulic systems, the Dutch Code applies an efficiency factor of 0.95 in calculations for determining operating power requirements. In comparison, AASHTO Movable applies a fixed factor of 1.56 to account for shape factors and height above ground level in establishing the base wind pressure for design of 10psf from the 50mph base wind speed[4].

Applying the above wind velocities the nominal wind pressure applied in design, adjusted for height and roughness length are as follows:

> Dynamic pressure in operation = 479 Pa (10.0 psf)
> Dynamic pressure for holding device = 640 Pa (13.4 psf)

Like the AASHTO Movable methodology, bridge power calculations account for acceleration forces due to inertia and friction, primarily due to trunnion/bearing friction. The Dutch Code also specifies calculation of the kinetic energy effect of the hydraulic fluid acting as a spring. Note that the Dutch Code prescribes a single value of 0.15 for trunnion friction whereas AASHTO specifies two values for bronze sleeve bearings, 0.12 in motion and 0.18 starting.

While the AASHTO Movable methodology treats the applied wind as a service load, the Dutch Code applies load factors for each of several conditions. Conditions applied to the hydraulic system, applicable partial factors, and effective factored design pressures are presented in TABLE-1.

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[3] In the Dutch Code the shape factor is applied to bascule bridges to account for the angle of bridge opening. The factor varies from 0.4 with the leaf nearly closed to 1.15 with the leaf at full open. The shape factor also accounts for the drag coefficient as a function of the span length to width ratio.

[4] AASHTO LRFD Bridge Design Specifications, 9th Edition, 2020, which applies to design of fixed bridge structures, uses 3-second gust wind velocity and applies factors in calculation of wind pressure to account for pressure exposure (ground surface roughness), elevation (height), and drag (shape factor). To better align the AASHTO specifications for movable bridges with those for fixed bridges the 3rd Edition of the AASHTO LRFD Movable Highway Bridge Design Specifications, published in 2023, introduced an alternative site-specific procedure for determining design wind pressure on movable spans.

TABLE-1 SUMMARY OF LOAD COMBINATIONS AND RESULTING WIND PRESSURES APPLYING THE DUTCH CODE						
Load Situation	**Wind Duration Factor**	**Partial Factor Wind**	**Partial Factor for Dead Loads**	**Capacity Factor**	**Effective factored pressure (Pa)***	**Effective factored pressure (psf)**
Below Operating and Holding Conditions apply the 13.4m/s wind and 479 Pa basic wind pressure						
Fatigue	0.25	1.2	1.0	1.0	190	4.0
Constant Velocity, Avg	0.5	1.1	1.1	1.0	348	7.3
Accelerating, Avg	0.5	1.1	1.1	1.0	348	7.3
Constant Velocity, Max	0.8	1.1	1.1	1.0	556	11.6
Accelerating, Max	0.7	1.1	1.1	1.0	487	10.2
Start from Closed	0.7	1.8	1.2	1.3	405	8.5
Hold Any Position	1.0	1.8	1.2	1.0	1137	23.8**
Below Holding Device design conditions apply the 15.5m/s wind and 640 Pa basic wind pressure						
Lock Leaf in Open Position	1.0	1.8	1.2	1.0	1520	31.7

*Partial Factor for Dead Load is not included in effective pressure as this factor only impacts the inertia load calculation. To present an effective pressure, comparable to AASHTO Movable values, the pressures are factored by the product of 1.05 measurement imprecision factor, 0.95 dimension factor, 1.15 dynamic factor, and 0.45 (closed position) or 1.15 (open position) for shape factor.
**This holding load is applied only for structural design and does not apply to design of the hydraulic system.

Review of the above tabulated values shows that the effective wind pressures are somewhat higher than the AASHTO Movable values of 2.5 psf for constant bridge velocity wind, 10 psf for maximum operating wind, and 20 psf for holding wind. The most significant difference is the constant bridge velocity wind pressure 7.3 psf (Dutch Code) vs 2.5 psf (AASHTO Movable). The design pressure for holding the leaf in the open position is similar to the AASHTO Movable value for holding a bridge normally left in the open position (30 psf).

For the case of operating with a cylinder removed from service, a methodology for determining the design wind loading for this temporary condition needed to be established. For this condition the number of hours per year that the bridge can be inoperable due to high winds was increased from 12 to 72. This reduced the design wind for this condition from 20.1m/s to 10.9m/s (24.4mph) and likewise, the design wind pressure. This approach enables the redundancy in the system to be utilized in a documented manner in the event of a cylinder being removed from service.

Movable Span Configuration

The Herring Bridge is a double-leaf trunnion bascule bridge providing a 50m wide navigational clearance between fenders and 4.5m vertical clearance in the closed (lowered) position. The bridge section carries two 3.65m-wide carriageways and a 4.5m-wide cycleway/footway eastbound and two 3.65m-wide carriageways and a 1.5m-wide footway westbound. Overall, the bridge width, including parapets, is 25.2m (82.7ft). To achieve unlimited vertical navigation clearance in the open position, each bascule leaf is designed to rotate 74 degrees.

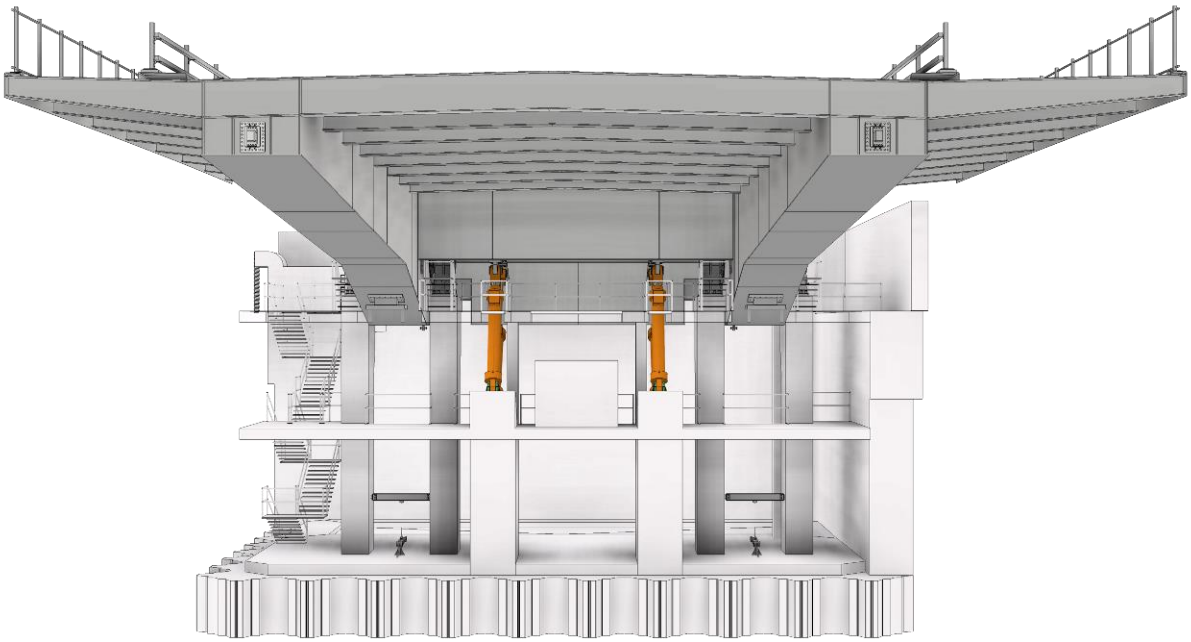

Figure 2 – Movable Span Rendering with front wall of bascule pier removed. Note the twin box girder configuration and trunnion columns under each of four trunnion bearings, one either side of each box girder

The movable span structure consists of a pair of steel box girders working compositely with a steel orthotropic deck. Each box girder is 2.06m wide and varies in depth from 3.80m at the tail end, to 5.42m at the trunnions, to 1.80m in depth at the tip of the span. Transverse floorbeams are typically spaced at 3.67m along the length of the leaf. Each counterweight is housed in a steel box spanning between the box girders. Between the counterweight and the forward live load bearings are a series of deep floorbeams and a pair of longitudinal operating girders on which the upper cylinder clevises are mounted. Overall, the box girders are 44.63m long, 10.63m from the back of the counterweight to the centerline of trunnions, and 34.00m from the centerline of trunnions to the nose of the box at the center joint. Each leaf has a total weight of approximately 1,257,000kg.

The movable span configuration can be described as a conventional, simple trunnion, deck girder, with the trunnions located below the deck level and the counterweight rotating under the fixed deck of the bascule pier. The carriageway deck joint is positioned 3.30m rear of the centerline of trunnions. Footpath deck joints are positioned 6.48m forward of the centerline of trunnions.

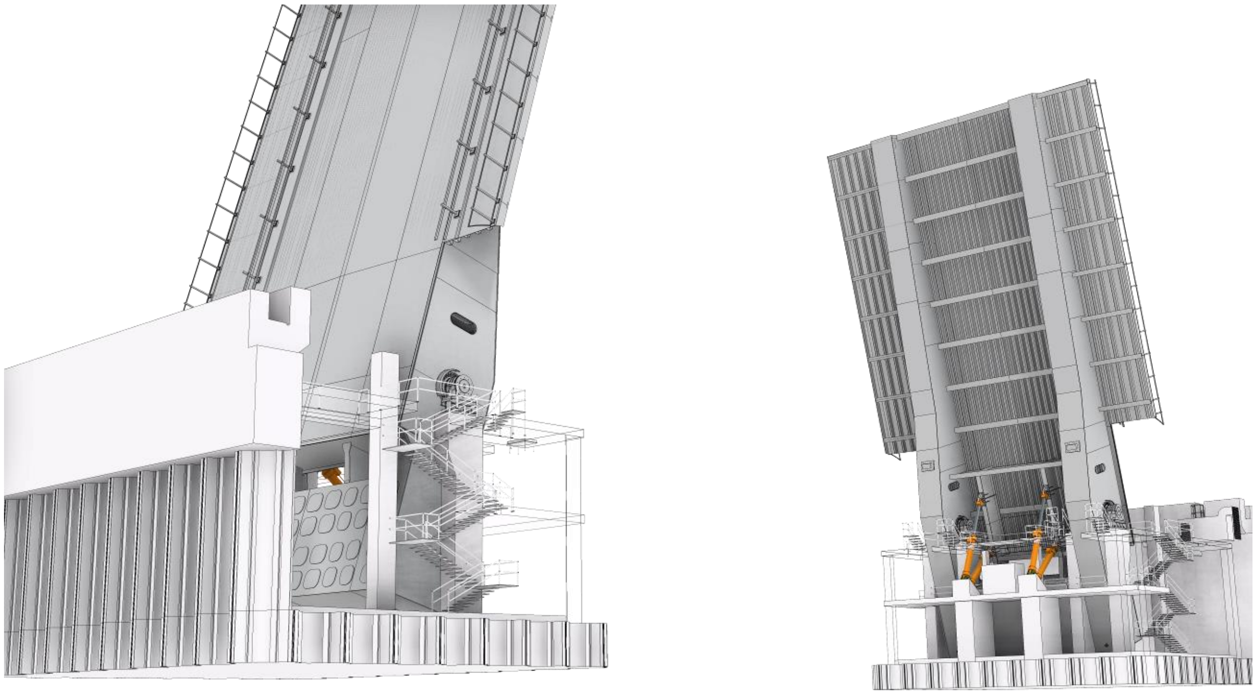

Figure 3 – Double-Leaf Bascule Configuration

The trunnion assemblies consist of alloy steel trunnion shafts, 640mm in diameter at the journals. Each shaft is fitted into the box girder webs with a hub and backing ring. The distance between trunnion bearing centers is 3.28m. Trunnion bearings are of the plain bronze bushing type. Bearing housings are of cast steel. Each bearing is supported on and fastened to a steel weldment with 4 each, M72 turned bolts and anchored to a concrete trunnion column with 12 each, M72 Class 10.9 anchor rods.

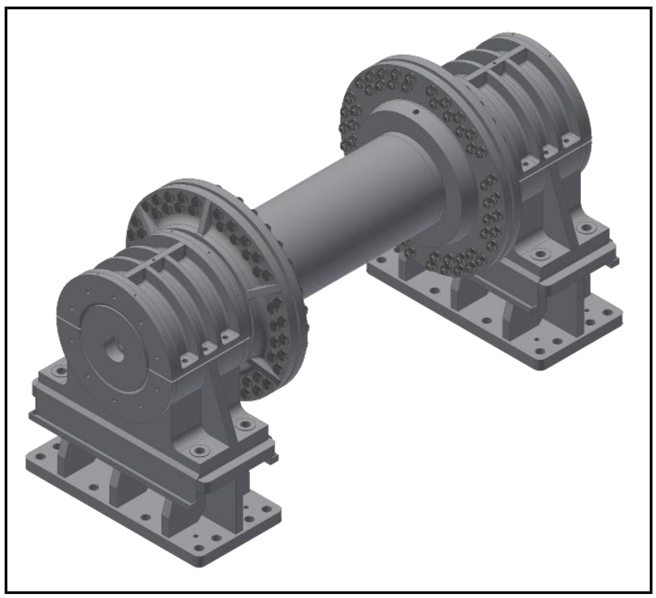

Figure 4 – Simple Trunnion Assembly

The owner's design review team had little familiarity with conventional plain trunnion bearings and expressed concern regarding water and debris intrusion into the bearing. As a result, a lip seal was added at the interface of the inside face of the bushing flange and the trunnion hub. This was in addition to a debris shield attached to the web of the girder and spanning over the bearing.

In addition to the trunnion bearings, each bascule leaf is supported on a pair of forward live load shoes, positioned 5.69m forward of the centerline of trunnions. These bearings take a small dead load reaction due to forward imbalance in the leaf and significant live load with traffic on the leaf.

Two nose locks (aka center locks) are located at the center joint between bascule leaves. These consist of an alloy steel bar that is supported and guided by a pair of guides, rear guide and forward guide, housed within the west leaf box girders. A linear-electric actuator drives each lock bar across the center joint and into a receiver mounted on the east leaf. When engaged the nose locks transfer shear across the center joint and maintain vertical alignment of the deck surfaces of the east and west bascule leaves.

Hydraulic Cylinder Drive System

Closed-Loop Cylinder Drive System

The most common hydraulic cylinder drive system for bascule type movable bridges involves double acting cylinders powered by an open-loop hydraulic power unit. This system has a proven track record in Europe and the United States and generally offers the simplest design and construction. However, open-loop systems have a drawback in that they are inherently inefficient. For the “open” system to provide adequate resistance for dynamic stability and resistance of overhauling loads, a “meter-out” function, such as a counterbalance valve, is required. Metering out involves adding active resistance typically through a flow restriction that creates back pressure downstream of the cylinder. At full flow metering out via a counterbalance valve can produce a pressure drop of 20 bar (300 psi) or more, resulting in significant inefficiency in the drive system. For example, the full flow of a Herring Bridge HPU is 640 l/m, which at 20 bar pressure drop is the equivalent of 21 kW (28 hp) of power that would be dissipated as heat.

An additional inefficiency in typical open-loop hydraulic cylinder drives for bascule bridges results from the basic geometric configuration of single-rod, double-acting cylinders. The effective area within the cylinder upon which the fluid pressure acts is different for each direction of action, i.e., there is a differential area acting on either side of the piston. When extending, the fluid performing the work acts on the piston for the full bore of the cylinder, referred to as the blind end of the cylinder. When retracting, the fluid acts on the annulus area which is the net of the full bore less the area of the rod, referred to as the rod end of the cylinder. Typically, the area ratio of blind end to rod end is about 2:1. For bascule bridges that are nearly balanced throughout operation, the controlling loading is primarily wind, which can act on either side of the deck. As a result, the blind end design pressure is typically less than the rod end design pressure. The corresponding pressurized flow to the blind end is approximately twice that required at the rod end. Designing a power unit for these two conditions of flow and pressure requires compromising on the overall performance and therefore the efficiency of the system, unless a significantly more complex hydraulic circuit is implemented.

For the Herring Bridge, the owner established sustainability as a key project goal and included it in the criteria for selection of a design-build team. With this in mind, the design team examined two innovative concepts to improve the efficiency of the hydraulic cylinder drive. The first innovation involves arranging the hydraulic cylinders in push-pull, tandem pairs, to equalize the effective area acting to drive the bridge open or drive the bridge closed. In effect this eliminates the inefficiencies of designing for two different design flow and pressure conditions as noted above. The second innovation was to take the first innovation one step further and couple the push-pull, tandem cylinder pairs with a closed-loop drive, made practical because the flow is essentially the same throughout the circuit and in both directions of actuation.

Cylinder Geometry

To achieve a near uniform flow throughout the circuit, each pair of cylinders is arranged to follow an equal and opposite kinematic motion. The cylinder position and relationship to the rotation of the leaf, and therefore the effective relationship between the line of action and the center of rotation of the leaf, is established so that linear velocity of each cylinder is the same, even as it varies slightly with the angle of opening of the leaf.

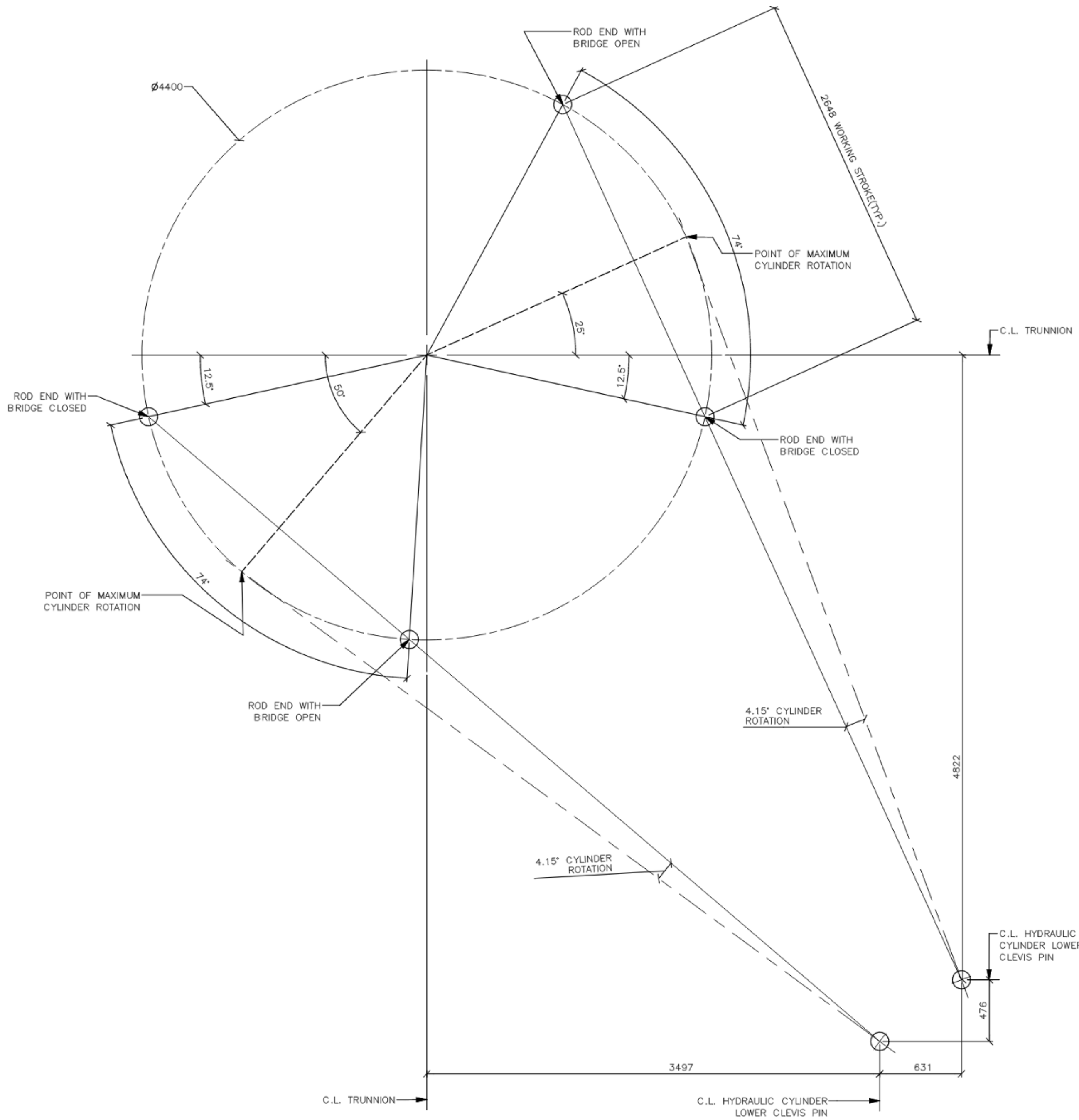

Figure 5 – Hydraulic Cylinder Geometry for a Push-Pull, Tandem Pair of Cylinder

In Figure 5, the cylinder on the right is collapsed with the bridge fully closed and extends to push the bridge open. The tandem pair on the left is fully extended with the bridge closed and retracts to pull the bridge open. For closing the action is reversed.

The effect of the push-pull, tandem pairs, is that of a double acting cylinder with equal area acting on either side of the piston. This produces nearly equal flows and pressures for the controlling design loading conditions. The differences in design loading (and therefore pressure in the cylinders) are primarily due to span imbalance. Flow variations are small enough to be inconsequential for either an open-loop or closed-loop hydraulic power unit. For the Herring Bridge, the controlling flows and pressures in the cylinders are as follows:

- Maximum Flow (per pair) 170 lpm
- Average Operating Pressure (constant velocity) 140 bar
- Maximum Operating Pressure (constant velocity) 200 bar
- Acceleration from Closed State 220 bar

Closed-Loop Hydraulic Circuit

Fundamentally, a closed-loop hydraulic system is a pump coupled to an actuator such that the action of the pump, including direction of flow and volume of flow, is reflected in the action of the actuator as reflected in its direction of operation and speed. Imagine a unicycle where the pump is the rider, and the actuator is the wheel. The rider can pedal forward or reverse and the wheel responds accordingly.

To be an effective machine a closed-loop hydraulic system needs a means of powering the pump and controlling the direction and magnitude of flow. In traditional hydrostatic drives a constant speed electric motor provides the power to a variable flow pump with an over-center swashplate capable of producing variable flow in either direction. An alternative method was employed for the Herring Bridge where a fixed displacement hydraulic pump, capable of reverse operation, was coupled to an electric motor controlled by a variable speed drive (VSD). This approach was selected to simplify the pump and take advantage of the ease and flexibility of programming options for modern VSDs. In this case the VSD provides full control of speed, acceleration/deceleration ramping, seating, and regenerative dynamic braking.

Unlike open-loop drives, closed-loop drives do not require a valve for control of flow direction. They also do not require a counterbalance valve for dynamic braking and control of overhauling loads as the motor/drive performs this function. Like open-loop drives, closed-loop drives require pressure relief valves to protect the system from excessive pressure. The difference is that closed-loop circuits use cross-port relief valves to relieve pressure by diverting fluid from the high-pressure side of the circuit to the low-pressure side as opposed to diverting it back to tank. Closed-loop drives require additional elements to address aspects unique to the design including:

- Charge pump/circuit – the loop must be continuously supplied with fluid to compensate for fluid lost through leakage in the pumps and actuators. The charge pump circuit continuously supplies freshly filtered fluid into the low-pressure side of the circuit.
- Flushing – flushing valves (hot oil bleed valves) to continually remove hot fluid from the low-pressure side of the circuit to allow for fluid conditioning, including cooling and filtration.

The most challenging hydraulic design element of coupling a closed-loop circuit to a hydraulic cylinder actuator was providing the holding functions and accommodating emergency stop (E-Stop) or sudden power loss conditions. Holding functions are important to safe operation and must be capable of holding the span in any position against wind and imbalanced loads. The holding functions must be fail-safe such that they are engaged in the event of a power loss or activated E-Stop. Leak free check valves are typically employed for holding. A drawback of conventional check valves for holding is that they set rapidly and can produce large stopping forces in the cylinders and attached structural elements due to the massive inertia of a movable span in operation. To avoid sudden stopping of a moving span and the associated inertia loads, a means to implement a fail-safe, controlled stop, is necessary.

In common open-loop systems, pilot-operated check valves (PO Checks) located in the cylinder manifolds secure pressure in the cylinders to hold the leaf in any position. Pressure supplied to move the bridge opens the PO Checks via cross ported pilot lines such that a solenoid or otherwise controlled valving is not required. A simple system using an accumulator and an Uninterruptable Power Supply (UPS) is worked into the circuit to prevent the PO Checks from suddenly closing in operation should an E-Stop be initiated, or a power failure occur. The UPS is supplied to provide electrical power to maintain the position of directional valves and an accumulator is connected to the main pressure supply to provide sufficient fluid pressure to operate pilot-operated valves such that sufficient fluid pressure remains in the cylinder manifolds to hold the PO Checks open until the counterbalance valve back pressure slows leaf motion to a stop.

The above system cannot be implemented for a closed-loop drive because the circuit is always pressurized so that cross piloting of PO Checks is not viable. An alternative system was developed for this project, comprised of employing solenoid actuated valves controlling the pilot valves that operate the PO Checks when the span is in operation. These valves are configured fail-safe such that a loss of power closes the pilot supply and therefore the PO Checks. To address E-Stop conditions in the closed-loop cylinder drive, the cylinder relief valves were designed to be staged. In the first stage, the PO Check valves close as soon as pilot pressure is lost. To cushion this effect, a first stage of relief valves is engaged to create a dynamic braking function. These relief valves provide a 90-bar braking pressure to slow the bascule leaf to a stop in a quick and controlled manner. Once the leaf has stopped, the second set of relief valves is engaged at 220 bar, the design holding pressure in the cylinders.

The PO Check valves and cylinder relief valves, including the dynamic braking valves, are located in the cylinder manifolds so that there are no hoses between these important safety features and the cylinder.

Hydraulic cylinders are mounted with spherical plain bearings at the rod end and blind end to avoid sideloading on the cylinders and accommodate minor construction tolerances in alignment. The project scope requires these bearings to be of the maintenance free type, such that they have provisions for lubrication and that they have a secondary external sealing system to prevent the ingress of seawater into the bearing surface. To accommodate all spherical bearing requirements, a maintenance-free bearing was specified along with a compatible lubricant. In addition to the typical seals that come with the spherical bearing, a second set of lips and O-ring seals were provided. This created a sealed cavity around the bearing while still allowing for some angular rotation of the joint.

Construction

General Construction Approach

The general approach to construction of the Herring Bridge bascule span focused on off-site pre-fabrication. Much of the off-site work was as is typical in Europe and the United States for movable bridges, including hydraulic cylinders, hydraulic power units, control systems, and steel fabrication. The primary difference in the European approach, as implemented for the Herring Bridge, is in the extent of the steel fabrication. The bascule leaf structure is designed as a fully welded assembly. There are no field splices or other bolted connections other than the connection of the machinery to the structural steel. The approach included full assembly of the bascule leaves, including partial counterweight construction, transport to the site by barge, and erection using a massive barge mounted sheerleg crane. As a consequence of this approach all machining of the structure necessary to establish machinery alignment and provision for attachment of machinery was performed after completing full assembly of the structural steel for both bascule leaves. This was determined necessary to avoid the effects of weld distortion on the alignment of the machinery. For the hydraulic cylinder system this included machining of the bottom flanges of the operating girders at the location of mounting the upper clevis assemblies. The general process for aligning the machinery in the steel fabrication shop included the following:

- Complete full assembly of both bascule leaves,
- Position the two leaves relative to each other as they will be at project completion in all three axes, oriented nose to nose,
- Construct an initial section of the counterweights, sufficient to allow each leaf to be supported under the main box girders at the trunnion location and live load shoe location,
- Adjust temporary supports to simulate the final profile of the deck in its final as-constructed orientation as a cantilever forward of the live load shoes,
- Perform detailed surveys of the fabricated steel geometry, including deck, girders, joints and machinery mounting areas, using a combination of traditional and laser techniques,
- Determine the best fit location of the trunnion axes, machine the bores in the girder webs to accept the trunnion hubs and face the girder webs perpendicular to the trunnion axes, and
- From the established trunnion axes, set out the locations for the machinery mounting surfaces, including live load shoes, nose locks, and upper cylinder clevises.

Once the upper clevis positions were established the bottom of the bottom flanges of the operating girders were machined to be level and at the proper position referenced to the trunnion and theoretical location of the lower clevis (See Figure 5).

The bascule leaves were fabricated in Belgium and barged to the site. Each leaf was estimated to weigh approximately 700 metric tons when shipped[5], comprised approximately of 560 tons of structural steel, 24 tons of deck surfacing, 10 tons of machinery, and 106 tons of heavyweight concrete counterweight. The leaves were set in position on the bascule piers with an 1800-ton floating sheerleg crane during a 72-hour closure of the river. Once set in position on the trunnion bearings and supported at the forward live load shoes, trunnion alignment was checked and trunnion bearing caps were installed and bolts torqued. Prior to the end of the allotted channel closure, the leaves were raised to the fully open position using the sheerleg crane and secured with the tail lock devices.

[5] Actual leaf weight was measured using load cells in the sheerleg crane rigging. The East Leaf weighed 711tons and the West Leaf weighed 730 tons. The difference between estimated and weighed values was attributed to variability in the heavyweight concrete unit weight and volume and inaccuracies in the load cell measurements.

Figure 6 – Bascule Leaves in Fabrication, Each leaf supported in it's final deflected condition for machining of the trunnion bores and other machinery mounting surfaces

In preparation for placement of the bascule leaves, the pier mounted machinery was installed, aligned and surveyed. This included the trunnion bearings, live load shoe masonry plates, lower clevis assemblies, cylinders, power units, and field plumbing. Figure 7 is a photograph of the West Bascule Pier the day prior to placement of the bascule leaf. The trunnion bearings (blue) are set and aligned. The trunnion bearing caps are positioned so that they can be lifted onto the trunnion journals once the leaf is set down. The cylinders (yellow) are positioned with the upper clevis connected so that they can be rotated into position and connected to the operating girders. Chain winches can be seen attached to the back of the front pier wall (to the right of the cylinders) and to the cylinders. The pad-eyes on the front wall are a permanent feature of the design, provided to allow for future maintenance or removal of a hydraulic cylinder. In construction they were used to maneuver the cylinders in both initial placement and final positioning. Also visible in this photograph is the access panel in the upper deck between the pairs of cylinders. This removable panel provides an opening to lift the HPU out from the platform below should it require replacement in the future. The upper deck provides protection of the HPU below from the elements when the bascule leaf is opened as well as providing inspection access to the inboard trunnion bearings and upper clevis assemblies.

Figure 7 – West Bascule Pier Prior to Crane Placement of the Bascule Span

Hydraulic Circuit Modifications in Construction

Prior to development of the fabrication drawings for the project, the hydraulic supplier was required to perform a hydraulic system simulation to confirm component selection and performance. In the process of developing the hydraulic circuit shop drawings the supplier suggested a modification to simplify the cylinder PO Check and cylinder relief valve module. Following review the proposed modification was adopted. The change removed the accumulator and replaced it with a solenoid-controlled staging of the cylinder relief valves. This modification was vetted in the simulation and then confirmed in field testing.

Startup and Testing of the Drives

The first lowering of the leaves was done using the manual needle valves on the cylinder manifolds. Initially the tail locks were released, and the load was confirmed to be held by the cylinders. The manual needle valves were gradually opened to bleed out fluid and the leaves lowered in a slow and controlled manner. Each leaf was found to be close enough to balanced that the final lowering (final 40 degrees on the East Leaf, 20 degrees on the West Leaf) required use of the charge pumps to overcome the trunnion friction and drive the leaf down.

Once the leaves were fully lowered, the hydraulic system operation was put through several tests at a reduced speed of approximately 20 percent of full speed. These tests confirmed raising, lowering, and holding functions. With the initial testing satisfactory, bridge construction proceeded including completing the deck surfacing, installing parapets, finalizing the counterweights and confirming span balance, completing adjustments of the live load shoes, and aligning and testing the nose locks.

As the above work was performed the control system was substantially completed and full speed operation and testing of the closed-loop hydraulic cylinder drive system was implemented. Finally, Site Acceptance Testing (SAT) was performed and witnessed by the designer and representatives of the owner.

Full speed operation was demonstrated with the speed and control managed by the bridge control system and bridge operator from the control desk. The hydraulic drives were found to follow the specified speed versus time curve, including acceleration and deceleration profiles and maximum

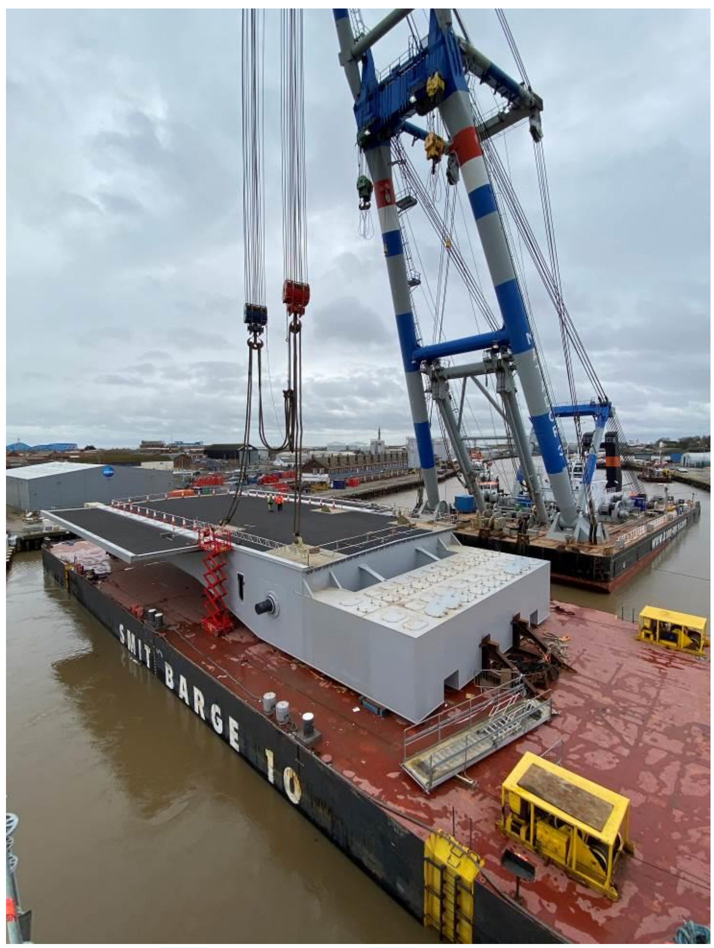

Figure 8 – 1,800 Ton Sheerleg Crane Lifting the West Bascule Leaf off a barge for placement on the West Bascule Pier

parameters for cycle time. In this writer's opinion the bridge operates as smoothly as any bascule bridge observed in more than 40 years in the industry, particularly evidenced in seating and behavior when subjected to wind gusts.

Manual lowering using the needle valves located in the cylinder manifolds was tested with the final span balance and found acceptable. With the leaves balanced per specifications they could be lowered without power using the cylinder needle valves.

Cylinder cushions were tested by fully opening the manual lowering needle valves and dropping the span uncontrolled. Both leaves exhibited a smooth, progressive, deceleration as the live load shoes approached the masonry plates and a soft seating at final contact.

A project requirement is the ability to operate a bascule leaf with a cylinder removed for service or replacement. With the decision to use two pairs of push-pull cylinders this criterion was applied by using one pair of cylinders to operate the bridge while the other pair is removed from service. This scenario was tested by opening the valves on one pair of cylinders so that they essentially free wheeled. As established in the project criteria, the bridge was operated with a single push-pull pair of cylinders using only one of the two main pumps at reduced flow of approximately half full speed. Operation remained smooth throughout the cycle, including acceleration, constant speed, deceleration, and seating.

As previously mentioned, an E-Stop or abrupt loss of electrical power is a scenario of importance in design. Both events were tested with each leaf running at full speed and both raising and lowering. The leaf stopped very quickly, within one to two seconds, but without evidence of stress, vibration, or rebound. The time to stop was short in comparison to past observations of bascule bridges with open-loop hydraulic cylinder drives featuring a counterbalance valve and accumulator as previously described, which generally stop in three to five seconds. However, despite the E-Stop deceleration being quicker using the solenoid-controlled pressure relief valve, it was not abrupt, nor did it raise any concerns of inducing excessive loads in the cylinders or the bridge. The pressure in the cylinders, as observed by watching the pressure display on the cylinder mounted pressure transducers, did not exceed the 90-bar setting established in the design. Note that the cylinder connections are designed for 220-bar pressure in the cylinder plus a partial factor for dynamic response.

Conclusions

European and American codes governing design of movable bridges have some significant differences in their details. However, the net result of compliant designs is not significantly different regarding steel fabrication, machinery and hydraulic systems. More significant are the differences in details and methods of construction. Some of these are in preferences, such as use of double sealing systems for spherical bearings. Others are inherent in the methods of design, fabrication and erection, particularly those associated with fully prefabricating movable spans off-site and erection of those massive assemblies.

The innovative closed-loop hydraulic cylinder drive presents some design challenges and associated complexities in the hydraulic circuit with regard to load holding and E-Stop functions typically addressed with simple PO Checks and counterbalance valves, commonly used in open-loop hydraulic cylinder drives. This project validated the selected solution, namely use of solenoid-controlled logic cartridge valves configured as check valves and solenoid-controlled pressure relief valves to assure a controlled stop during an E-Stop or power loss.

The goal of achieving a more efficient drive system was achieved by using the dynamic braking capabilities of a closed-loop hydraulic drive coupled with a VSD controlled electric motor. The result was exceptional control through all test aspects of speed control and wind conditions.

Acknowledgements

The project was delivered through a design-build process by a joint venture of BAM UK & Ireland and Farrans Construction (BAM/Farrans JV) as the contractor and Dublin, Ireland based Roughan and O'Donovan (ROD) as the lead designer. H&H, as a subconsultant to ROD, led the development to the movable span configuration and prepared final designs of the mechanical, hydraulic, and electrical systems for the movable span and the structural steel for the back section of the bascule leaves, including the counterweights and interfaces with the trunnions, hydraulic cylinders, and live load bearings. The bascule leaves were fabricated in Eeklo, Belgium based Victor Buyck Steel Construction. Hydraulic systems were supplied by Qualter Hall & Co., Barnsley, UK and their primary hydraulic supplier Rexroth, UK.