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SAFETY IN BIG NUMBERS

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STEEL OVER WATER

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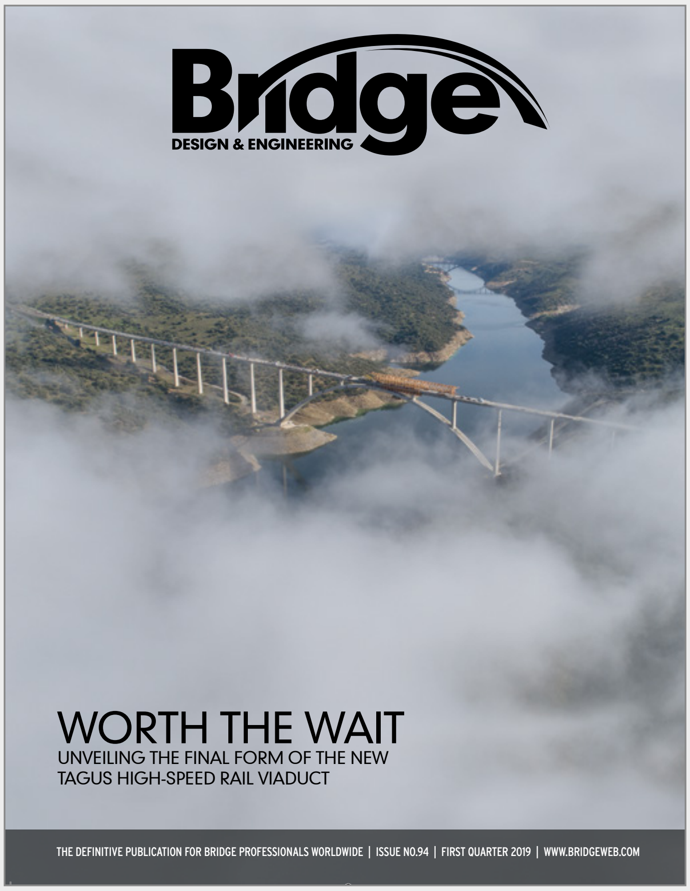


Now that the new bridge is in service, the old bridge will be refurbished *(Roman Sidler)*

SISTER ACT

The final stage of a complex railway project in Switzerland is currently under way, with completion due later this year. Ian Firth, Andreas Galmarini, Matthias Ludin and Steen Savery Trojaborg report

Completion at the end of last year of an elegant new railway bridge over the Hinterrhein River in eastern Switzerland has enabled work to start on a programme of renovation and improvement work on its historic neighbour. The new bridge, near Reichnau, has been dubbed *Sora Giuvna* – 'Little Sister' – in deference to the 19th century steel truss bridge that it stands alongside. Both the new 200m-long bridge and its historic neighbour carry single-track railway lines, and they are in a highly significant and sensitive location. Not only is this the meeting point of the two principle tributaries of the upper Rhine, but the surrounding area includes notable bridges by Christian Menn, Max Bill and Mirko Roš, and used to be the site of innovative timber bridges by the Grubenmann brothers. Hence the location has long had a historical significance for Swiss bridge engineering.

Client for the new bridge is the Swiss regional rail company Rhätische Bahn; the construction of the new structure allows the last single-track stretch of line between Chur and Bonaduz to be eliminated, enabling two-way working on the Chur to St Moritz and Chur to Disentis-Muster routes.

As well as increasing capacity and robustness of these lines, the new layout with two independent single-track bridges will make maintenance easier. The bridges form part of the feeder line to Rhätische Bahn's historical Albula route, which was added to the list of Unesco World Heritage Sites in 2008.

Consultants Cowi and Walt Galmarini developed the design for an international design competition in 2015, working with Danish architect Dissing & Weitling and local landscape architect Hager Partner. The steel superstructure construction was built by Schneider Stahlbau, Joerimann Stahl and Toscano Stahlbau, with the foundations and abutments by Erni Bauunternehmung.

All bridge designs must relate to their context, responding to the specific constraints presented by the location; in this case there were very particular challenges. The mountainous topography and beautiful landscape, the confluence of the two rivers and the many historical and cultural factors make this a very special place. The challenge was to respect these factors and above all to devise an elegant, modern design capable of standing directly alongside the historic 1896 truss bridge, complementing the original, while still retaining its own notable character.

The existing truss has an unusual bracing pattern, and a majestic presence, so the design team quickly concluded that the new bridge should be as transparent and slender as possible – not easy in a railway bridge – so as not to detract visually from the historic structure. Refurbishment of the existing bridge is part of the overall project and was planned to start after the new bridge was completed.

The landscape works that were necessary for the new bridge included cutting back the mountain slope between bridge and railway station to make room for the additional track; this solution was preferred to the alternative, which was to build large additional retaining walls, and it turned the focus towards the bridges instead. The design needed to find a synthesis between the environmental and technical constraints, between architecture, landscape and the art of engineering, enabling both bridges to shine.

In addition to crossing the river, the new railway line, which follows a gentle plan curved alignment, had to cross the busy A13 highway on the Reichenau side. The old concrete bridge which carried the existing railway over the A13 also needed replacement. The alignment meant that this crossing would be highly skewed, and with limited headroom clearance over the road, both of the new railway bridges required a shallow construction depth.

As part of the competition, participants were able to choose whether to use a single structure to cross both the river and the highway, or whether to do so with separate bridges. Several factors supported a clear preference for combining them into a single bridge. Spatial constraints alongside the road, the highly skewed alignment, access difficulties for construction and the desire to respect the elevations of the existing bridge and its stone abutment all contributed to the decision. For visual consistency, the separate, single-span replacement bridge for the existing rail track had to have the same cross-section and depth.

One of the early decisions taken by the team was to build the bridge in steel. This was a decision driven as much by landscape and context considerations as technical and engineering expedience. The other notable road bridges in the area are generally concrete, and the existing railway bridge is steel; concrete for roads, and steel for railways. This seemed to fit with the spirit of the place and the historical context, in keeping with the characteristic steel structures of so much railway infrastructure. But also, as slenderness and transparency were going to be key design considerations, and as light weight was going to be an essential factor for constructability, steel became the

Lifting the eastern section onto the western section ready for the launching operation

natural choice. The bridge design needed to minimise the deck construction depth in order to provide sufficient headroom over the road. To achieve this, the structure is a trough girder, with a U-shaped cross-section formed by trapezoidal steel boxes on each side, with the tracks supported on ballast on top of a steel plate stiffened by shallow transverse cross-beams underneath. The cross-beams are closely spaced at 1m centres to keep stresses low, particularly for fatigue, and to keep the bridge soffit as clean as possible there are no visible longitudinal stiffeners.

In order to reduce the effective spans and minimise overall depth, the trough girder is supported on inclined integral props standing on concrete piers aligned with the stone columns of the existing bridge. This results in a main span of 63m and a girder depth of only 1.7m, achieving the desired slenderness of the concept. The inclined props form a four-point support to the girder, creating so-called 'quadropods' which became a major feature of the design. Careful shaping and detailing of these quadropods was required, particularly at the top where they taper to a welded connection to the girder soffit at a point where fatigue is a primary design consideration. The quadropods are integral with the girder, which acts as a tie between them, and are supported on the slender concrete piers by large-diameter pin bearings concealed behind removable steel cover plates.

Between the river and the road there is a small triangle of land within which a supporting pier was required alongside the stone abutment of the old bridge. After testing various options, the team converged on a solution involving a skewed V-shaped pier placed parallel to the road. This avoided any headroom clearance issues over the edge of the highway and created a coherent language for the support arrangement over the entire bridge length by echoing the shape of the quadropods. When viewed along the bridge axis, the V-pier and the quadropods present a consistent form and a clear expression of the structural system. But the skewed arrangement also meant that the two longitudinal girders have different spans, introducing some interesting asymmetry in the bridge behaviour.

The design went through several iterations before settling on the optimum articulation scheme, which involves a combination of bearings that allow movement and continuous structures flexible enough to accommodate movement. The bridge is fixed at the west abutment, and all longitudinal traction and braking forces are accommodated here. In keeping with the bridge owner's request, there is just one expansion joint to accommodate all thermal and other longitudinal movements, at the extreme east end. In between, the bridge girder is fully continuous and integral with the quadropods.

This means that the concrete piers have to be flexible enough to accommodate some longitudinal deflection at the top, where the pin bearings are, and the quadropods experience rotations with one pair of arms moving up and one pair moving down under the passage of a train.

At the V-pier, sliding bearings support the girder to allow longitudinal movements, and the legs are tied together at the top with post-tensioned high strength steel bars in order to stop them spreading apart under load. There are three bars to permit them to be replaced one at a time in future, should that be necessary.

The slender concrete piers stand on piled foundations, and the design brief required that pile caps were placed at a low level, approximately 7.5m below ground level on the east side, to reduce the risk of undercutting in the event of extreme scour. Thus the piers extend some distance below ground level, increasing their flexibility and enabling them to accommodate the required movements.

There is a fine line between allowing sufficient flexibility for thermal effects while at the same time retaining enough strength and stiffness to support the loads. This was the subject of extensive investigation.

The initial concept was to fix the bridge longitudinally at the east abutment, and terminate the bridge at a skew angle, parallel to the road. However, with this arrangement, the girder would have experienced a large twist under railway loading, and more importantly a very large rate of change of twist as trains passed over the abutment. This would not only have infringed the serviceability limits of the code,

The 'quadropods' on the piers enabled a reduced main span of 63m *(Roman Sidler)*

View along the centreline showing pier-top bearings, which will be concealed behind removable cover plates *(Andreas Galmarini)*

but no doubt would have also caused discomfort for the passengers.

The sharply-skewed end means that the vertical deflection of the two edge girders under a passing train is very different, causing a transverse crossfall or twist of the section, so the train leans over sideways. As it passes from the bridge onto firm ground beyond the abutment, the train returns upright again, and it is this dynamic rocking motion that needs to be controlled. The problem was compounded when the decision was made to move the longitudinal fixed point to the west abutment, because a skewed expansion joint is definitely undesirable.

So the skewed end was replaced with a square end, involving an extra 11.5m of steel girder on one side. This extra length of span would have required a significantly deeper and heavier girder, at least on that side, but this was highly undesirable. So the solution was to introduce an additional bearing at the point where the skewed end bearing would have been. With this arrangement the axial rotation still occurs at the intermediate bearing position, but there is no sudden change in rotation as the train passes over the abutment.

In order to avoid uplift at the end bearing when train loads are applied in the span over the road, it was necessary to control the amount of permanent load in this intermediate bearing. Thus the bridge was first installed without the intermediate bearing so that all the permanent load at that end of the girder was initially carried by the end bearing. Then the intermediate bearing was jacked in to a pre-determined load, reducing the permanent load on the end bearing but not so much that uplift would occur under transient live load.

Building a structure so close to a live railway line with overhead electrification and limited space for temporary works, coupled with the proximity of the busy highway, forced the team to carefully consider possible construction methods from very early stages. It was clear that the steel trough girder, quadropods and V-pier – some 960t in total – would need to be fabricated off site and delivered in short sections by road for site assembly. This is common practice and achieves best quality with minimum disruption, reducing risk and construction time.

An accessible area of level ground beside the river on the west bank was available for lay-down and assembly, and a temporary river bank extension was permitted here so as to reduce the reach of the crane. A smaller assembly area could also be made available behind the eastern abutment alongside the railway. So the questions became: how large could the assembled pieces be? Heavier pieces meant a larger crane but fewer operations – how could they be erected? By crane, by launching, or both? And could it all be done without additional temporary supports?

The team established that a large crawler crane standing on the extension of the river bank in the assembly area would be able to reach far enough to install the quadropods and the river spans as individual lifts, and could just manage to place the V-pier. The bridge is fully welded throughout, so this meant welding the girder sections together and to the quadropod legs out over the river. But the real challenge was how to place the girder sections over the V-pier and the highway.

The busy road could only be closed to traffic for a very few nights and there was no possibility of access off the road at that point or room to place a crane there. The initial idea was to assemble the spans on the east side and launch from there towards the west. In the end, the solution chosen was to use the crane to install the four western sections from the west abutment to the eastern quadropod, and then to assemble the eastern sections as a single piece, place it on top of the already erected spans, and launch it across the road in a single operation, finally lowering it into position. This all went remarkably smoothly.

Finally, once all the sections had been fully welded and the final paint system applied, with the ballast added and tracks and railway equipment installed, it was time for the load test. All went well with the bridge performing satisfactorily, and the new track was successfully opened to rail traffic in November 2018. After completion, trains were diverted onto the new bridge to enable refurbishment and improvement works to be carried out on the original structure and for the existing concrete bridge over the road to be removed. Then the 51m-long replacement span for the original rail track, which has the same form as the new bridge, will be launched over the road, with completion expected in late 2019 ■

Ian Firth is a consultant at Cowi; Andreas Galmarini is director and Matthias Ludin bridge engineer at Walt Galmarini; and Steen Savery Trojaborg is managing director at Dissing & Weitling

The eastern spans were launched over the western spans in a single operation

SAFETY IN BIG NUMBERS

The maximum information possible is being extracted from the Pont de Normandie for real-time and long-term evaluation

A structural health monitoring solution is being implemented on three major highway bridges spanning the Seine Estuary in France to help ensure their safe, effective and efficient management, write Matthew Anderson and Anthony Smith

The three crossings are benefitting from the comparatively new development in structural health monitoring that combines sensor fusion, big data and web-based IoT technologies. Positioned at the mouth of the Seine Estuary, the port of Le Havre is the fifth largest port in Northern Europe and crucial to the French economy. It is the country's leading container port for French foreign trade, vehicle import and export, and is the worldwide leader for wine and spirits. Inland communications have long been important, with a crossing of the Seine necessary for unhindered access to Paris and beyond.

The strategic highway network in this region includes the three key bridges that comprise its two Seine crossings. The oldest of these is the Pont de Tancarville, a single span suspension bridge located 28km to the east of the city. Opened in 1959, this 1,420m-long bridge with a central span of 608m carries Paris-bound traffic on the N182 and A131 highways. A second Seine crossing was added in 1995, much closer to the port of Le Havre, carrying the A29 highway and providing a significantly more direct connection to the city of Caen, the southwest and Brittany. The Pont de Normandie is a cable-stayed bridge with a total length of 2,143m and a single central span of 856m; both bridges held world records when they first opened to traffic. Two kilometres to the north, on the approach to the Pont de Normandie, is the location of the third of the major bridges in the vicinity; the Pont sur le Grand Canal du Havre, a rigid steel-framed bridge traversing one of the main port channels.

In 2018 the operator of these three bridges, the Chambre de Commerce et d'Industrie Territoriale Seine Estuaire, sought assistance from James Fisher Testing Services and Cowi in designing and commissioning an upgraded structural health monitoring solution, as the existing systems approached the end of their operational lives.

As part of the refurbishment project, the team's first task was to review the current monitoring installations. Based on the findings, they were able to configure a comprehensive solution that would deliver state-of-the-art functionality based on the latest big data, sensor fusion and internet-of-things technologies. This major refurbishment project is the first on which the team has partnered, and it combines significant synergies between the two. Namely, JFTS' strengths as a structural health monitoring innovator, technology developer and system integrator; and Cowi's expertise in data analytics and sensor requirements, as well as capability in using the data collected by the system to provide accurate performance modelling and insights on future structural condition.

The project involves upgrading the various existing monitoring systems that have come to the end of service life. The upgrade comprises an initial review of the existing systems, their refurbishment, and the installation of selected additional sensors. The goal is to have quantitative information to characterise both the environmental conditions at the location of the three bridges including wind conditions, temperatures and rain intensities, and the structural responses that these and the bridges' operational loadings create.

To maximise insights into the performance of major infrastructure such as strategic highway bridges – while allowing for advanced analytical operations that might extend to the prediction of future condition using concepts such as machine learning – a

The Pont de Normandie's weather station (left) has been upgraded (centre)

large amount of real-time data will be generated from a multiplicity of sensors. For example, in the case of the new system being fitted to the Seine Estuary bridges, displacements are monitored permanently by a system of strategically-located GPS antennae. The strain of selected components is also measured, as well as cable vibration levels, to mention just some of the performance measurements continuously being recorded. This large amount of data provides the basis to characterise abnormal structural behaviours, and to inform a proactive approach while managing the bridges.

The new structural health monitoring solution provided by JFTS will be based on the company's Bridgewatch solution, which enables automated, intelligent structural health and performance insights to inform operational decision support. The system uses real-time data acquisition and advanced processing to improve safety, manage traffic flow and minimise bridge closures due to unscheduled maintenance.

Analytical processing of recorded data in order to detect longer-term trends and predict future performance, however, requires the use of web-based, big data technologies. Many of these are readily available for the latest generation of structural health monitoring systems, proven in sectors as contrasting as online gaming, video-on-demand services, international banking and automated share market trading. Similarly, the analysis requirements of such state-of-the-art systems are able to harness the type of parallel processing approaches used in sectors such as automotive and aerospace for large, highly non-linear analysis operations.

In order to manage and leverage the advantages of big data, Bridgewatch operates on JFTS' Smart Asset Management System. The Sams technology stack includes the operating system and related support programs and all runtime environments necessary to support the application, as well as database warehousing software and utilities for version control.

This approach provides one of the key innovations of the refurbished monitoring systems on the Seine Estuary bridges. While some of the new sensors that JFTS is specifying will better characterise the structural responses – for example, new inclinometers and strain gauges – the main innovation relates to the combination of data from all of the different monitoring systems into a single centralised software platform. This will allow correlation of data from different sensing systems, from weather stations to GPS, and hence maximise the information that can be extracted from the data, both immediately in real time as well as for longer-term trend evaluation and predictive analysis.

Rather than simply embark on a wholesale replacement of the installed monitoring

MACHINE LEARNING AND PREDICTING FUTURE PERFORMANCE

The Sams/Bridgewatch system is configured to monitor a range of different bridges around the world. The system harnesses big data technologies and flexible, web-accessible parallel computing resources, to enable highly sophisticated forms of structural health monitoring to be carried out.

For example, the system can be configured to automatically execute sophisticated analysis operations based on a fixed schedule, or according to pre-set data triggers such as threshold exceedances. These can be either individual sensor inputs such as a given load, temperature, displacement or wind speed for a given direction, or a prescribed combination of such inputs or derived parameters such as bending stress. Alternatively, analyses may be triggered on demand or from another analytical process.

Machine-learning routines can be configured within Bridgewatch to predict future performance trends based on the complex data sets, which range from displacements to traffic loadings, temperatures and wind speeds. In a highly complex system such as a major suspension bridge, assessing subtle trends in the vast quantity of multi-sensor data generated can be extremely challenging.

The use of deep-learning neural network methods can enable multiple layers of non-linear information processing for unsupervised self-learning performance based on large amounts of sensor-derived data. Advanced analysis routines can be used to automatically calculate trends in the expected future performance deterioration of structural details of concern.

Any divergence between the predicted performance and real-time measured data, or an increase in the predicted level of structural deterioration, could be used as a trigger for further analysis and investigation. One such analysis operation that might be used on this through-life data is that of stochastic subspace identification.

For a welded structure, for example, there will be a known overall stiffness on completion. If a fracture occurs in part of the structure the stiffness will be changed, but it may not be possible to spot this in the complexity of recorded data, due to other factors such as prevailing temperatures, wind speeds and traffic loadings.

Stochastic subspace identification enables the numerical manipulation of systems where not all variables are known, in order to help identify and isolate the causes of deterioration based on the live loadings applied.

Early detection of root causes for even comparatively incipient problems should thus be identifiable, enabling early rectification or even preventative action to be taken in a planned way, avoiding the costs and disruption of the more intensive interventions that might otherwise be required at a later stage of deterioration.


The installation of new and refurbished sensors is an ongoing process

hardware, JFTS is endeavouring to extract the maximum possible value from existing serviceable equipment, hence minimising the cost of the system upgrade. A significant number of sensors from previous installation phases – in some cases even from the original construction – are being re-used following a strict performance verification process. In other cases, hardware is being replaced or augmented in order to ensure complete and effective integration with the new Sams and Bridgewatch system.

The approach to system and component testing is rigorous; all sensors are tested in the factory prior to any installation works. Once the sensors are installed, including those units carried over from previous installations which have been tested and verified in situ, the full system will be subjected to commissioning tests. This process will be used to verify that the complete measurement chain works as planned, from the sensor attached to the structure to the web-based interface that displays and processes the data.

The installation of the Sams/Bridgewatch system and associated new and refurbished sensor hardware is ongoing and the software platform to manage all data is being customised to be ready early this year. Once initial testing has been completed over the coming months, the system will provide complete continuity with the previous legacy monitoring data reports, while also enabling the creation of an accessible database of information and structural monitoring for future analytical use.

The combination of sensor fusion, big data and web-based IoT technologies is a comparatively new development in the world of structural health monitoring and offers the prospect of new levels of insight into structural health and proactive management of operations. These systems enable efficient day-to-day monitoring operations while also facilitating large-scale advanced analytical processes that can yield insights that would otherwise not be discernible. In this way, advanced analytical methods can be used to predict the path of future performance deterioration, thus enabling proactive maintenance and operational management.

But while the concepts are already well proven in other industries, they bring some clear challenges too, not least in terms of the management and effective manipulation of the vast quantity of data generated. It is also the case that automated analysis can never fully substitute for human intervention and interpretation; an area in which Cowi will continue to support the Chambre de Commerce et d'Industrie Territoriale Seine Estuaire. At its very best, structural health monitoring and effective infrastructure management thus requires the combination of these state-of-the art technologies with more conventional approaches – including that of regular visual inspections ■

Matthew Anderson is head of bridges and structures at James Fisher Testing Services. Anthony Smith is an independent consultant

STEEL OVER WATER

Preparation work is under way for a complex operation that will see the replacement of a busy rail bridge at the heart of the Swedish capital, writes José María Sánchez de Muniáin

The critical rail crossings in central Stockholm are to be replaced over the next two summers *(Shutterstock)*

By the end of an eight-week period the existing 235m-long, 770t steel bridge has to be removed and replaced with a 1,380t structure, as well as be ready to carry rail traffic. Project Getingmidjan consists the replacement of a 2km section of railway to the south of Stockholm's main train station and across the Island of Riddarholmen. The route was first opened to trains in 1871 and today is the busiest in Sweden.

The current infrastructure, which dates back to the 1950s, is approaching the end of its useful life. The Swedish Transport Administration commissioned Implenia to carry out the US$98-million project, which started in 2017 and is planned to be completed by 2021.

As well as replacing tunnels, building retaining walls and installing upgrades to noise protection, earthworks and cabling, the project includes the replacement of two steel rail bridges to the north and south of Riddarholmen Island.

As 80% of the country's rail network is potentially affected by this section, which connects to major cities such as Gothenburg and even Copenhagen in Denmark, the work is scheduled to take place during eight weeks of rail transit closure. The south side bridge will be replaced this summer, and the north will follow with an identical closure in 2020.

The existing concrete substructures of both bridges are to be renovated and reinforced by adding layers of concrete, with the intention of increasing their lifetime by around 120 years and enabling them to withstand the heavier load of the new superstructure.

At the time of writing, work on the foundations of the first pier of the south bridge was about to begin. The south bridge has five sets of piers in the water and two on land; once this work is completed and 400mm of extra concrete has been added to the width and length of the foundations, which are currently 7m x 10m in area, and 4m below water, work will move to the north bridge.

The most critical time of the project will be the summer railway closure, says Implenia production manager Guido Thyssen, when a whole raft of procedures will need to take place in precise chronological order to ensure the success of the operation. "Roughly it is split four weeks for the removal and installation of the new bridge, and the remaining four weeks for the railway works.

"First will be the removal of the existing superstructure, then the installation of the new steel superstructure and the bearings at the top of the piers. Then the installation of the railway tracks and the electrical signalling system, which needs to be tested. The final joints will also need to be welded and painted on site after installation," says Thyssen.

The removal and installation of the south side bridge is being undertaken by specialist contractor Sarens, which began planning two years ago. On paper the scope of the work may appear straightforward, but a number of restrictions and challenges relating to the location mean that the operations have required much consideration, and a number of revisions to the lifting operations.

The project involves removal of the three sections that make up the bridge, and their replacement with steel sections comprising two 95m x 15m x 3m sections and one 45m x 15m x 3m section.

The dominating factor for the lifting plan has been a restriction on carrying out land-based operations in central Stockholm, which means that virtually all the lifting operations have to take place on water.

The first part of the plan will see the three steel bridge sections being loaded onto a 100m-long barge in Tallinn, Estonia. After the two longer sections are loaded on the barge, one will be jacked up and the shorter section inserted underneath. The sea barge will then travel 400km across the Baltic Sea to Södertälje, a town ▶

▶ 30km southwest of Stockholm. When the cargo is required, the steel sections will be individually loaded out onto twin barges that can negotiate the Södertälje Lock, which is too narrow for the sea barge.

While the new steel sections are waiting in Södertälje, the removal operation will begin in Stockholm. The current lifting plan involves placing two steel beams transversely across twin barges 60m long by 22m wide. At the ends of the beams, which will cantilever from one side of each barge, will be four jacks. On the opposite side of the cantilever a crane will be placed, at this stage acting only as ballast.

The twin barges will then be manoeuvred beneath the steel bridge section, which will be raised using the jacks located on the cantilever beams. The twin barge will move out and a 50m long by 17m wide transport barge will be positioned beneath the bridge, and the section loaded onto it. The old steel spans will then be taken to Vasteras, around 100km northwest of Stockholm, for dismantling.

A particular challenge arises for the 45m-long section of the bridge that crosses the land to the south, and where there is insufficient space for a land-based crane.

For this section, self-propelled modular transporters will initially shift the section longitudinally onto the adjacent pier, where the steel deck section will have already been removed. As this pier is in the water, the SPMTs will work in tandem with the crane on the twin barges, which will help guide the section onto the pier. Once the section is on the pier, and fully reachable by the crane, the crane will be repositioned to lift and load out the section onto the transport barge.

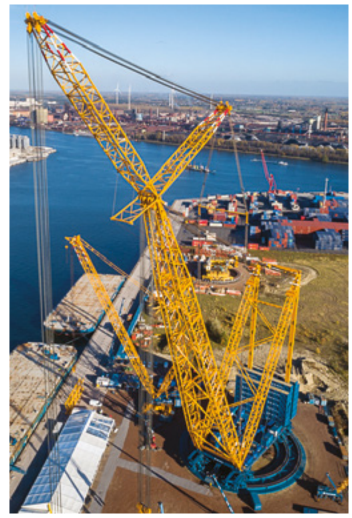
Many options were considered for the removal and installation procedure, but these were limited by site conditions and the rigid eight-week closure. Implenia's regional manager (bridges and structures) Gernot Reismann explains: "A big issue was to moor equipment and to anchor equipment because we have tunnels in the water for cables, and we couldn't put any load on the foundation areas or on the abutments on both sides. That is why finally came up with this solution with the cantilever, an easy solution that is not over complicated."

Options involving lifting smaller sections piece by piece could have increased the risk of delays, as opposed to lifting large sections prefabricated off site. "Every technical issue we apply has to be in accordance with the principle of redundancy and simple replacement of equipment. Cantilever with hydraulics is a simple physical concept," adds Reismann.

The lifting plan has undergone a number of iterations over the last two years. Among the options considered was the placing of modular barges carrying SPMTs underneath the bridge. Also considered was removing the sections with SPMTs on provisional beams on the pier, but there were concerns about how this might impact on the foundations and the piles. A solution involving two lattice boom cranes on two barges, with the lifting capacity to lift the bridge section directly from its foundation onto a transport barge was also studied.

The eight-week rail closure is due to begin on midnight 23 June 2019. Another will take place in 2020 for the replacement of the north rail crossing ■

GIANT MAKES PORT DEBUT



A crane capable of lifting 5,000t made its heavy presence felt during a launch event in November at the Port of Ghent in Belgium. The SGC-250 crane is thought to be the largest crane in the world in size and capacity. The latest addition to the Sarens fleet has a maximum load moment of 250,000t, allowing it to lift a maximum weight of 5,000t, or 2,000t at 100m radius.

During the special launch event Sarens crew demonstrated its slewing and hoisting capability.

The SGC-250 has the same features and flexibility of a fully-mobile ring crane with winches and cables, hook blocks and the ability to slew 360°. Thanks to several wheel bogies on double ring beams and spreader mats, the SGC-250 never exceeds ground pressures of $25t/m^2$. The crane's main boom can be extended from 118m to 160m, and the jib can be extended up to 100m. This combination provides a height of about 250m.

The crane can operate on two hook blocks: one on the main boom and one on the jib, enabling it to quickly cover different parts of the construction site.

Sarens has invested in the crane's continuity with a full redundancy system on the hoisting and slewing system, achieved by connecting and steering all 12 engines with six power packs.

According to Carl Sarens, director technical solutions at Sarens, the crane has been developed to respond to an increasing trend towards modularisation. "Our clients now prefer to pre-assemble large portions, or modules, in a controlled environment and then transport and lift them into their final position," he said.

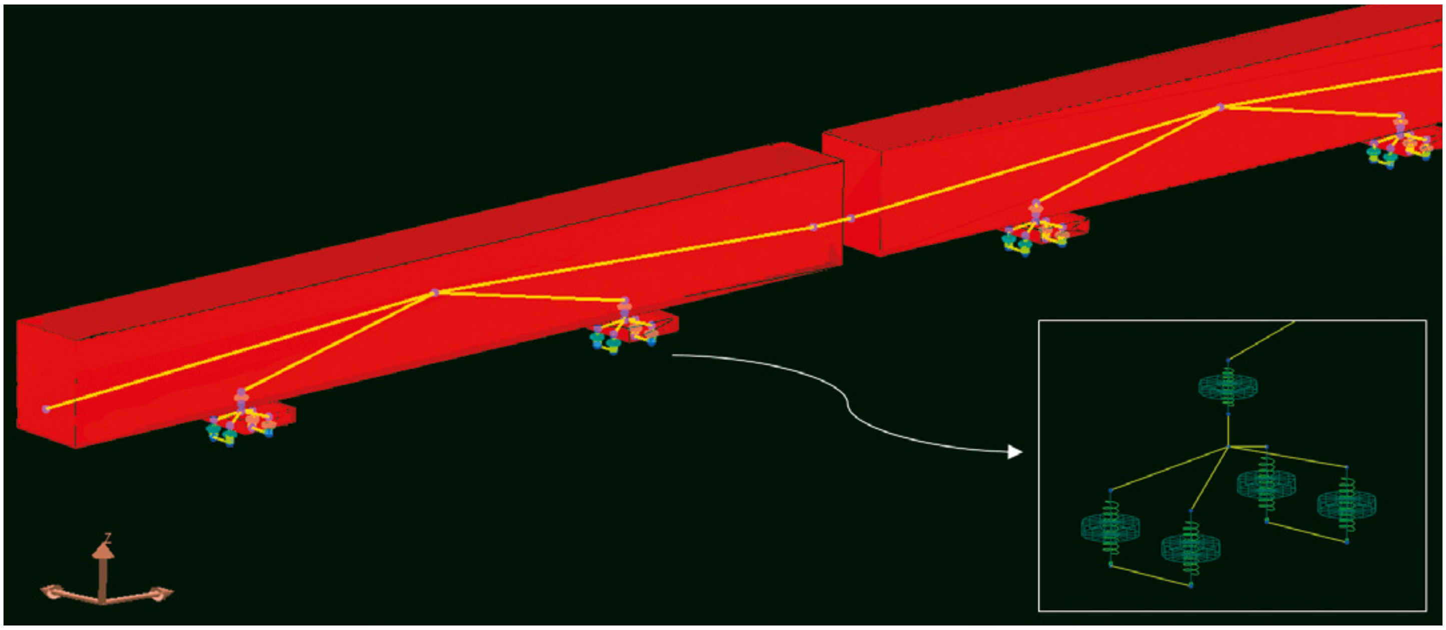
Sarens
www.sarens.com

JACKING FLEET EXPANSION

Lifting specialist ALE is expanding its fleet of jacking solutions in readiness for upcoming civil engineering projects throughout Europe. The lifting specialist is taking delivery of four new Mega Jack 300 towers at its UK branch, bringing the total amount of towers in its global fleet to 20. "We have secured several civil projects where this system is ideally suited; it will demonstrate the system's strength and capabilities to optimise project schedules," said Russ Jones, ALE director in the UK. According to ALE, there are a number of UK-based bridge projects planning to take up the new system in early 2019.

The Mega Jack 300 was launched in 2018 as a compact and versatile automated jacking system that enables site optimisation and project efficiency where space is restricted or congested.

ALE Heavylift
www.ale-heavylift.com



The train is modelled as a sequence of cars, each a multi-body system created from rigid bodies, springs and dashpots. The train is shown graphically in Larsa 4D

ON THE RIGHT TRACK

High-speed rail design takes a step forward with dynamic new methods for vehicle-track-structure-interaction analysis on curved bridge structures. Maria Fedorova, Mettupalayam Sivaselvan, and Joshua Tauberer explain

In the bridge engineering industry, academic research can drive the use of new construction methods, components, and materials, accelerating the translation of that research into new products that address modern challenges. A collaboration which began two decades ago is still bearing fruit today with the development of new technologies to support the delivery of high-speed rail bridge design.

A relationship between the University at of Buffalo's Multidisciplinary Center for Earthquake Engineering Research and Larsa was established 20 years ago when professors Michael Constantinou and Andrei Reinhorn formed a collaboration that would benefit both academia and the specialist engineering sector.

Early efforts of that relationship were integrated into Larsa 4D's inelastic and seismic element library; today the collaboration has evolved to support the delivery of state-of-the-art rail projects.

At high speeds, such as the 400km/h proposed for the new California high-speed rail project, resonance and coupling of the vehicle with the natural frequencies of the structure exacerbate structural demands. To quantify these design considerations, initial phases of the collaborative efforts resulted in the implementation of a new vehicle-track-structure-interaction analysis. First iterations were limited to two-dimensional vehicle, track, and linear elements, but proved that they were necessary for the design of high-speed rail structures. The latest version enables three-dimensional implementation of vehicle-track-structure-interaction analysis on curved high-speed bridge spans.

Traditionally railway bridges are designed based on static analyses with static loads multiplied by a dynamic magnification factor to account for the effect of train loads. However, Eurocode EN1991-2 clearly states that such a design approach is unable to predict the resonance effect from high-speed trains. Therefore, dynamic analysis with time-varying loading is required for many bridges supporting trains travelling at speeds of 200km/h and upwards.

High-speed rail has many operational restrictions that affect planning and design, including the requirement for tracks that are predominantly straight with shallow curves and without sudden changes in elevation. These restrictions explain the fact that, for example, about half the total length of high-speed railway lines in China consists of bridges and aerial structures, while in Spain some viaducts reach up to 3km in length.

According to the Eurocode, such analysis should be performed either using a high-speed load model, which consists of a series of moving vertical loads and represents an envelope for dynamic effects of multiple real trains, or by solving the train equations of motion simultaneously. The latter approach requires vehicle-track-structure-interaction analysis. Use of a high-speed load model is convenient in terms of designing a structure for a range of possible train types. This is especially important considering the requirements of interoperability in Europe, where high-speed trains travel across borders and need to be compatible with all the tracks and structures they use. At the same time, however, the validity of high-speed load modelling is limited, depending on the train weight and geometry. Another consideration for bridge design for high-speed trains is that for curved tracks, centrifugal forces must be included in the analysis, which complicates the use of high-speed and similar moving load models. Therefore, derivations of new load models may be necessary for those trains with non-standard geometric or mechanical parameters.

The USA has similar requirements for the design of high-speed rail bridges. According to the California High-Speed Train Project documentation, vehicle-track-structure-interaction analysis is required for final design if the structure does not meet the requirements of a simplified analysis, with train effects represented as moving loads. In this case, a dynamic train model must be built and must include the masses of wheelsets, bogies, and car bodies, as well as stiffness and damping of the suspension systems. Taking into account these considerations, Larsa is developing a VTSI analysis engine capable of performing dynamic analysis of high-speed rail bridges including interaction with train models.

Mathematically, vehicle-track-structure-interaction can be represented as a system of three sets of equations of motion — for the train, track, and bridge subsystems — coupled with one another. VTSI analysis calculates displacements, velocities and accelerations at various locations on both the bridge and the train, as well as contact forces between the wheels and the rails. These can then be checked to ensure compliance with design requirements. For example, vertical deck accelerations must be limited to guarantee traffic safety and avoid destabilisation of the ballast; passenger comfort is checked based on car body accelerations, and the track safety is verified based on the time-varying contact forces.

There are three main types of algorithms for solving such a mathematical model. The first type seeks to solve the three sets monolithically using specialised VTSI software. This approach cannot be easily implemented in existing structural analysis software since separate vehicle and bridge models have to be combined together. The second type solves the three sets of equations separately, relying on iterative procedures. While this approach is convenient, it might require significant computational resources since the convergence of the solution can be slow. The third type of VTSI analysis, which is implemented in Larsa 4D, is based on complementing the system of equations of motion with constraint conditions. This approach solves the equations of motion of the vehicle and bridge in separate modules and communicates the forces and motion at the interface between them. This leverages the bridge analysis capabilities of Larsa 4D in the VTSI context.

The bridge is modelled using standard structural or finite elements, such as beam and plate elements, box girders, cables; in fact any of the elements available in Larsa 4D. The train is modelled as a sequence of cars. Each car is represented as a multi-body system composed of rigid bodies, springs and dashpots. The train and the track are coupled together by means of kinematic constraints. In order to provide higher continuity in the interpolation of these constraints, non-uniform rational B-splines or 'nurbs' are used to construct the time-dependent influence matrix which corresponds to the positions of wheels on the rail. The rail is modelled as a 3D beam using an isogeometric approach, which employs the same interpolation functions, or nurbs, for both geometry and displacements. Such an approach offers two advantages. First, higher order continuity is achieved at the inter-element boundaries. This allows for a smooth transition when a wheel travels from one discrete rail element to the next. Second, in the case of a curved track, the longitudinal geometry of the track can be represented exactly; a curve generated by computer-aided design software can be included in the model to represent a rail.

The system of constrained equations of motion to be solved requires careful consideration of the time-integration scheme. As available research suggests, some amount of numerical damping is necessary to avoid spurious high-frequency numerical oscillations in the contact forces — Lagrange multipliers. Therefore, the generalised-method is employed to discretise equations of motion in time. This scheme provides accuracy at low frequency and the desired numerical damping at high frequency.

The crucial advantage of the algorithmic approach that was selected is its capability to incorporate into the analysis any bridge structure that can be modelled in Larsa 4D and any train based on Larsa's train template library. The library allows a user to specify geometric and mechanical parameters of the various wheels, bogies and car bodies used on the train. In a case where the type required is not in the library, a new type can be implemented on request from a user.

As high-speed rail systems expand around the world, a range of analysis and design alternatives are being developed. The vehicle-track-structure-interaction engine described above provides a convenient and universal platform for railway bridge analysis ■

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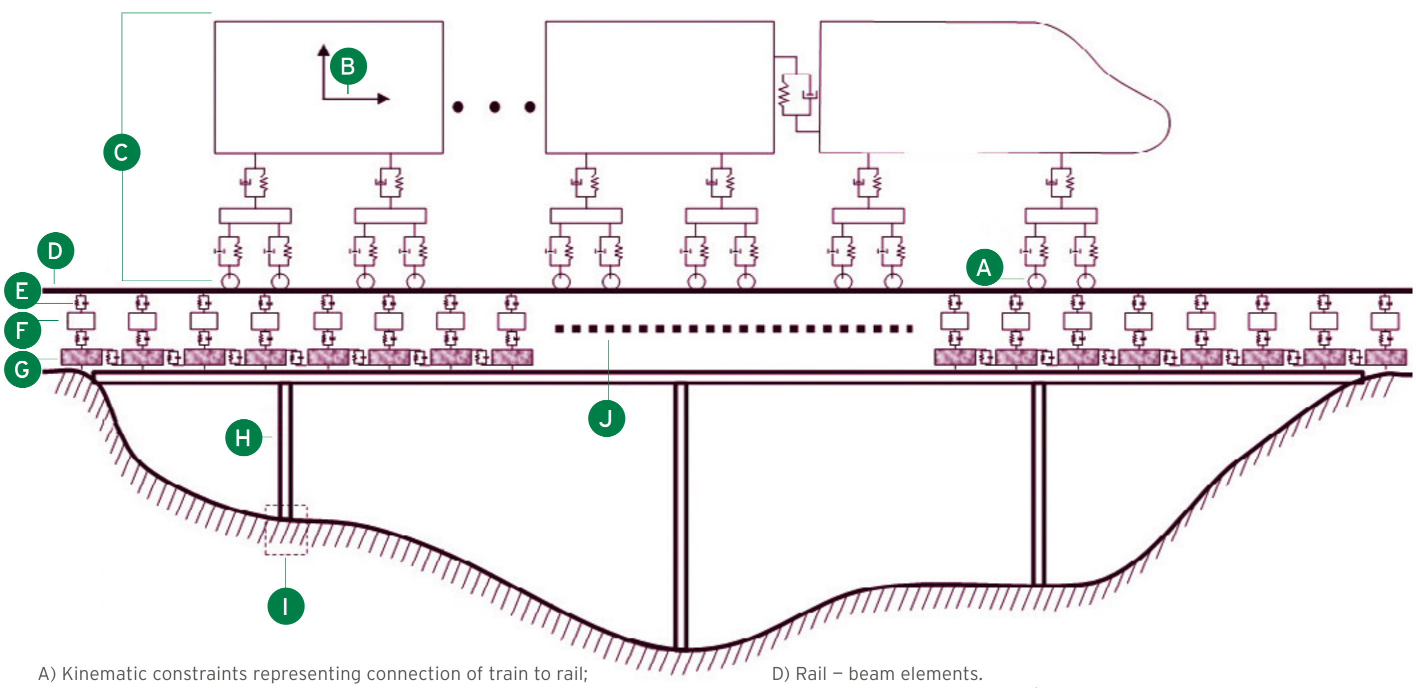

A) Kinematic constraints representing connection of train to rail; Lagrange multipliers are contact forces; inequality constraints to represent contact and separation; Hertzian/Kalkar contact models.
B) Car co-rotational frame – geometric non-linearity due to track curvature is accounted for by large displacements and rotations of, but small rotations within, this frame.
C) Train modelled by assembly of rigid bodies, and (possibly non-linear) springs and dashpots.
D) Rail – beam elements.
E) Rail pad – non-linear spring/dashpot elements.
F) Sleeper – rigid body or beam elements.
G) Ballast – non-linear spring/dashpot elements with additional mass.
H) Columns – beam elements.
I) Soil spring elements if necessary.
J) Deck – beam elements (possibly with box sections, plate girders etc), plate elements.

INTERIM COATING SOLUTION PINPOINTED

The linseed oil was still present in all structures a year later

Monitoring took place every three months

Two UK charities that manage nearly 2,000 bridges and structures in the country's 27,000km cycle network intend to use linseed oil to protect their wrought-iron and early steel bridges.

The decision by Sustrans and sister charity Railway Paths follows the publication of a new study suggesting that linseed oil could be an effective, low-cost, environmentally-friendly alternative coating for the protection of metallic structures, and in particular wrought-iron bridges, in the short to medium term.

The research carried out by Dave Gent, Paul Thomas and Max-Xavier Woof focussed on four wrought iron bridges and viaducts in Derbyshire, UK, owned by Railway Paths.

The paper highlights the fact that the cost of painting often becomes prohibitive due to issues arising from accessibility to all parts of the structure; the surrounding environment; and the complexity of the new paint protection system. As a result, the cleaning and repainting cycle is often not maintained, which results in a shortening of the structure's lifespan.

The paper also points out that unplanned repair works are often pushed back to the next funding period when budget can be allocated; a low-cost, short-term painted protection that can retard corrosion until a long-term solution is in place would be of significant benefit.

The researchers applied a single coat of linseed oil to the four structures and monitored them at three-month intervals over a 12-month period, recording the effects of the linseed oil.

The uncoated coins showed greater deterioration than those painted with linseed oil

In parallel, a number of small coin-sized samples of the metallic bridges were placed in an accelerated climate chamber, with regular sprays of heated salt water to mimic weathering over a number of years. The coins were coated with one, two or three layers of linseed oil to investigate if repeated painting improved the longevity of the protection.

During monitoring the team found that the linseed oil displaced the water from large and microscopic crevices, spreading out via capillary action whilst still liquid, before stiffening up over time to form a glossy coating over a larger area than that over which it had been originally applied.

On-site observations suggested that the oil performed better on structures that had not been substantially cleaned; the surface crevices caused by prior corrosion providing a roughened surface for the oil to seep into and increasing longevity.

The team also observed that when it rained, the oil initially followed the water into the nooks and crannies of the structure, displacing the water to provide further protection. Where linseed oil coated the brittle and flaky remains of historic paintwork, this became flexible and more firmly attached to the surface of the structure, suggesting that the oil could yield additional benefits in rejuvenating existing coatings.

In all instances, the linseed oil was still present on the structures a year later.

The accelerated testing demonstrated that the uncoated coins showed greater deterioration compared to the coins painted with linseed oil, and the researchers approximated the observed life span of the coating to three to five years in the real world.

Dave Gent, chief engineer at Bridgeway Consulting, said: "Although we do need to do more testing, this early study shows that linseed oil has great potential as a relatively cheap, environmentally-friendly alternative to the chemical-based paints that are generally used to maintain metal bridges. It is non-toxic and requires no cleaning of the metalwork before application, so the oil could be easily applied by most people and at most locations."

Sustrans asset manager Paul Thomas added: "This traditional method of metal protection doesn't pollute the environment, and could help save us money for other maintenance projects. As it requires no special skills it could even be carried out by our volunteers."

Sustrans now plans to use linseed oil for future maintenance work and the team will help promote the eco alternative to other bridge owners and conservation groups.

The report of the research - *An alternative corrosion protection for wrought-iron bridges* - was published in the Proceedings of the Institution of Civil Engineers *Engineering History and Heritage*, volume 141, issue 4.