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Making Heavy Architectural Structures Move

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Introduction
There is a special intersection between architecture and mechanical engineering that exists where the architectural form is enhanced by movement. These structures require a seamless interaction between the architecture and the engineering in order to maintain the architectural intent whilst also ensuring that the movement required remains reliable throughout the structure's life.

This paper examines the technical details and challenges on several key structures, predominantly but not exclusively moving bridges.

Twin Sails bascule bridge, Poole, United Kingdom
The Poole Harbour twin sails bridge was built to relieve traffic congestion which occurs when the existing double lift bridge operates. The bridge consists of two 23.4m long and 13.8m wide triangular spans which, when raised, look like the sails of a boat. The design was selected as part of an architect led design competition looking for a second road and pedestrian crossing of the busy Poole Harbour. The bridge carries a single carriageway in each direction along with a wide pedestrian walkway/ cycle path.

Figure 1 - Twin Sails Bridge in raised position. Dave Morris @ Spears & Major

Technical challenges
The design of the Twin Sails bridge had two key challenges associated with the operating equipment:

1) The two triangular decks have a 30m long joint between the two moving spans along which each of the decks has varying stiffness due to the varying width and section depth of the deck. A method of ensuring that the two decks deflected together and act as a single entity was required to prevent steps in the surface which could present hazards to pedestrians, cycles or vehicles.
2) Whether there was benefit in including a counter-weight or some other system of providing assistance to the two hydraulic cylinders that lift each deck, to reduce the substantial power demand and hydraulic forces during lifting operations.

Both challenges had to be solved in a sympathetic manner that did not detract from the aesthetic of the bridge.

Options Considered and the Selected Solution

As with any moving bridge a robust and reliable solution is required.

The challenge of the diagonal joint between the two moving decks could have been solved with locking pins that were actuated either hydraulically or electrically, however, as the joint crosses both of the carriageways there were concerns that debris from the road could fall into the mechanisms causing either jamming or accelerated wear. There were also concerns over access for maintenance of mechanisms within the carriageway.

The design solution selected was to include two tabs along the main joint, the tab closest to the hinge on each leaf would be the lower element whilst the corresponding tab furthest from the pivot axis would be the upper element. In this way as the two decks lowered in unison the upper tab would rest on the corresponding lower tab on the opposite span, and as the deck section closest to the pivot axis was wider and stiffer it would deflect less and thus the narrower element on the opposite span would be supported at all times (Figure 2). This solution was in effect passive as it did not require any mechanism to provide support and thus the maintenance liability was significantly reduced.

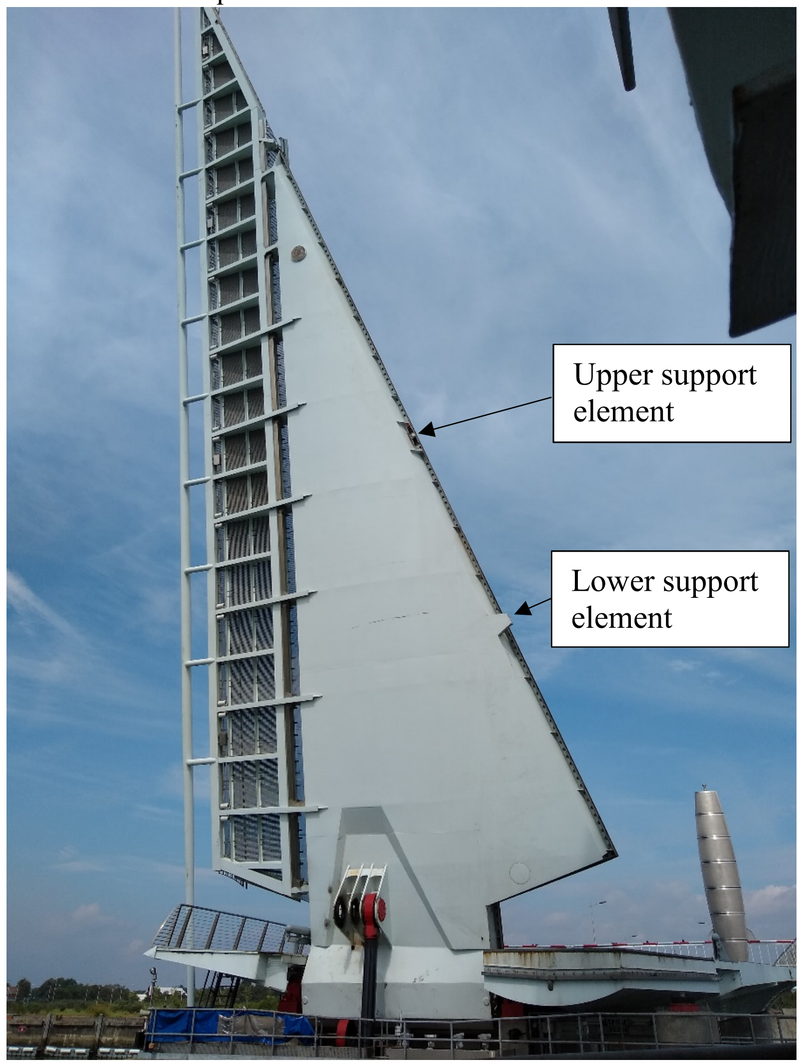

Figure 2 - Underside of deck showing passive supports

The options considered for the challenge of providing assistance to the hydraulic lifting cylinders were to:

1) Install an integral counter-weight in a section of deck directly behind the pivot. This would require a large counter-weight chamber so that the counter-weight could swing around as the bridge rotated.
2) Install a hanging counter-weight whose center of mass could be located further from the pivot but would require a deeper counter-weight chamber.
3) The inclusion of a bank of hydraulic accumulators which could be charged up between bridge operations and provide some of the driving pressure required to lift the bridge.

Option 1 and 2 were discounted due to the significant size that the counter-weight chamber would have to be to provide any reasonable assistance to the lifting mechanism. This larger chamber had cost implications, environmental implications in terms of restricting the flow of the harbour due to more structure being in the water and also would have detracted from the visual intent of the design.

Option 3 was also discounted due to the significant complexity and number of accumulators that would have been required. These would have needed to be housed in a large room, regularly inspected due to pressure equipment regulations and gwould have been a maintenance and safety liability requiring replacement several times throughout the 120 year life of the bridge.

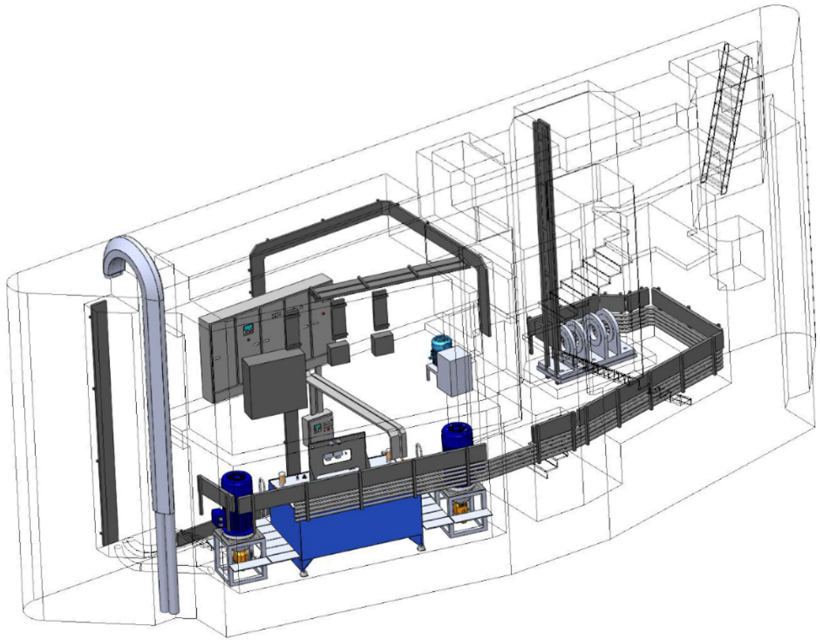

Figure 3 - 3D model of plant room showing how full the pivot pier was even without a counter-weight

For the above reasons, the bridge was designed without counter-weights. In subsequent years in Europe more emphasis has been placed on the embedded carbon within a design. These embedded carbon studies have shown that unless the bridge operates very frequently or can only be powered by heavily polluting methods of generating electricity, the use of a counter-weight does not always make environmental sense from an embedded carbon point of view either. The pivot bearings and hydraulic cylinder we painted a bright fire engine red to draw attention to the mechanical elements. The red colour also hides any grease that may have collected around the equipment during maintenance.

Figure 4 - Underside of deck showing upper cylinder mount and pivot bearings

Woolbeding Glasshouse, United Kingdom

Figure 5 - Woolbeding Glasshouse with sepals in the open position. ©Hufton+Crow

The Woolbeding Glasshouse (Figure 5) is a Thomas Heatherwick designed, 16m tall glass and aluminum kinetic structure which houses a collection of temperature sensitive plants. The glasshouse forms the latest in a series of follys (a non functional building created to enhance the natural landscape) built by the owners of Woolbeding house over previous decades. The glasshouse consists of ten 'sepals' in the shape of an inverted diamond. Over a period of four minutes the sepals open into the shape of a crown.

Technical challenges

The key mechanical challenge on this project was enabling the ten sepals to open in a smooth and synchronized way whilst the mechanism was not visually intrusive, would not be a hazard to the public either when static or in motion and be operable and maintainable by staff with minimal training that look after the wider Woolbeding estate.

Options Considered and the Selected Solution

The key assessment criteria for the options to actuate the sepals were:

- Aesthetics
- Robustness and reliability
- Safety
- (Ease of) Synchronization

A cable based solution was investigated as this would have been a fairly visually minimal solution as the actuating mechanism could be hidden beneath the ground. However, it would not have been as ‘pure’ a solution with cables arranged inside and outside of the glasshouse.

Figure 6 - Woolbeding Glasshouse from the air in the open position. ©Hufton+Crow

The use of a curved gear rack located around the hinge was investigated; this was discounted due to the very visible solution and the need for the gear rack to be a large radius to achieve suitable gear tooth loading. Due to the size of the sepals and the associated torque requirements, the use of a direct drive onto an axle at the hinge was also not suitable. This would have required a very large gearbox, high torques at the pivot and would have caused problems with the glazing design due to the small area that transferred most of the loading through the structure.

The only realistic solution was the use of a linear drive system such as an electrically driven linear actuator or hydraulic cylinder. Both of these could be aligned with other structural elements so that their visual bulk was disguised. It also allowed a reasonable lever arm to be achieved about the axis of rotation.

A hydraulic solution was selected in the end on the basis that the cylinder could be designed to be sleek with minimal bulges and under power failure or emergency stop conditions could bring the glass sepal to a stop in a more controlled and steady way than electric linear actuators.

The ten sepals are controlled through a PLC system which monitors the inclination of each sepal via an encoder. The operator stands within the glass house to control the movement. The hydraulic power pack is located in a separate building meaning that there is very little noise as the sepals move. The mechanical

Figure 7 - View from within the glasshouse with the sepals closed. note that the mechanism is hardly visible. ©Hufton+Crow

elements were painted to match the aluminium structure and blend in with the background so that when inside the glasshouse the plants are the main focus.

Outcome

The completed glasshouse was formally opened to the public in late spring 2022. Due to the unique and striking design and the already high profile of Mr Heatherwick the structure has attracted a lot of attention from both the general and more specialist architecture and engineering press. In virtually all instances the reviews have been positive and it has attracted a significant number of visitors to what is usually a quiet series of formal gardens.

Merchant Square Fan Bridge, Paddington, United Kingdom

The Merchant Square footbridge is a bascule bridge which was the winning entry of an architect led design competition to replace an existing connection across a 17m wide section of canal in Paddington, London. The design consists of five separate fingers which rotate by differing angles to form a fan when in the fully open position. Due to the required alignment the deck spans are around 20m long and the total width of the bridge is 3m (so each finger is 0.6m wide). A key feature of the design is the above ground counter-weights, each one marked with its mass. In the raised position the counterweights are all flush with the ground and hence due to the differing angles that each finger raises to the five corresponding counter-weights have differing shapes.

Figure 8 - Fingers in raised position. Note that the counter-weights are all flush with the ground. ©Edmund Sumner

Technical challenges

The key challenge on this project was achieving synchronized deck lifting of each finger to five different angles whilst also enabling flexibility of operation for maintenance and inspection purposes. The budget available for the complete bridge was very limited. Additionally, the slender nature of each finger meant that its torsional stability was critical. In order to achieve the visual interest of the fan in the raised position the axis of rotation of the five fingers were not in line. The combined challenges of cost, torsional stability and the layout of the rotating axes meant that a simple but sturdy solution was required. The final challenge was the limited space to install the deck fingers. Road access was limited and hence the structure had to be brought to site on barges and then lifted into position with a relatively small crane.

Options Considered and the Selected Solution

The requirement for each finger to open to a different angle whilst also moving in a synchronized way during operation meant that several options were considered.

The simplest way of achieving synchronized operation would have been to mechanically link the decks together. This can be achieved via a single winch shaft with five winch drums each of differing drum diameter such that the rate at which the cable is drawn on to the drum and hence the rate at which the each finger lifts is mechanically fixed by the drum diameter. The advantage of this is the simple method of achieving synchronization. However, it also means that all of the fingers have to lift even during maintenance activities and if there was any need to operate them out of sequence, for instance during commissioning, this would not be possible.

Figure 9 - Merchant Square Fan Bridge mechanisms

The solution adopted was to create a 0.6m wide module which included a narrow hinge assembly along with a hydraulic cylinder. Each finger was equipped with an inclinometer to measure its angle, with the synchronization achieved via the electrical control system. The individual control of each finger meant that commissioning was much simpler, maintenance activities can be carried out on each finger separately and the ability to slightly vary the speed of each finger, particularly during the initial few seconds of the raising movement, was achievable by varying the flow to each finger. The downside of this solution is that it requires a more skilled maintenance team if adjustments are needed to the control system, however, there would not be any adjustment possible if they had been mechanically linked. The mechanical components were painted a bright green colour. This coupled with the masses of the counter-weights being stamped into each one enables a greater understanding from the public as to how the bridge operates.

Outcome

The bridge opened in 2014. Due to the short length of canal that it crosses the need to open for access reasons is very limited, however, as a kinetic sculpture it is operated every Friday lunchtime. The popularity of this event has been such that the bridge is now also operated on a Saturday to accommodate more visitors. The project has gone on to win several national and international engineering and architectural awards.

Figure 10 - Counter-weights with deck in lowered position.

Lower Hatea Te Mata a Pohe (The Fish Hook of Pohe) rolling bascule bridge, New Zealand

The Lower Hatea Rolling bascule is one of the worlds' first rolling bascule bridges actuated by hydraulic cylinders. The majority of previous rolling bridges were rolled via an elevated gear rack driven by a motor mounted on a large frame structure. The aesthetic vision for the bridge was of a simple fishhook motif that was uncluttered and elegant.
The project is an excellent example of where the mechanical engineering is intrinsically linked to the aesthetics of the bridge, rather than being hidden or disguised.

Figure 11 - Te Mata a Pohe bridge in the lowered position. ©Patrick Reynolds

Technical challenges

With a rolling bascule bridge there are multiple variables each of which has a direct impact on not only the geometrical performance (air draft achieved and navigational width) but also the aesthetics. For example, the radius of the rolling track impacts on how far the bridge translates backwards for a set angle of movement: the larger the radius the greater the translation, also, the larger the radius the lower the contact stresses. The amount of horizontal translation affects the lever arm and stroke of the hydraulic cylinder which in turn affects the required bore diameter and buckling capacity. The buckling capacity impacts on the rod diameter which then further impacts on the bore diameter. The angle of inclination of the two counter-

Figure 12 - Te Mata a Pohe bridge in raised position. ©Patrick Reynolds

weight arms impacts the angle that the deck can lift to. The radius of the rolling track and angle of the counter-weight arms also have a significant impact on the appearance of the bridge.

Solution

In order to assess all of the variables at once and understand the visual and engineering relationship between all of the variables, a computer model was created, something that historic rolling bridge designers did not have. This enabled each variable to be adjusted visually whilst also automatically adjusting the mechanism sizing. A plug in for the 3D modelling software Rhino was used called Grasshopper. An additional plugin called Rabbit was used to assess many hundreds of options in very quick succession and the optimum solutions output so that their visual aspects could be considered by the architects. The ability to almost instantly assess a set of conditions or re-run the assessment with different target values meant that what would have taken an engineer and architect many months to work through could be achieved in a morning.

Figure 13 - Te Mata a Pohe in raised position. Note the yellow hydraulic cylinders.

Outcome

The resulting bridge has been a great success. In recent months it has achieved over 20,000 openings with very few reliability issues. The project has featured in TV commercials, has been warmly accepted by the public and has won several international architectural and engineering awards. The style and arrangement of the bridge has inspired several other similar moving bridges in recent years.

Lille Langebro twin swing bridge, Copenhagen, Denmark

The Lille Langebro project was built to move busy cycle and pedestrian traffic off an elevated road bridge, by giving them their own bridge which crosses the Copenhagen harbour at a level closer to the water and more suited to the surrounding land levels. The design was the winning solution to a design competition. A key aspect of the winning design was the triangular main beams which run down each side of the deck and which slowly twist across the entire length of the bridge. The bridge is a twin span swing bridge with a static approach span at each end. At the joint between the two moving spans a full moment connection was required in order to achieve the desired slender deck structure.

Figure 14 - Lille Langebro in the closed position.

Technical challenges

The key technical challenge was achieving the moment connection between the two moving spans. The client had explicitly stated that they did not want locking pins in the design. Even if locking pins had been acceptable, these would have had to have been very significant adding weight and visual mass to the deck structure a long distance from the pivots.
A method of carrying the compressive and tensile forces along the top and bottom of the beams respectively was required.

Solution

The solution that was developed is believed to be unique. It consists of a compressive pin at the top and a tensile hook at the bottom of the beams (Figure 16). These are connected to large bore through rod hydraulic cylinders (so that the net flow in and out of the cylinder is always zero) which are hydraulically linked so that any tension experienced at the top of the beam is matched by an opposing force at the bottom. Additionally, as the bridge expands and contracts the moment connection mechanism can adjust for this passively by moving oil between the two cylinders. The amount of preload between the upper and lower elements was adjusted during commissioning to enable a level of structural damping to be achieved. Due to the frequent operation of the bridge pressure decay in the system is not an issue, however, the system does monitor the pressure in the system and if required

Figure 15 - Lille Langebro compression and tension sockets.

can briefly power up the hydraulic power unit to reapply the preload.
All of the mechanisms on this project are hidden from public view behind covers or integrated into the bridge structure. Access for maintenance and inspection was a key requirement and this is balanced against avoiding vandalism.

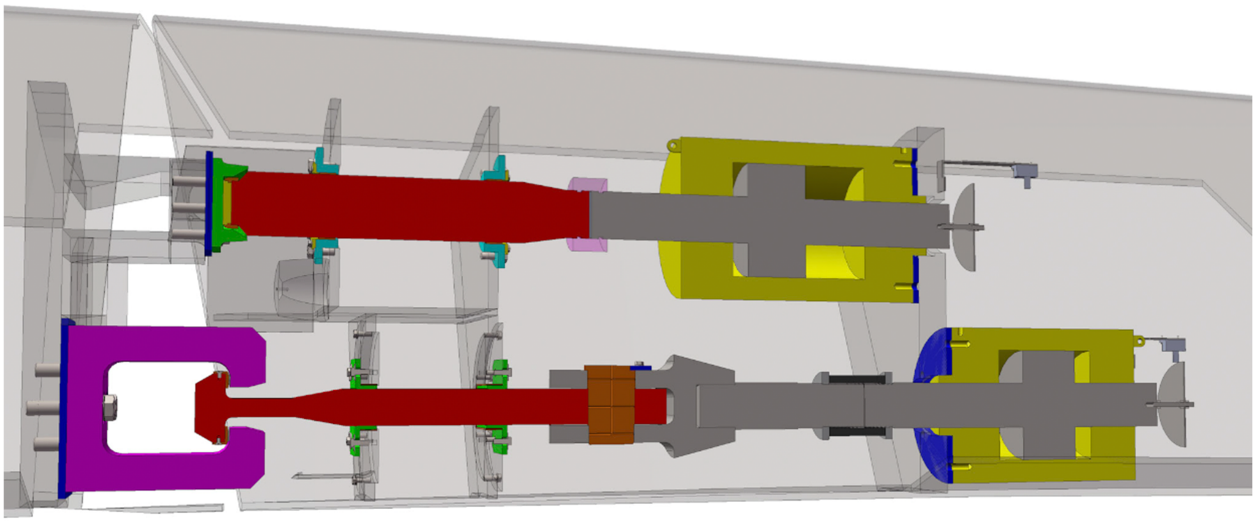

Figure 16 - Lille Langebro moment connection 3D model. Yellow elements are the through rod hydraulic cylinder. Red are the actuated compression and tension pins.

Outcome

The bridge was completed and opened to the public in August 2019. It has gone on to win numerous awards including the Supreme Award for Engineering from the Institute of Structural Engineering. A standalone paper looking at this project has been produced by the author for this conference. It is titled An Innovation in Swing Bridge design.

Conclusions

In order to maintain the architect's aesthetic vision whilst also ensuring that the engineers' aims of a reliable and robust solution are delivered, the design team consisting of architects, structural, mechanical, civil, electrical and hydraulic engineers must all work together. The success of the project is reliant on the delivery of a solution that does not detract from the appearance but that retains the ability to access equipment for maintenance and inspection. It is also worth noting that there is no benefit designing something that looks amazing but that never works reliably. The most successful projects are those where the engineering and architecture are inseparable and each needs the other to function, both structurally and visually.

Where the mechanical elements are significant and can not be hidden due to their size or operation, attention can be drawn to these elements through the use of colour. This also allows the public to better understand how the structure moves and what element is providing that motive force.