Bridge
DESIGN & ENGINEERING

–IN EXTREMIS

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behaviour of the structure, whether it's floating or not. There are no codes that govern that interaction between the wind and the waves, so we are having to develop new methods of establishing rules for dealing with this," he continues.

"Why has this not been a problem before? Usually structures such as those used in the oil and gas industry don't suffer from interference with the mainland. In general it's easier to understand how the waves will behave because they are not influenced by local conditions, by the bathymetry and so on. At the shoreline, however, they are influenced both by bathymetry and the wind, and the wind is also influenced by the topography. It's very complex. As well as the induced waves, which are influenced by local factors, you have swell waves, which are generated a long way away from the site, and that interact with winds at the site."

The fjords are surrounded by high mountains which cause turbulence; Jakobsen says that the monitoring equipment present has recorded the largest ever vertical winds, which have direct implications for deck behaviour.

The monitoring and investigations are particularly important in enabling designers to consider these site-specific environmental loadings. "This is vital since we are looking at very unusual concepts such as 5km-long floating bridges," Jakobsen continues. "The longest floating bridges that currently exist are around 1km.

"The knowledge gained through this work will add value to the existing codes, with respect to these types of structures - we will close the missing links in terms of understanding," he says. "The main benefit is that we are looking at bridge designs that may open up opportunities for strait crossings all over the world; those that at the moment may not be feasible."

The first of the extreme bridge crossings is planned to be built at Bjørnafjord, as this will have a substantial impact on economic activity by improving access between Bergen and Stavanger. The concept design was selected last year after several years of research and development, and there is expected to be an announcement later this year to confirm which of the two consultants will take the design forward to prepare the tender.

Two consulting teams worked independently to assess the shortlisted options for a floating bridge; both concluded that the most suitable concept was a C-shaped floating bridge which will be more than 5km long and will cross the 550m-deep fjord. The most important criteria were structural reliability, functionality, cost and aesthetics.

The team that is chosen will develop the basis for the tender specification, before the government takes a final decision whether to proceed with the project or not.

Feasibility studies are also starting into the crossing of Sulafjord, Jakobsen reveals. "This is a very harsh environment - much more open to the ocean - and it will be even more extreme than Bjørnafjord. Usually the fjords are sheltered by islands and so on, but Sulafjord is not at all, so it will be quite exciting!" he predicts. A big site investigation is also under way at this location; the water depth here is about 500m deep, but the crossing will be shorter than Bjørnafjord.

A decision on bridge type for this location is not expected before 2022; a framework contract involving three companies was awarded at the start of this year, and concept development will follow a similar process to

CLIMATE CONTROL

Extremities of climate and environment can influence material choice when durability is a central concern. Dar senior associate Wassim Dergham explains the conditions that drove design of almost 50km of viaducts for two new highway links in Kuwait (*Bd&e issue 91*).

"The location of the Sheikh Jaber Al-Ahmad Al-Saber Causeway experiences very severe environmental conditions - it is a marine environment with high chlorides, high humidity and big variations in temperature. Temperatures can vary from 21°C to 60°C, with a high of 63°C recorded during construction of the bridge," Dergham says.

This severe environment affected the selection of materials, particularly the concrete mixes and the choice of aggregate. "Gabbro aggregate, a type of granite, was selected as aggregate rather than limestone materials which were not suitable for the harsh environment. The design also specified stainless steel rebars in the concrete that was exposed to the marine environment, in the piers and the pier caps," he adds.

A controlled permeability formliner was used for concrete that was cast in place, which improved the density of the concrete by allowing water to escape during curing, but not cement. "The durability requirement for the concrete was very high; it's a 100-year design life for the bridge," he explains.

Another aspect where material choice was driven by the corrosion climate was the safety barriers on the viaduct. These were made of galvanised aluminium sections; the challenge was to achieve the high galvanisation content necessary to resist corrosion in this environment.

In addition, the design had to take account of possibility that bored drivers might speed up, given the extreme length of the crossing; hence the safety barriers are designed to contain vehicles travelling at 140km/h, rather than the norm of 100km/h.

The local climate also creates difficulties for maintenance, says Dergham. Sand migration on the bridge during storm conditions can sometimes be at such volumes that lanes become blocked.

Last year a chemical tanker caught fire under Ulsan Bridge in South Korea (*Shutterstock*)

Tower foundations for the Chacao Channel Bridge in Chile, which is being built close to the site of the largest earthquake ever recorded

September. The dramatic explosion and fireball, which was caught on dashcam by a car on the bridge, was within metres of the deck. This underlined the potential for disaster, and reinforced the wisdom of implementing measures on recent bridges. Comments MacKenzie: "On the Ozman Gazi Bridge in Turkey we designed the main cable and suspension system for the possibility of fire, and introduced fire suppression systems, which are effectively 'sprinkler' systems attached to the main cable."

Shake down

Unpredictable forces are not always accidental or deliberate; for structures in seismically-active zones they are a central consideration, but the focus is more often below ground. Cowi's Paul Sanders recalls seismicity being a big concern in the design of the 3km-long Ozman Gazi Bridge across Izmit Bay. "Here the challenge was the foundations, and the solution was to design a seismic isolation system on the seabed using rubble to create a slip plane between the seabed and the underside of the foundations," he says. "We designed the main towers to slide on the seabed and displace by around 1m, which is similar to what happened to the Akashi Kaikyo Bridge in Japan, which was under construction when the Kobe earthquake struck."

Design of Chile's Chacao Channel Bridge, which is currently under construction, employed a similar approach, confirms Svein Erik Jakobsen of Aas-Jakobsen. His firm is working with consultant Systra for the design-build contractor Consorcio Puente Chacao, led by contractor Hyundai Engineering & Construction. "The most challenging aspect has been the seismic forces as it's a hotspot," he says. The site is close to where the biggest earthquake ever recorded took place, and it has been difficult to get the right solution to resist both the extreme seismic loads, and the behaviour of the earthquake itself. Designers must consider an event with a lot of energy in very high periods, with foundations that can move relative to each other in all directions.

One difficulty is agreeing the upper bounds, he adds. "Of course you have codes and regulations for what you need to design in terms of return period. But the client will always say 'what happens if the earthquake is bigger?' We have to find agreement between the owner, designer, contractor and so on." The project has already been in development for almost a decade, and the earthquake history for the site had to be updated after the 2015 event which was more severe than had been predicted.

The most obvious extremes for foundations are in flood-prone regions such as Bangladesh, notes Sanders, and on projects such as the Jamuna and Padma bridges, offshore construction techniques assisted with construction. Experience from past projects is being used for the foundations of a different type of infrastructure, Sanders reveals. "We've recently been designing foundations for a high-voltage power line across the Padma River; it's a 400kV line which uses pile-driving technology adopted from the oil industry. The line has enormous foundations with 3m diameter piles going to about 100m below the river bed, and each pile alone weighs about 400t," he says. The piles are designed to address very challenging environmental conditions, including scour levels down to -57m, which coupled with the seismic requirements, vessel impact and so on are very demanding. "With towers that extend to about 150m high above the water, you have something approaching a 200m-long cantilever," Sanders continues.

"These days the tools are readily available to analyse such structures and this is all being done to produce economies in the design. But without these tools, I wonder whether it would have been at all possible to design these bridges properly? We certainly would not have been able to do it on an economic basis. With the scour effects that we are seeing, the feasibility would certainly have been called into question and people would have just said - look it's too challenging, let's think about building the bridge somewhere else."

Marco Petrangeli of Integer reiterates the issue of extreme ground conditions - and points out that they are not always in the most obvious locations. "There are lots of places where you cannot build a bridge because you cannot stabilise the ground, it is simply overwhelming and instead you need to relocate or increase the span. We have plenty of examples on the Italian Appennini, and I am not sure if any new solutions exist."

His experience in Constantine in Algeria is particularly telling. He recalls working on a project more than a decade ago to salvage the Sidi Rached Bridge, Africa's largest masonry arch and a national monument, from slope instability, and notes that the ground subsequently restarted its motion. Further intervention is likely to be necessary, Petrangeli suggests, with the adjacent, subsequently-built Salan Bey Bridge also impacted.

Future proof

Past experience shows that bridge designs will continue to evolve to meet whatever


The formwork solutions for the Temburong Bridge towers had to withstand wind speeds of 45m/s

Construction – in extremis

How do bridge designers and engineers approach the execution phase of projects in extreme locations and facing challenging environmental factors? Khalifa Bokhammas investigates

As expertise, materials and equipment technology have evolved, so has the desire to connect locations hitherto considered too challenging to bridge, whether due to poor soil conditions, prohibitively long span lengths, or factors such as high winds and seismicity.

Several projects like this have recently been launched or completed, including the new unifying link in Brunei Darussalam. Temburong Bridge connects the previously isolated Temburong District with the rest of the country via a 30km-long structure, including 14km of marine viaducts, two navigation channel cable-stayed bridges, and a 12km section through a swamp forest. Not only did the client demand there be minimal environmental impact when building the swamp viaduct section, but the soil also consisted of soft peat overlying soft marine clay at depths of 70m. To overcome the twin challenge, a unique top-down method of construction was developed, whereby all work was undertaken from deck level, including material delivery and piling.

Access was also an issue when building the three A-shaped pylons for the navigation bridges in Brunei Bay, since there were a limited number of barge cranes with a high lifting capacity in Brunei. This limitation saw the creation of a now-patented construction method involving the fabrication of the pile caps within a precast concrete shell fixed to the steel pile casing to allow work to be carried out in a dry environment.

Concrete casting methods

Building across a large expanse of sea meant the formwork solutions for the three towers, two 113m tall and one 110m high, needed to withstand winds of 45m/s. "Our HACS7 system is used in environments with normal wind speed conditions, such as apartment blocks between up to 30-40 storeys high in urban environments," says Jongguk Lee, senior vice president of the technical sales team at Haegang. "But in situations where those criteria are exceeded, such as building bridge pylons in the ocean, HACS10 is recommended. The entire working space is fully covered by safety nets and protection screens, giving workers the feeling of safety and increasing working efficiency. Normally HACS10 can be auto-climbed in winds up to 25m/s. If the client wants a higher wind-load capacity, we customise our system to meet their requirement."

As well as being deployed on the pylons of Temburong Bridge, HACS10 is also being used for two ongoing projects spanning seawater in South Korea: Uncheon-soho and Saemangeum bridges, both of which are subject to high wind speeds and rough seas.

The capacity to withstand strong winds is also a key characteristic of formwork for the deck of the Cebu-Cordova Bridge across the Mactan Channel in the Philippines.

The new link is a 7.5km toll bridge expressway under construction in Metro Cebu, Philippines. Undertaking the work is a construction joint venture involving Acciona, DMCI and DM Consunji. The project will link Cebu City and Cordova via a 653m-long cable-stayed bridge with a 390m-long main span and 52.5m vertical shipping clearance.

Rúbrica Engineering has engineered, fabricated and supplied the formwork solution for the deck. This consists of four underslung form travellers, allowing the installation of the cable-stay anchorages on the upper side of the deck as well as the reinforcement cages. The solution provided by Rúbrica Engineering also includes casting the pier table using two form travellers temporarily fixed at each side of the pylon without any additional scaffolding. The two form travellers at each pylon are erected by means of heavy lifting strand jacks installed on top of the pylon bottom shafts at the deck elevation by employing tailor-made lifting structures also designed by Rúbrica.

According to Javier Fernández, special

The design of the form travellers for the new Cebu-Cordova Bridge needed to account for high seismicity and winds *(Rúbrica Engineering)*

set, whereby we brought pieces to site and connected them as we went along."

The client also required that the non-replaceable components of the bridge had a 125-year service life. To make sure this was not compromised during construction, the contractor undertook stringent quality controls. "On the design side, we had to look at creating a concrete mix with better resistance to permeability, so there were four different mix designs depending on the location, with the deck being one of the more stringent ones," Nader explains. "Now, when it came to construction, it was extremely important to conduct quality control on the concrete pours on site to make sure they met the minimum thresholds. It was more stringent in terms of the amount of testing that we did compared to the average project to make sure that we met the requirements. The steel was also painted with organic zinc paint to protect it from corrosion, and it is expected that the structure will have to be repainted every 25 years."

projects director at Rúbrica. "As the bridge is in an area with high seismic activity and extreme winds, the whole design of the form travellers needs very close coordination with the construction JV teams and bridge designer to discuss every detail of the construction stages and form-traveller-structure interaction, geometry, interferences, interfaces and model analysis." Load combinations have also been studied so that worst-case situations are analysed, and in terms of weather, the traveller has been designed to resist winds up to 250km/h from typhoons. "Nowadays, it is more and more common to have construction sites in places with extreme conditions. I must say that the local conditions have not been the highest values we have encountered when compared with previous projects, but it is the combination of natural hazards and variables that make this project unique," adds Fernández.

Offsite approaches to construction

One way around the challenge of casting concrete in extreme weather conditions is offsite construction. This approach was deployed to a significant extent in the construction of the new Samuel de Champlain Bridge, which opened last year in Montréal, Canada. Project teams were not only set the task of undertaking work through the freezing weather, with winter temperatures ranging between highs of -4°C and lows of -12°C, but also had to follow an accelerated construction timeline since the old bridge was in urgent need of replacement, having been severely damaged by de-icing salts over its service life.

Marwan Nader, engineer of record on the project and design manager for TY LIN International, the managing partner of the structural design JV behind the new bridge, says, "The Montréal weather shuts down the ability to do any meaningful construction for at least three months of the year. This dictated the way we thought about the job as designers and builders, stimulating some 'out-of-the-box' thinking, such as the avoidance of all field welding and the use of bolts to connect elements of structural steel."

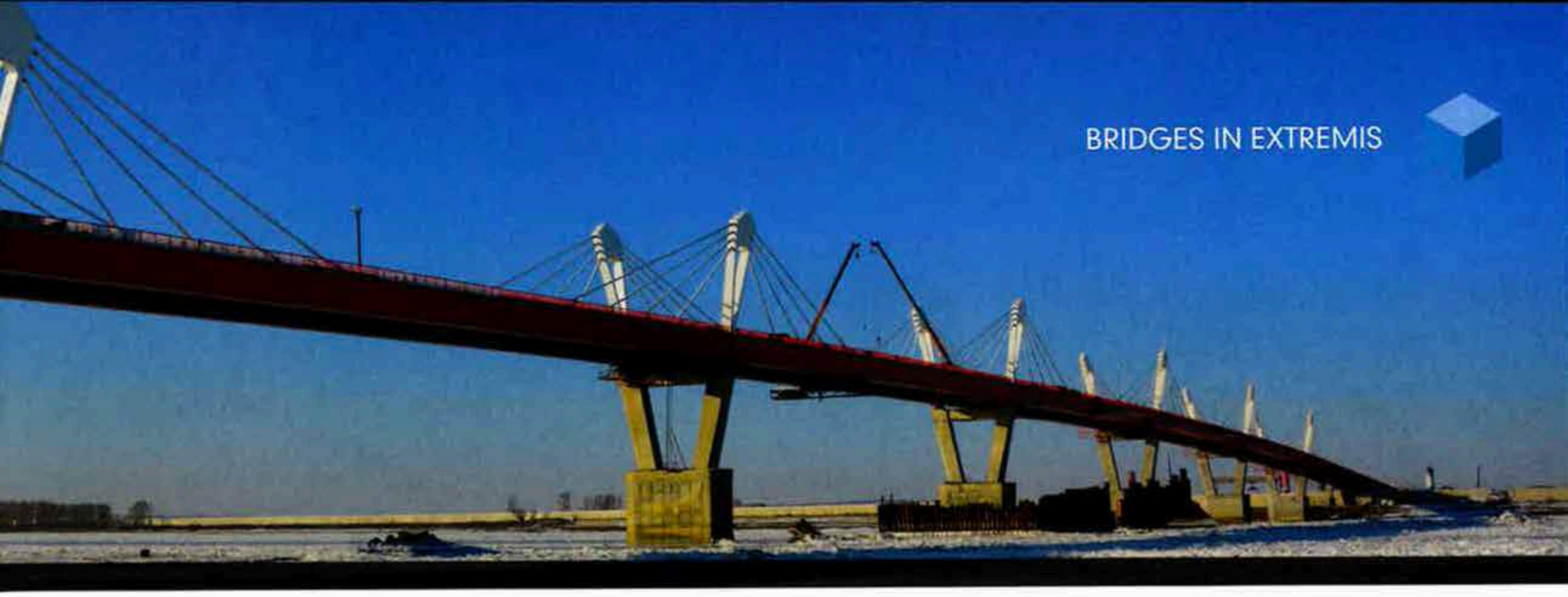
When it came to concrete, precasting was used as much as possible. "This allowed us to fabricate both structural steel and precast sections of concrete in a shop within a controlled environment," he explains. The fabrication of the steel pier caps is one example of this: the elements were fabricated in a yard, where they were also subject to a trial assembly process before being transported to the site for final installation. "Once the components were on the site, our activities were limited to things like bolting, stitch-casting the precast deck slab panels, grouting and post-tensioning. The whole bridge was really assembled like a large Lego

Cable installation at sub-zero temperatures

Freezing temperatures were also faced by builders of the Blagoveshchensk Bridge in Russia, which is set to open later this year. The 1,080.5m-long road bridge over the Amur River is strategically important since it will connect the cities of Blagoveshchensk in Russia and Heihe in China.

The structure is being built using a two-pronged approach, with Russian and Chinese specialists working simultaneously from their respective banks. As a result, the project is effectively two extradosed cable-stayed bridges built by different countries using different standards but linked at closure. Freyssinet supplied and provided technical assistance for the 48 stay cables on the Russian part of the bridge. According to André Coudret, manager for cables and structural equipment at Freyssinet Major Projects Division, some coordination meetings with the Chinese side were necessary as part of planning, but apart from that, work continued independently on the projects.

One shared challenge was the weather, with temperatures sometimes approaching -30°C. Coudret points out that Freyssinet was well prepared for such a site, having completed bridges in similar conditions in Russia, including the cable-stayed Russky Island Bridge in Vladivostok, Russia, which is ▶



rubber isolators," says Javier López Giménez, head of international business development at Kawakin Core-Tech. "The equivalent damping ratio of the HDR bearings at 175% shear strain is 17.3%.

"On some projects, HDR bearings are designed to consider the dissipation of energy and to accommodate vertical loads and rotation, which means their dimensions are confined to a certain extent. By separating the functions and just focussing on the dissipation of energy, we were able to maximise the energy dissipation capacity.

"The approach gives more freedom to design and to use the devices more flexibly. If you make a bearing that must accommodate large vertical forces and dissipate large amounts of seismic activity, you will have to design a bearing with very large dimensions. In this case, the function separation helped maximise energy dissipation and allowed for more economic design."

On another project, Suginazawa Daiichi Viaduct in Shizuoka Prefecture, southern Japan, large displacements caused by concrete shrinkage have also had to be factored into the design and manufacture of the 96 HDR bearings. The crossing, which is under construction, will have a total length of 852m and comprise 23 spans with an average length of 35m. The superstructure will be a continuous prestressed concrete girder, meaning a high amount of shrinkage needs to be considered when installing the HDR bearings.

"When you design and build seismic isolators, you have to consider the deformation of the concrete, as well as earthquakes. The greater the potential displacement caused by these two factors, the larger the bearing will be in the plane and vertical dimensions," López Giménez explains. "This would make it an expensive bearing, so to reduce the size, the bearings deployed on this bridge will have a post-slide mechanism." If the bearings were installed in the usual manner, ie with no pre-imposed deformation and with the centre of the lower and upper mounting plates under the same vertical line, concrete shrinkage would see them be displaced away from the ends of the bridge, which would be exacerbated by a seismic event. To counteract this, the bearing will be installed with an initial shear deformation and, after that, the deformation of the girder due to concrete shrinkage will bring the bearing back to vertical alignment.

Another type of post-slide mechanism involves installing the bearing with no pre-deformation. Once most of the concrete shrinking deformation has taken place, the bolts that connect the lower plate of the bearing to the base plate are removed and jacks are used to push the lower plate back until it is vertically aligned with the upper plate. The base plate and lower plate are then reconnected.

Looking ahead at what new developments the seismic isolation segment might hold, López Giménez highlights that an area of focus in Japan is further improvements to the anti-ageing properties of the rubber in HDR bearings. "There are some chemicals used in the rubber which make the material better able to dissipate energy; however, the anti-ageing characteristics of the rubber with these additives are not as high as without them."

Elastomers are particularly vulnerable to ozone attack, and only a trace amount of the gas can initiate cracking. "Japan has very strict testing of materials to ensure rubber used on HDR bearings can resist ozone attack, but on Suginazawa, they wanted something with even better characteristics." On this project, therefore, Kawakin used chloroprene rubber as a cover for the high-damping rubber to increase service life even further.

"The idea of using chloroprene rubber for this outer layer is something Kawakin has developed with other Japanese companies, and Suginazawa Daiichi Viaduct is one of the first projects where Kawakin has provided this newly developed product. Looking ahead, there could be more of a focus on this kind of idea. We know that HDR bearings can maintain their performance for many years. For example, companies have removed these bearings installed on bridges 30 years ago and shown that their properties are still very similar, even after all those years of service. However, failure of rubber bearings was observed in the Tohoku Earthquake that occurred in Japan in 2011, and one theory is that microscopic cracks caused by ozone may have played a role."

As a result, the market for enhanced HDR bearings protection is rising and Japanese manufacturers and engineers, including Kawakin, are increasingly looking to provide even stronger rubber compounds and anti-ageing systems to avoid the development of micro-cracks.

Overcoming multiple challenges

High seismicity is just one of the challenges facing the construction of Chacao Bridge in the Los Lagos region of Chile, 1,100km south of Santiago – an area where the most powerful earthquake ever recorded, at 9.5 on the Richter scale, struck in 1960.

Combining the risk of seismic activity with high wind speeds of more than 200km/h and strong tidal currents of 18km/h, this location has rightly been described by many stakeholders and observers as one of the most challenging bridge sites in the world.

The bridge will have a total length of 2,754m between anchor blocks, three reinforced concrete pylons, a suspended north span of 324m, two main spans (1,155m and 1,055m) and a south approach viaduct of 140m. The deck will be 23.8m wide and carry four lanes of traffic. The 175m-high inverted-Y-shaped central concrete pylon will be built on Roca Remolinos – a small reef in the middle of ▶

the channel. The project contractor for the scheme is Consortium Puente Chacao, which comprises Hyundai Engineering & Construction, OAS, Systra and Aas-Jakobsen.

Due to the bridge having two suspended spans, the central pylon needs to be sufficiently stiff to carry asymmetrical loads. Consequently, the pylon cannot develop plastic hinges and will absorb longitudinal eccentric loads through tensile and compressive forces in the legs. Meanwhile, the seismic load on the suspension system is mainly located between the main cables and decks, which use a fixed connection instead of fuse solutions seen on other major projects. To accommodate the high wind loads, the 25m-wide orthotropic steel box girder deck has a relatively slender profile with a thickness of 3.27m.

Although the strong tidal currents did not govern any aspect of the bridge's design, they have had a major impact on construction, particularly during offshore piling works for the central pier. "To position the barge for piling, it had to be done very quickly during the window between two of the four daily tides. The position of the Roca Remolinos also complicated the barge operation as it has a varied topography and the top of it is only 3m below sea level," Bénédicte Pich, deputy engineering manager for Systra, says.

To undertake the foundation works, Trevi Group Chile used a Soilmec SC-120 crane, which had a rotary SA-40 attachment, with the support of a 400t service crane operating on a jack-up barge.

"We prepared a special jack-up barge for this project, and the construction of the bored piles for the central pylon was successfully finished last October. The installation of steel casing, which was the first step for pile construction, was the most challenging work because the current speed is very high, and it is very difficult to install the steel casing in the target position in these conditions." Jongmin Lee, structural engineer at HDEC, says.

The 36 piles have a diameter of between 2.5m and 2.78m and were driven to depths of between 54.5m and 58.5m. The permanent casings have a variable thickness and temporary casings were used to guide and protect them during installation due to the strong currents present in the area, according to Trevi Group.

Once piling for the central pier was completed, the issue of the tides became less of a problem since the pile cap is above sea level. To facilitate construction of the central concrete pier and its foundation, CBB Ready Mix, which is supplying concrete for the bridge, built a cement plant in the middle of the channel and as of June last year had dispatched 9,000m^3 of concrete from the plant. The company estimates that 110,000m^3 of concrete will be needed for the entire bridge, scheduled for completion in 2023.

"At the moment, we are working on the construction of the bored piles for the north pylon by using the same jack-up barge," Lee explains in late March. On the north pylon, where the piles reach depths of 90m and have permanent casings of 60m in length and 180t in weight, the construction process is initially carried out by driving the casings with a hydraulic hammer (IHC S-600) and then excavating the pile to the final level by means of a reverse circulation drilling system.

Installing the steel casing for the piles of Chacao Bridge was challenging due to the fast-flowing currents

High-performance materials

The properties and behaviour of concrete are major considerations for bridges facing extreme environmental challenges, whether that be in considering the extent of its shrinkage, as on Suginazawa Bridge, or using bespoke mixes to mitigate chloride attack, as on the new Samuel de Champlain Bridge.

Over the last few decades, a new class of concrete known as Ultra-High Performance Concrete has emerged to address specific problems in industrial and structural applications. Indeed, UHPC's high packing density and dense microstructure make its use particularly beneficial on bridges exposed to high levels of rainfall and deicing salts. The steel fibres generally incorporated into the mix also give UHPC superior durability and mechanical performance over conventional concrete. "When talking about building bridges in extreme environments, UHPC's durability is its most defining feature," Oliver Budd, principal engineer at WSP, says. "The water-to-cement ratio is much lower, and it also has silica fume in it, which means chlorides and other deleterious particles can't make it through the matrix."

This lends UHPC to several applications on bridges facing extreme challenges, including as a coating on offshore piers, among others. "In the US I saw a UHPC link slab being poured, which is obviously somewhere where water can leak into the bridge and cause deterioration. Another advantage of a UHPC link slab is that it can be retrofitted to a structure much more easily because a conventional link slab would require quite a lot of the existing deck to be broken out. Using UHPC as a deck overlay is another application that showcases its durability, and in Switzerland, they have undertaken this on 50 bridges. The UHPC forms such a good bond with the concrete that it acts compositely, and it's so durable that you don't necessarily need waterproofing over the top of it."

For projects facing challenging soil conditions, UHPC's durability could also see it used to an increasing extent in pre-cast piles. UHPC piles are sufficiently robust that they can be driven even under difficult solid conditions where ordinarily traditional concrete piles could not, and steel would be the only option. Its high strength means the piles can be pre-stressed, reducing section size. The benefits of reduced section size can be carried over to other structural elements too, and where offsite construction is favoured, this would likely lead to lower transport costs.

While certain properties of UHPC lend themselves to significant performance advantages over standard concrete, it does not necessarily deliver benefits in all situations. For example, the product's tight matrix is a significant fillip when reducing the effect of chloride, but it can cause problems when exposed to fire. "The matrix is so tight that water particles have nowhere to escape to when heated, so you get more spalling than

you would with traditional concrete. One way to mitigate that is to include polypropylene, which melts and provides a path for the water," Budd explains.

The lower water-to-cement ratio also means a significant amount of heat is generated during mixing, which requires ice and a more controlled set of environmental conditions than normal concrete. "The heat of hydration is so high and it goes off so quickly that it's not really an option to mix it in a plant and then deliver it to site in a wagon. This means you have to batch-mix onsite," Budd highlights.

However, since offsite construction is gaining more favour across the structural engineering community, particularly for sites facing harsh environments, this aspect of the product might not prove a major barrier to use on large-scale projects but could be more of an issue when it is being used for remedial work.

An ancillary issue caused by the different way UHPC is mixed is that it also needs a different execution standard. As Budd points out, "The current standards aren't really geared up for the kinds of properties of UPHC, with different countries taking different approaches." As a result, the country in which a project is located and the standards and level of local acceptance that exist could inform the engineers' decision as to whether to specify UHPC as a material. Another determining factor could be cost: "UHPC is only available as a proprietary mix from certain companies, so it's obviously more expensive," Budd says.

Nonetheless, the higher price of the material can be offset by savings made through smaller and lighter structural elements, as well as by the lower transport costs, and it looks likely that acceptance and demand will rise in the future.

Fire safety

Another alternative material to steel and conventional concrete which has gained traction in the bridge industry over the last few decades is fibre-reinforced polymer. The advantages of FRP bridges are similar to UHPC and include outdoor weathering resistance, durability, high stiffness and strength-to-weight ratio, offsite manufacture, minimised installation times and potential weight savings, making it another candidate for use as a material for bridges facing extreme challenges, both natural and man-made.

Like UHPC, the resources and standards for bridge engineers to refer to are still growing and vary by country. The Ciria-Composites UK 2018 C779 publication *Fibre-reinforced polymer bridges – guidance for designers*, is one up-to-date resource to refer to, but there are no recognised standards in the UK. As structural Eurocodes are in still development, those undertaking FRP projects can find themselves venturing into new territory.

This was a challenge faced by APB Group, the contractor for two 28m-long FRP footbridges installed over rail lines in north-west England in 2019. As the first FRP bridges over railway lines in the UK, the bridges were also the first required to meet fire safety guidelines from Network Rail – the owner and infrastructure manager of most of the railway network in Great Britain.

"Network Rail has a particular fire performance standard, which isn't something you'd automatically think of when building a steel bridge. But, since FRP is plastic and therefore combustible, you do have to consider damage by fire," Trevor Fielding, technical business manager at Finnester Coatings, says. As a result, Network Rail required that the bridges meet the standard BS476 Part 7: Class 1. "The standard looks at surface spread of flame, so you set fire to specimens and measure the distance the flame travels across the surface. Class 1 signifies that the final spread of flame is no further than 165mm from the ignition source after ten minutes."

To meet this standard, the contractor decided to use Hybridred, a spray-applied coating made by Finnester Coatings that was originally approved under EN 45545-2 to provide fire resistance for train carriages.

"When exposed to fire, the Hybridred technology forms a ceramic shield that prolongs ignition times and slows the spread of the flame, thus protecting the FRP underneath" Fielding says. The tough, chemical- and weather-resistant surface of the product means it also repels dirt and graffiti, leading to savings in maintenance costs.

While neither of the bridges will face particularly extreme challenges during their service life, the case study does serve to highlight the issue facing projects that use novel materials.

FRP as a material has been in existence for several decades, with the first FRP bridge having been built in Perthshire, Scotland more than 25 years ago. The fact that standards are continuing to be rolled out perhaps illustrates the slow uptake of technological advancements in the construction industry when compared to other sectors.

Indeed, deviating from standard materials and practices presents contractors with an array of challenges; however, the benefits on individual projects and for the wider industry, in terms of learning and knowledge sharing, are surely worth the effort, particularly when we continue to push designs and projects to new and previously unexplored realms