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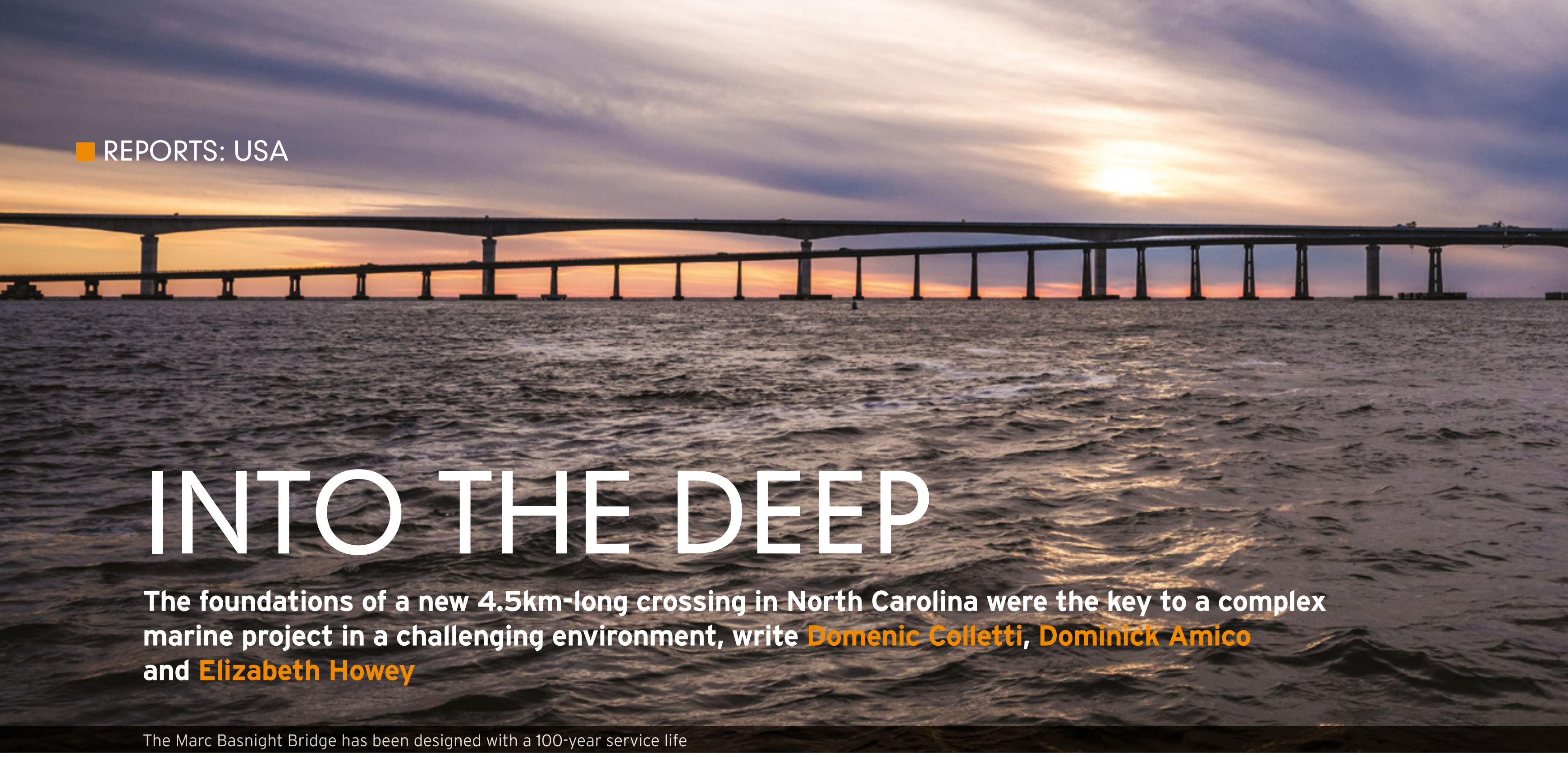


INTO THE DEEP

The foundations of a new 4.5km-long crossing in North Carolina were the key to a complex marine project in a challenging environment, write Domenic Colletti, Dominick Amico and Elizabeth Howey

The Marc Basnight Bridge has been designed with a 100-year service life

After nearly three decades of planning, the new Marc Basnight Bridge on North Carolina's Outer Banks has overcome a remote location and a challenging, constantly changing channel to maintain a connection for residents who live, work or vacation in this scenic area. The US$252 million, 4.5km-long bridge conquers the treacherous currents of one of the most dangerous inlets on the Atlantic coast, with constantly shifting bathymetry and violent storms, while resisting up to 26m of scour below sea level, 169km/h winds, and vessel collision forces.

Some of the pile tips are 40m below the water surface

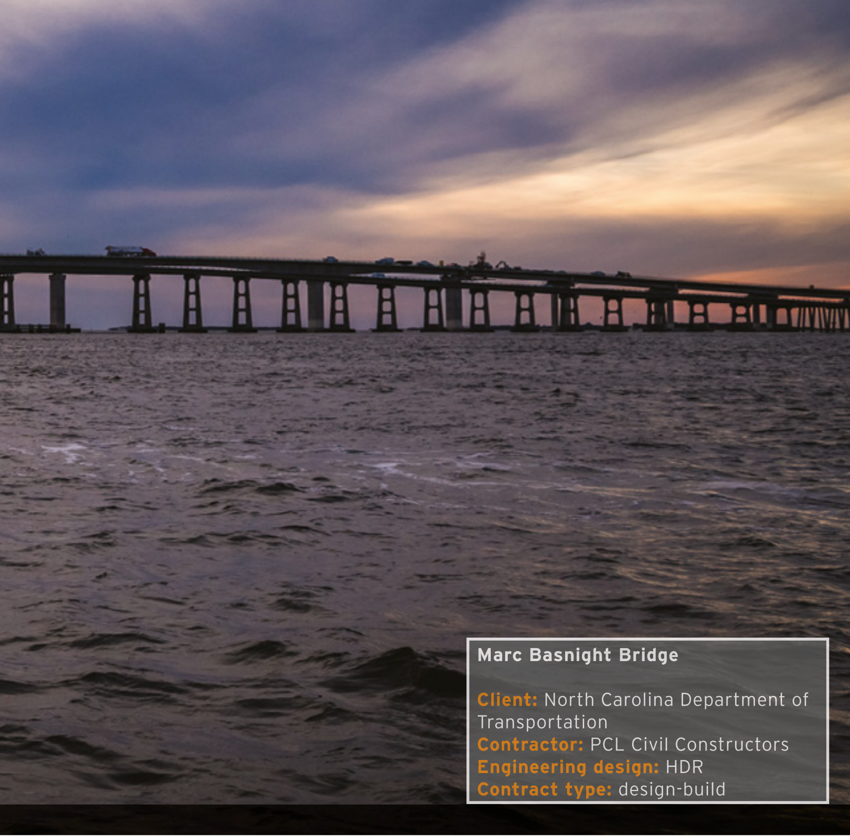
The new bridge, designed with a 100-year service life, faced a number of challenges, but foremost was creating the right foundation. To achieve a more durable structure, the bridge incorporates concrete piles jetted and driven as deep as 40m below sea level, with their required depth verified in the field using a first-of-its-kind method to determine long-term pile axial capacity after significant scour loss. In many ways, the project wasn't a bridge job – it was a complex marine foundation job with a bridge on top. Given the harsh environment and strict requirements for durability, the foundations were the key to the entire project.

A series of barrier islands, the Outer Banks are essentially a 322km-long series of sand bars, several miles offshore, known for their beautiful beaches, historic lighthouses, and abundant flora and fauna. The islands were reachable only by boat for decades until a series of bridges were built in the mid- to late-20th century to improve access for the many tourists who visit the area each year. One was the Herbert C Bonner Bridge, opened in 1963, which carried North Carolina Highway 12 across Oregon Inlet.

The Bonner Bridge improved access to eight communities in the southern Outer Banks. However, the bridge began to suffer from deterioration and damage within just a few years of opening. Oregon Inlet, while beautiful, is inhospitable, and subject to harsh storms including hurricanes and Nor'easters. Severe scour undermined the bridge's concrete piles, while salt spray corroded its steel. For the next five decades, the North Carolina Department of Transportation regularly completed repairs and retrofits to maintain the bridge. After a dredge struck the bridge during a storm in 1990 and collapsed several spans, the need for a new structure was clear.

After decades of study by NCDOT, a team composed by PCL Civil Constructors and HDR was chosen in 2011 to design and build the replacement for the Bonner Bridge. As the lead design firm, HDR provided all roadway, geotechnical and bridge design as well as environmental permitting services. Design and permitting was largely completed by early 2013, but litigation delayed the groundbreaking until March 2016. Less than three years later, the bridge was opened to traffic on 25 February 2019.

The highly dynamic environment proved to be one of the most challenging aspects of the project for both the designers and the contractor. The location of the bridge, adjacent to both the Atlantic Ocean and Pamlico Sound, subjects the bridge foundations and superstructure to severe scour, storm surge, and strong wind and wave forces during tropical systems and Nor'easters, along with vessel collision force effects. The inlet itself is also very dynamic, constantly changing as tides and storms move the loosely deposited sand, shifting the size, shape, and location of the natural



Marc Basnight Bridge

Client: North Carolina Department of Transportation
Contractor: PCL Civil Constructors
Engineering design: HDR
Contract type: design-build

The piles were installed by a combination of jetting and driving

channel from day to day, and sometimes from hour to hour.

To maintain navigation under the Bonner Bridge, which had a single 40m-wide span high enough for ships to pass under, the US Army Corps of Engineers dredged the channel nearly non-stop, year-round. Part of the requirement for the new bridge was to create a much wider navigation zone. The replacement Basnight Bridge features nine 107m-wide spans, which each provide sufficient vertical and horizontal clearance for navigation. As the inlet's natural channel shifts, lights and other markings can be moved from one span to another to indicate which channel should be used by ships, reducing dredging needs.

The varying conditions across the Oregon Inlet led the team to divide the bridge into five regions – north and south approach spans, north and south transition spans, and the centre navigation unit – with each region's design tailored to fit its distinctive subsurface and scour conditions, span length and height requirements, and load demands.

To facilitate delivery of the massive bridge at a practical cost, each design features an assembly of simple, but proven and reliable, structural elements – piles, pile caps, girders and bents. Each of the regions lent itself to a design approach that included widespread use of repetitive construction elements. The saltwater environment and the owner's emphasis on durability, corrosion resistance, and a 100-year service life indicated the need for a concrete structure, while the remote location of the project site also suggested the broad use of prefabricated elements and modular construction. All indicators pointed to the use of precast concrete as the optimum design solution.

The extensive use of precast concrete elements offered multiple advantages. Precasting Florida I-beam girders, box girder segments, bent caps, columns and piles in an off-site precasting yard, under controlled conditions, resulted in the production of extremely high quality and extremely durable concrete elements; these levels of quality and durability would have been difficult to achieve in the harsh marine environment of Oregon Inlet. The precast elements were also very economical: fabrication off-site was much less costly than using cast-in-place concrete at the remote project site. Minimising field construction work from barges and a work trestle also led to much faster, much safer construction while reducing the duration and extent of temporary environmental impacts in a very environmentally sensitive area.

Multiple refined soil-structure interaction analysis models were run for every bent on the bridge using FB-Multipier soil-structure interaction analysis software, considering various scour depths from no-scour to full-scour conditions. The design of the centre navigation unit in particular included multiple individual FB-Multipier software models and a global 3D Larsa model of the entire 1km-long unit with superstructure and substructure. The superstructure and substructure design teams conducted 14 full design iterations to determine the bridge's ideal articulation scheme and optimise the design. The final design features a scheme with two fixed piers and match-cast, post-tensioned, precast hollow box column piers.

To analyse the hydraulic design conditions, the team considered the hurricanes ▶

Most of the bridge deck is supported by precast Florida I-beams

that have affected the Oregon Inlet area for the past 160 years, using a modelling procedure based on the latest storm hindcasting technologies. Local pier scour computations employed the most modern equations and methodology, including validation by means of physical model scour tests performed at the Hydraulics Laboratory at Colorado State University for several of the more complex piers.

Scour depths varied considerably along the length of the bridge, with the approach spans subject to shallower depths, the transition spans subject to deeper scour, and the centre subject to the deepest scour and highest vessel collision forces.

With design scour depths as deep as 26m below the water's surface and high lateral loads including wind loads, wave loads, and ship impact loads, the foundations had to extend to a significant depth, through a consistent layer of dense sand to obtain adequate lateral resistance. Following an in-depth review of various foundation options, including traditional drilled shafts and innovative systems such as hybrid pile-shaft foundations, the design-build team elected to use jetted and driven prestressed concrete piles.

To verify how future scour affected each pile's required long term axial resistance, the HDR team developed a first-of-its-kind method for calculating predicted scour loss incorporating the jetting and driving installation procedure. To the knowledge of the design team, driven pile bridge foundations subject to scour as deep as 26m below sea level have not previously been designed and constructed in the USA with consideration of this type of long-term scour evaluation. Traditional methods of estimating the loss of pile capacity due to scour would have been extremely conservative, especially considering the planned pile installation method, as well as extremely difficult to achieve in the field without damage to the concrete piles.

The geotechnical engineering team instead developed a simple procedure for taking an in-situ measurement of the actual pile resistance at a given bent, incorporating its jetting-then-driven installation method, using dynamic analysis with the Pile Driving Analyser system. This field-measured resistance was then used to calculate the long-term pile capacity under the design scour conditions. The procedure was thoroughly vetted by geotechnical engineers within both HDR and North Carolina DOT, as well as independently reviewed by two separate international experts in pile foundations. Because it used the actual, measured resistance of the pile, rather than a conservative calculated value, the method helped avoid the risk of being over-conservative and driving the pile to a much higher load, which would have resulted in increased construction durations, longer piles, and greater risk of damaging the piles during installation.

Foundation work began amid the choppy waters in the middle of the inlet with jetting used to advance each pile through the inlet deposits. Upon reaching 3-6m from the required tip elevation for adequate lateral resistance, the team switched to driving the piles the final distance. The piles' final tip elevations are as deep as 40m below the water surface – significantly deeper than required under normal conditions.

The transition spans and navigational unit feature up to thirty 2.3m^2 piles in a battered configuration to provide greater lateral resistance against wind, water, and ship impact loads under deeper scour conditions. Meanwhile, the approach spans, with significantly less scour and ship impact loads, are supported by pile bents with three or four 1.4m-diameter cylindrical vertical piles. In total, there are 669 piles measuring more than 24km of pile length combined.

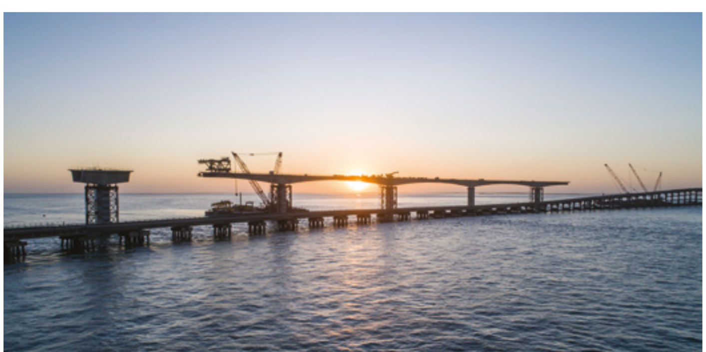
For the majority of the bridge – all of the approach and transition spans – the superstructure consists of a conventionally-formed cast-in-place lightweight concrete deck supported by precast, prestressed concrete FIB girders. The deck is conventionally reinforced with stainless steel reinforcing. The majority of the bridge has a roadway cross-section with two 3.7m lanes and two 2.4m shoulders, with an out-to-out deck width of 13m.

The 1km-long navigational unit consists of 11 spans constructed as a single unit, with a typical span length of 107m and end span length of 61m. The single unit is a post-tensioned concrete segmental structure comprised of 238 single-cell precast box girder segments supported on post-tensioned precast concrete columns, and is believed to be the third-longest continuous precast, balanced-cantilever segmental concrete box girder unit in the USA.

The new bridge was officially dedicated on 2 April 2019, during a rainstorm that exemplified the challenging marine environment it was built in. The extensive use of precast concrete elements greatly enhanced the quality and durability of the structure, while simultaneously facilitating faster, safer, and more economical construction. In total, over 40km of precast concrete structural elements were used in the construction of the bridge – 5.5km of precast cylinder piles, 19km of precast square piles, 1km of precast bent caps, 0.5km of precast columns, 14km of precast FIB girders, and 1km of precast segmental box girders. In terms of concrete volume, two thirds of the 69,000m3 of concrete used in the structure was precast.

The former bridge is scheduled to be demolished by early 2020, with much of its material reused to create artificial reefs to enhance fish habitats. Designed to last well into the next century with minimal maintenance, the Marc Basnight Bridge will be a lifeline for communities during hurricanes, an economic boon for an area reliant on tourism, and an iconic structure that will be used for generations

Domenic Coletti and Dominick Amico are senior bridge engineers at HDR; Elizabeth Howey is senior geotechnical engineer, also at HDR



The navigational section is 1km long and consists of 11 spans

The Bonner Bridge that opened in 1963 is due to be demolised in 2020

The new bridge is located at the most visited destination in South Africa

ADDED ATTRACTION

A number of design and installation challenges were overcome during the replacement of a 22-year-old swing footbridge at the historic V&A Waterfront in Cape Town, South Africa, writes Khalifa Bokhammas

While both the new structure and its predecessor are swing bridges, building and installing the replacement was not simply a case of swapping like with like. This was because growing footfall meant that the client – the V&A Waterfront – required a wider pedestrian bridge to more effectively accommodate the hundreds of thousands of people crossing it every month. The 1.24km^2 mixed-use waterfront in the Table Bay Harbour area serves as a popular destination, drawing around 24 million visitors a year, with significant development work also being undertaken at other locations around the site. This not only affected the bridge's design but also presented an operational challenge to the stakeholders involved in the project, including contractor Stefanutti Stocks.

As structural engineers and design team lead for the project, SMEC South Africa teamed up with COA Architects and Eadon Consulting to work through various typological options for the new link. Among those considered were a bascule and lift bridge; however, it was deemed that a swing bridge would still be the best solution in terms of the time and electrical energy needed to operate it. The two main goals during the bridge's design were to create a new 42m-long structure that was able to match its predecessor in terms of being able open and close in 90 seconds and 100 seconds, respectively, but with the capacity to allow more pedestrians to cross at any one time. Other specifications included the bridge being able to operate in wind speeds of up to 60km/h and withstand impact by a vessel from either direction, in which case it should swing free in a way that would protect the mechanical equipment. Also specified was that the full 31m width of the cut be unobstructed for the passage of vessels, for whom vertical clearance should be infinite.

To accommodate a larger number of pedestrians, the new deck is significantly wider, measuring 4.5m, compared to the original's 2m. The lower part of the deck is a steel girder framework bolted to a 0.5m-wide central steel spine beam. The latter protrudes almost 0.5m above most of the length of the upper part of the deck, which is made of timber. The spine beam and 14.5m-tall mast angled at -20° from the vertical are both fabricated steelwork and are bolted together at the pivot point.

Due to the new deck being more than double the width of the old one, SMEC South Africa decided not to use the same structural support techniques as the old bridge. While the previous design used backstays attached to bearings on a rotating mast, the larger size and heavier loads of its replacement would have made the construction of backstays and anchor blocks much more difficult, particularly given the limited space available on the quayside and the many buildings in close proximity to the bridge. As a result, the new design employs a slew bearing which rotates a cable-stayed deck attached to a mast. Four, 28mm full-locked coil steel cable-stays supplied by Redaelli fan out from the top of the mast to the spine beam. The longest of these measures 35m, while the shortest is 19m. According to Redaelli, since the environment is particularly aggressive, it used a zinc aluminium alloy called Galfan to protect the cables, which have a minimum breaking load of 775kN.

"We wanted to avoid using backstays to limit the amount of land-based works as much as possible," John Anderson, general functions manager for the structures team at SMEC South Africa, says. "Most of the new bridge components could be made in a fabrication yard, welded together on Jetty 2 a couple of hundred metres from the bridge's final position and moved to the installation point," he adds.

With this solution settled upon, SMEC South Africa also needed to consider the donut pile ring that would house the slew bearing as well as electrical systems needed to swing the bridge. Following geotechnical investigations at the site, there was concern that the piling works might unsettle the 19th century quay wall, a packed stone wall perched on the edge of a rock shelf. Other considerations were the vibrations felt in adjacent buildings, cormorants nesting nearby, and the health and safety of pedestrians using the old swing bridge. Therefore, to reduce the magnitude and duration of the vibrations, a 100mm diameter pilot hole was rotary cored using a Boart Longyear DB520 drilling rig to act as a guide hole for a larger diameter pile bit. Following this, the hole was grouted to improve its integrity before boring with an Odex drill system for the eight 8m-long, 600mm-diameter steel-cased piles. A steel slew bearing adaptor ring was stressed down onto the concrete pile cap and connected to the slew bearing using 66 bolts. ▶

The existing bridge remained operational during these works, with the centre of its pivot 6.3m west of the corresponding point on the new bridge. However, to allow space for the construction of the new structure's abutments, the docking point for the original bridge needed to be moved further up the quay. A temporary nosing and abutment were built at the docking point to allow for this, which meant that the angle of rotation was reduced from 90° to 80°.

"We had to reanalyse the existing bridge for being slightly out of alignment as the backstays were no longer in line with the front stays. We also limited the loading on the bridge from 5kPa to 3kPa during that period for this reason," says Anderson.

On 21 May, the lifting team of Teemane Cranes set about removing the original footbridge. "For the removal of the old bridge, we had to improvise as we could not be provided with the full drawing or installation guide," says Riaan Geldenhuys, director at Teemane Cranes. "We had three days to remove the old structure and went over by half a day, which was due to the bridge being so close to the sea water, and the salt did not have a good effect on the steelwork." The team dismantled the structure into several sections: two backstays, the mast, two tension rods, the deck, and two abutments.

While the old bridge was being removed, Teemane Cranes also assisted in installing the slew bearing onto the donut pile cap. The following day, on 24 May, the loading phase of the new bridge from Jetty 2 onto a barge was undertaken. As the team were not able to use lifting lugs on the structure, the decision was taken to sling around the deck and ring beam, where there were four main I-beams capable of carrying the imposed load. The original rigging study and lifting plan were formulated for a bridge weighing 54t. However, Stefanutti Stocks decided to hold off on the installation of the wooden deck until the bridge was installed, meaning the bridge was 10t lighter when lifting. Thoughts then turned to ensuring the bridge would be level on the sling, which was made more challenging by the fact that its centre of gravity was within 10m of the slew ring, creating 90mm of structural flexibility in the deck.

Another challenge was that the barge transferring the bridge to the installation position could not position itself in a way that would allow the team to lift straight up, slew the crane 180° and place it on the barge. To accommodate this, the bridge was turned in mid-air while the crane was slewing.

For the installation phase, several factors were taken into consideration in formulating a strategy, in particular the logistical challenges at the point of installation, where the team had an area of roughly 12m by 17m in which to operate the crane and only one access road. A LTM1400-7.1 Liebherr crane was used with an outrigger footprint of 12m by 12m. "We had to consider turning circles; tyre pressures; the bearing pressures of the crane outriggers against the allowable pressure provided; and spectators, meaning that ample staff were needed to assist and guide the cranes and auxiliary vehicles moving equipment and counterweights in and out," Geldenhuys remarks. The maximum allowable pressure on the quayside was 200kPa.

As of 10:30 am on 25 May the bridge was hanging level in mid-air and lowered into its final position at 4:30 pm that day.

Given the heavy footfall on the waterfront, the entire project was scheduled to ensure that works were undertaken during the quieter months of the South African autumn and winter. A ferry service shuttled passengers across the cut between 21 May, when the old bridge was removed, and 21 June, when its replacement opened to the public. The new bridge was officially unveiled at an opening ceremony on 11 July

Client: V&A Waterfront
Contractor: Stefanutti Stocks
Structural engineers and design team lead: SMEC South Africa
Architect: COA Architects
Mechanical engineers: Eadon Consulting
Fabricator: Anchor Steel
Mechanical sub-contractor: Hyflo
Lifting team: Teemane Cranes
Barge team: Guerrini Marine Construction
Cable supplier: Redaelli

Construction took place only metres away from the existing bridge in operation

The slew bearing adaptor and slew bearing were joined by 66 bolts

Four steel stay cables connect the mast to the spine beam

Rendering of how the finished bridge will look and *(inset)* the flax fibre that is used in the biocomposite

JOURNEY OF DISCOVERY

How does a local authority end up initiating the introduction of a new material for bridge construction? **Helena Russell** finds out

The risk-averse approach that publicly owned bridge authorities commonly adopt to the use of new materials and bridge types is often cited as a barrier to progress. Engineering firms, academics and product manufacturers can find it difficult to persuade bridge owners to be the first to test innovations on full-scale structures. But one local authority in the Netherlands is bucking this trend in its efforts to support the development of more sustainable materials for bridge building

In Friesland Province, in the north of the Netherlands, the world's first bridge made out of plant fibres is expected to open to the public by the end of this year *(Bd&e issue 95)*. The 66m-long 'biocomposite' pedestrian and cycle bridge is being built using a material that combines flax fibres and a bio-based resin and will replace an old highway bridge which crosses the Van Harinxma Canal near Ritsumasyl. It is being manufactured in two pieces – one 32m long and one 34m long – by Dutch company Infra Composites.

However, the local authority in charge of building the new crossing did not set out to create the world's first biocomposite bridge. In fact, as Friesland Province programme manager Sjoerd Vrieswijk explains, they did not even know that biocomposites existed when they started the project. Nonetheless, this emerging material proved to be a natural fit for the province's main aim of pursuing 'circular' technology.

"Since the province of Friesland wants to be a leader in the circular economy in Europe, we thought we'd combine that ambition with use of more environmentally friendly materials for construction," Vrieswijk explains. "Over the last couple of years we saw the use of composites increasing in popularity as a replacement for concrete and steel, and to take this one step further, we set out to try and find a material with similar properties, but with a smaller ecological footprint." The structural properties of the fibres and the resin were most important: the stiffness of a bridge is determined by the modulus of elasticity of the fibres, and research revealed that flax fibres come closest to glass fibres in terms of stiffness. The properties of the bio-based resin were the same as those of a traditional resin.

"We had a site near Leeuwarden," Vrieswijk continues. "The Ritsumasyl Bridge over the Van Harinxma Canal, which dated from the 1950s, needed to be replaced." The work was part of a larger programme of work in the local area, covering almost 40 infrastructure projects in and around the city of Leeuwarden, including three aqueducts, several rail viaducts, new highways and even a bus station. "This was pretty much the last project in the programme, so we wanted to make a statement," reveals Vrieswijk, "just as we did building the two wooden bridges in Sneek a decade ago."

The province found the answer on both counts in flax. "Production of linseed oil leaves flax as a waste product," Vrieswijk explains. "With the combination of flax and resin we found a replacement for glass fibre composite."

Flax is a natural fibre - and hence a renewable resource - that is grown in France and Belgium. Among other characteristics, it has a low specific weight, low carbon footprint, and good thermal and acoustic properties, providing a level of insulation.

Narrowing it down to flax took some time – in the tender documents a whole range of plant fibres were considered, including hemp, jute, bamboo, banana and pineapple leaves, cotton, coconut and even wood. The most promising of these turned out to be flax and a wood fibre called 'Bio-Mid', which is made from sawdust and can be more consistent, but as yet is not widely available.

The project took almost two years to get to the point of construction through material development and extensive testing. Vrieswijk reveals that at the very start, they did not even know what kind of bridge they would build, and identifying the optimum bridge type and design was all part of the remit of the building team that was assembled in the early stages.

The set-up is not a traditional client-contractor relationship, according to Vrieswijk. "We formed what we call a building team. Working alongside us we have Strukton as contractor, with Antea Group as their engineering partner for the civil construction. Mechanical engineering is done by Spie, and the composite bridge itself is being built at Delft Infra Composites, with Lightweight Structures responsible for their engineering.

Overall engineering is coordinated by a combination of Sweco and Witteveen & Bos." The team has also linked with a number of technical universities and colleges acting as development partners and back-office assistance, and UK firm Structeam has been commissioned to carry out some extra quality checks in the composite bridge design.

In the case of Friesland municipality, the key to overcoming risk aversion was the fact that this project followed on from a series of complex infrastructure commissions that had been overseen by the local authority. "Over the last couple of years we became more and more experienced in building complex infrastructure projects, most of them within time and budget," Vrieswijk says. As a result, they had built a level of trust with the decision makers. But he stresses the importance of the argument that the technology would deliver benefits in terms of circularity and energy reduction; this factor enabled them to leverage political support on a wider platform.

"The main purpose of the new bridge is to provide a link in the area's network of cycle routes, so it needs to be functional and aesthetically pleasing," agrees Vrieswijk. "But secondly, we hope we can start a movement towards using materials with a smaller ecological footprint.

"It is a matter of supply and demand: if there is no demand for alternative materials, factories won't produce them. Being a launch customer, we hope to arouse the interest of other parties to join this movement. And, once we've succeeded in using flax and resin on this scale and for this type of object, we're sure more will follow.

"Nature supplies us with enough options to consider for replacing traditional materials," he suggests. "However, putting them into service is not straightforward because not a lot is known about the behaviour, wear, and so on of these materials."

To try and address this, the project team carried out an unprecedented range of research and testing before construction began, partly to establish what combination of materials would work best, and also to identify the most appropriate type of bridge, which turned out to be an asymmetric swing bridge.

Four different technical universities – in Delft (the Netherlands) Leuven and Ghent (Belgium) and Osnabrück (Germany) – are directly involved in the project, carrying out a wide range of engineering and testing work. The latter included the creation of a full-scale model.

"We started by exploring all kinds of combinations of different fibres and resins, and we tested them on various parameters, such as interlaminar shear, tension and compression, UV resistance, fatigue, and creep. This allowed us to narrow it down to a couple of promising combinations," he says.

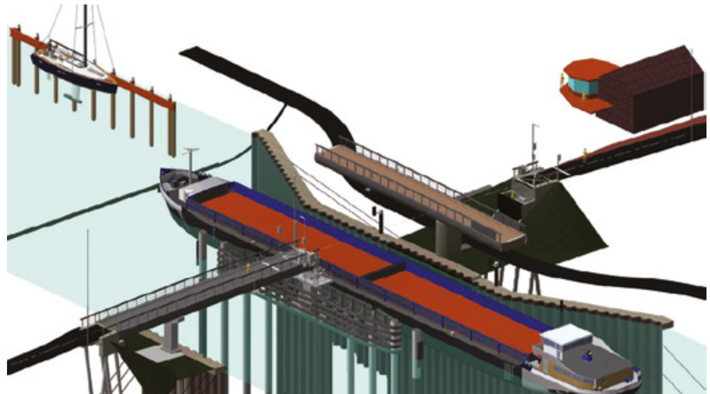
"We investigated those further, tested the interlaminar shear of the combinations, and eventually came up with the flax and resin combination that we are currently using," Vrieswijk goes on. He estimates that thousands of tests have been carried out to get to this point. "After this we created a full-scale model of a 12m section of bridge deck, which was tested for more than a month at TU Delft for fatigue and wear. We stopped it after reaching a testing lifespan of more than 100 years, as we only needed to prove it could last for 50 years.

"However, it has been quite a challenge convincing those who have to maintain the bridge once it is in use," Vrieswijk admits. "Usually you can predict the lifetime, deteriorations and degree of maintenance that steel or concrete bridges require. In this case, we had zero information. So you can imagine we really had to take these people with us, step by step, all through the process."

Getting building permits approved was also difficult – an obstacle that will be familiar to anyone who has been involved with implementing new technologies or materials. "The local government really had no idea how to judge the building application," Vrieswijk recalls. "So we found a professor at TU-Delft whom we put in touch with the local authorities. He looked into our applications and gave the local authorities a positive report to give them confidence to issue approval."

Extensive testing is generating a huge amount of data and has enabled the team to establish a valuable knowledge base for this novel material. The intention of the parties involved is to make this available as a public resource. "The use of bio-based materials

Abutments and piers are under construction at the site



3D view of the swing bridge which is being built

in a complex structure delivers a lot of data," says Vrieswijk. "Combining the data and making it accessible for anyone who's interested is a challenge in its own way. The collaboration between contractors, engineers and universities and high schools adds a lot of value to the project."

A complete digital monitoring system will be integrated in the structure during construction, and the data will be open source, so it will be freely available on the internet. Data collection started from the first laboratory tests, and all this information, as well as data about forces in the construction and ageing, will be accessible for anyone who is interested.

The project's significance is being recognised not just at a local level, but also nationally, winning an award from the Dutch National Congress on Circular Economy, and even overseas, with invitations to showcase the project at international events.

Furthermore, the importance of the project goes way beyond its transportation benefits. "Building a bio-based bridge supports the region's ambition to be a leader in circular economy," Vrieswijk explains. "With this bridge, we are really setting an example and putting our words into action. And we're not doing this alone, we're doing this with our design, construction and education partners.

"Of course this process and the bridge itself is more expensive than a traditional bridge, especially because it's the first of its kind and was, therefore, also a journey of discovery. But we really want to make a statement with this bridge and start a movement to think differently about building materials for civil construction. This costs more than just building a bridge."

The challenge of building with a new material and the value placed on gathering and sharing research information in order to advance the technology have led to some delays on delivery, as Vrieswijk explains: "We had some setbacks in the engineering phase: we did some extra checks and double checks that took a couple of months. More recently, the monitoring system in one part of the bridge was damaged during the assembly process. We had the choice of accepting the loss of data to keep on schedule, or stick to our pioneering-and-sharing process. We think it's more important to gain and share data on the innovative materials than to meet the schedule, so the bridge will now be ready to use this November, instead of October."

Vrieswijk is enthusiastic about the potential of flax as a building material for infrastructure and wants to encourage others to follow it up. "By all means explore and experiment with this promising new material," he urges. "Make use of the knowledge we've gathered over the past two years to help us take this even further!" ■

COLLISION COURSE

Software for 3D non-linear soil-structure interaction analysis of bridges under lateral and other loads is the result of 25 years of development, write Henry Bollman, Michael Davidson and Gary R Conzolazio

Development of FB-Multipier began with a focus on providing designers with a tool for efficiently conducting complex finite element analysis of bridges subjected to vessel collision loading. Since then, increasingly broader features have been added and, driven by ongoing bridge engineering research, it has been validated based on physical field tests of bridge and foundation structures.

A wide range of bridge configurations and foundation types can be modelled in FB-Multipier and several analysis types are available. Static analysis types include preload, load combinations, buckling, and load distribution for bridge models. FB-Multipier also offers dynamic analysis capabilities, from time-varying force or acceleration, to seismic response spectrum and vessel collision. The program contains lateral stability analysis algorithms that allow for iterative and automated determination of the minimum pile embedment required to prevent soil or structure failure, as well as workflow efficiency features for the automated determination of controlling load cases.

FB-Multipier adopts a Winkler modelling approach to represent soil-structure interaction. Soil strength parameters can be specified at the top and bottom of each layer to automatically generate resistance along the lengths of embedded piles and shafts. These curves are then used to develop non-linear springs which are 'attached' to the buried pile/shaft nodes and represent the soil lateral, axial, torsional, and tip resistances. Group effects are included for lateral, axial skin and tip resistances through p-multipliers and axial/tip group efficiency factors. Leading and trailing row p-multipliers are automatically assigned based on foundation motions.

FB-Multipier allows for both linear analysis and non-linear analysis formulations, and a discrete element formulation is used to model the non-linear behaviour of piles, pier columns and pier cap members. The discrete element accounts for both material and geometric non-linearities. Non-linear material behaviour is modelled by integrating material stress-strain curves over the cross-section assigned to each element. Non-linear geometric behaviour is modelled using P-delta moments, which are the product of axial force and relative displacements that occur across the element length. Because members are discretised into multiple elements, the deformed geometry of members accounts for the effects of stiffness changes due to concrete cracking, reinforcement yielding and slenderness. Pre-defined structural member shapes include circular, rectangular, square, bullet, H-sections, and pipes. Rectangular and square sections can include circular voids common to many standard concrete pile sections. Tapered sections are also an option, and, for circular sections, confinement effects for concrete strength may be considered resulting from shear reinforcement and/or steel casings. Strength calculation algorithms in FB-Multipier compute section capacity through generation of biaxial strength interaction diagrams for prestressed concrete, reinforced concrete, and steel cross sections.

Force results obtained from analyses (ie demands) are combined with section capacities to form demands/capacity ratios, which are printed and graphically displayed for pier caps, columns, and piles. Interaction diagrams can draw upon user-defined phi factors or those in codes.

For bridge design, it is typically necessary to list minimum pile penetration in bridge plan documents so as to satisfy lateral loading requirements. Assessing lateral stability involves modelling, analysing, and post-processing numerous configurations to find optimal pile embedment lengths. Manual generation of the parametric set of structural configurations and cataloguing of the pertinent output, such as lateral displacement versus embedment depth, from each model can be labour intensive.

To streamline this process, the Minimum Pile Tip Embedment feature automates incremental modification of pile lengths and post-processing of lateral load analysis results. A full set of input and output files is generated for each trial embedment length and may subsequently be reviewed. The MPTE feature automatically runs a series of trial embedment lengths, each involving incremental model changes relative to a designated base model, and catalogues design-pertinent results, such as pile lateral displacements and pile axial forces, across the set of computed responses. Results obtained facilitate efficient determination of the embedment at which a structure begins to become laterally unstable under a specified set of loads or load cases. The MPTE feature is complementary to other lateral-load analysis modes in FB-Multipier, such as pushover analysis. Further, the determination of minimum pile tip embedment can be analysed under numerous conditions of loading and soil support.

A typical example could entail determining the minimum required pile embedment length to satisfy lateral stability under a vessel collision loading case. The pier under consideration is in a hammerhead configuration, with a 22.3m tall rectangular pier column, 1.7m by 4m cross section, and tapered pier cap, 10.4m in length. Supporting the hammerhead pier is a square waterline footing 8.5m wide and 2.1m thick, and 25 square prestressed concrete piles of 0.61m in width, which are plumb and embedded in loose to medium-dense sandy soil.

A model of an individual pier, identified as being vulnerable to vessel collision loading, is extracted from a larger multiple-span bridge model and analysed to determine pertinent design forces. Vessel collision loading is taken as 8,000kN, applied at the waterline footing. To mimic the presence of superstructure resistance, an opposing lateral load of -890kN is applied at the pier cap level. As context, the opposing lateral load was previously determined to be the maximum component of impact force that is permitted to be shed at the substructure-superstructure interface. Twenty-one trial embedment lengths are investigated, with a maximum embedment of 18.3m in trial 1 and minimum embedment of 6.1m in trial 21.

After running the analysis, results are viewable from within the FB-Multipier interface, so no manual post-processing is required. Plots of maximum pile-head lateral displacements are also viewable across all embedment lengths. Further, direction-specific displacements, as well as maximum and minimum axial forces, can be plotted and exported. Using the controlling displacements and axial forces, trends in non-linear soil response, with respect to pile embedment length, can be reviewed, and a minimum pile tip embedment length selected ■

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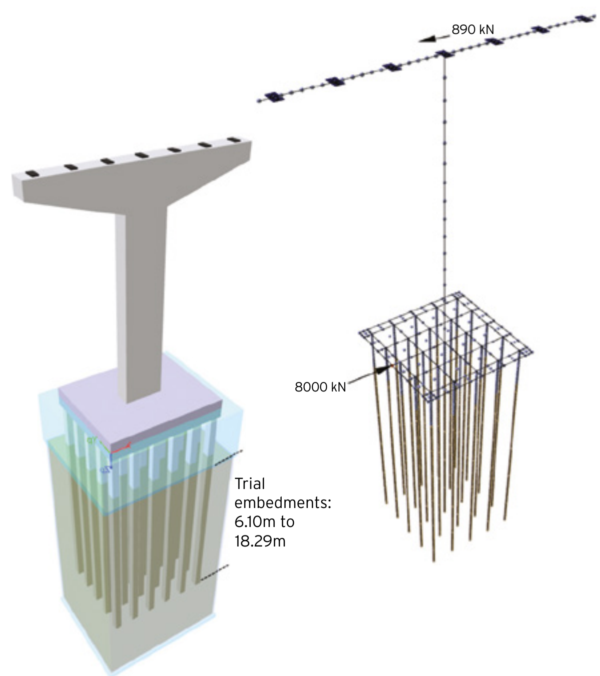

Different embedment lengths can be quickly analysed and then viewed on the FB-Multipier interface