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How ground support and logistics are key to delivering swifter TBM tunnel projects

Lining solutions for aggressive environments

Single-pass, double-pass, sacrificial thickness, HDPE, the options on the table for wastewater tunnel linings are numerous. Who has chosen what and why? asks Kristina Smith.

Water authorities face something of a conundrum when designing new wastewater tunnels. Public money must be spent wisely and spread as far as possible, but it must also be spent on infrastructure that will still be functioning in 100 years, 120 years, or even longer.

Crucial to the lifetime performance of a wastewater tunnel is how its lining holds up to decades of service. It must deal with erosion, abrasion and corrosion, the impacts of which change over time. Future scenarios – such as higher populations or lower flows due to water conservation – could change the picture again.

Decisions on optimum lining solutions for wastewater tunnels depend on several factors: climate, the composition of

sewage, gradients, flow rates, and dosing, among others. Local practices and the client's appetite for risk are strong influencers too.

Yet, even in a sector where authorities are understandably resistant to new materials and methods, new solutions are being put to the test. Following on from concrete expert Charles Allen's presentation at last year's British Tunnelling Society Conference on new approaches to sewer tunnel linings, we looked at a selection of wastewater tunnelling projects and asked how they determined the best lining solution for them.

Silicon Valley Clean Water – safe solution

Design-build contractor Barnard-Bessac JV with its designer Arup and client Silicon Valley Clean Water (SVCW) looked at ten

possible lining options for the lining of \$206m Gravity Pipeline Project. The new 5.3km long, 3.3m diameter pipeline will collect flows from surrounding areas and take it to a water treatment plant.

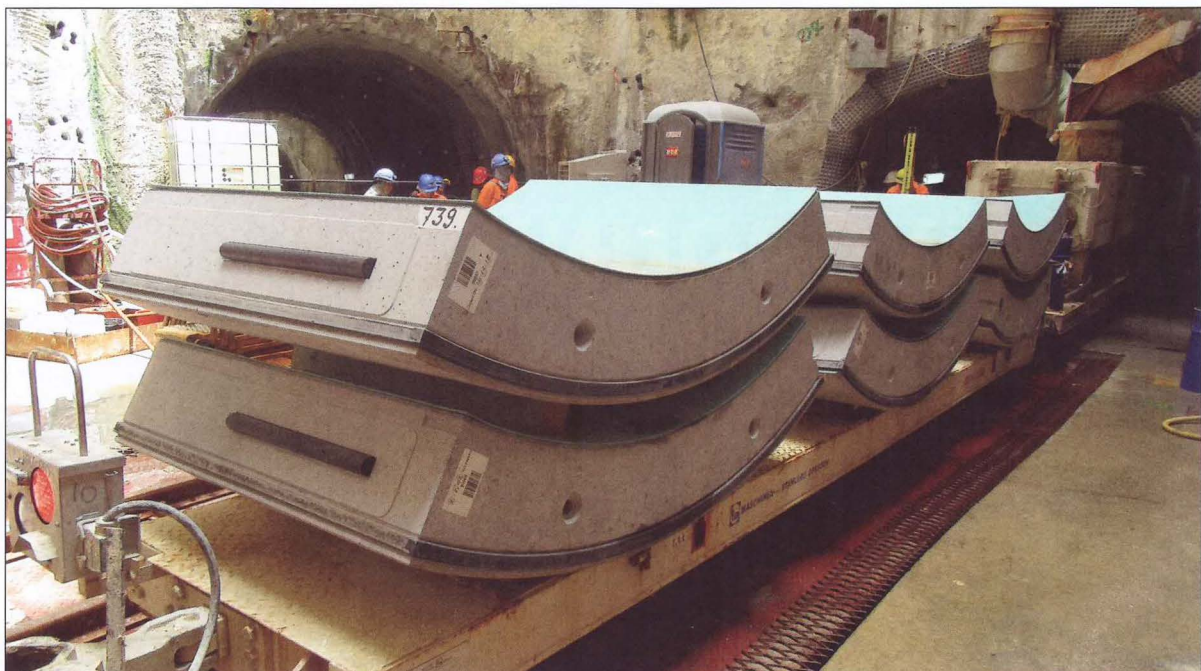
The project was procured using Progressive Design-Build to engage both the contractor and engineer early in the process and hence make the most of their know-how. From the ten lining options on the table, three were seriously considered: a traditional two-pass lining with the fibreglass reinforced polymer mortar pipe, tunnel segments with a cast-in HDPE lining, or concrete with high-alkali aggregate and an additional sacrificial thickness.

The last of those three options, involving limestone sand and aggregate and high concentrations of fly ash and pozzolan, did look attractive says Arup lead tunnel engineer Luis Piek, not least because it would have delivered millions in capital cost savings compared to the traditional two-pass system.

However, there were challenges.

Each of the three branches of the Doha South Sewer are coated in a different colour of HDPE to help track down any lining damage in the future.

Credit:
Kumar Gaurav Singh



SVCW has no control of the wastewater coming into its system which meant it would have had to monitor incoming effluent and employ automatic dosing. The risks were considered too high.

"The bare concrete solution, while technically feasible, would have required continuous monitoring and testing and tight controls of the dosage system from SVCW which did not make that solution viable for them," says Piek.

The project team also looked at casting HDPE liners into the segments, of which two solutions were considered: HDPE sheeting with field-welded seams, and Herrenknecht's Combisegment system which includes gaskets on the edge of the HDPE liners to avoid post-installation welding. However, there were concerns about the impact of the external water pressure potentially pushing against the HDPE liner.

"The HDPE sheet manufacturer provided a calculation table demonstrating an upper limit for sustained water pressure of 2.0 bar and we were just about at that level," says Piek. "We needed some form of pressure release under the lining to protect the plastic cleats from being pulled out of the concrete," says Piek.

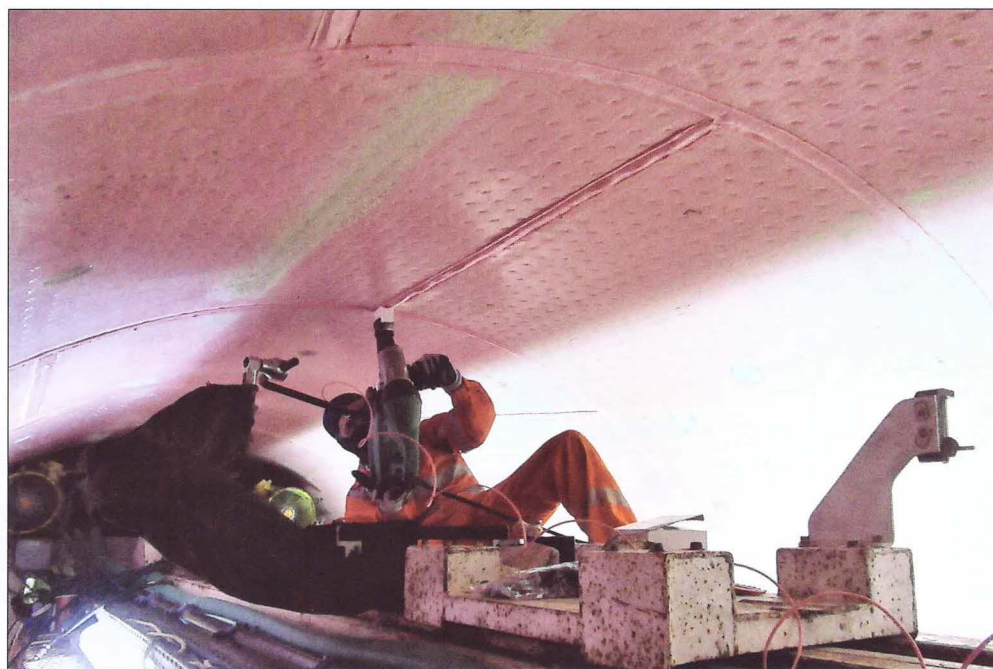
The field welded solution would allow this pressure relief by leaving some invert seams open, and Herrenknecht did propose a pressure-relief valve integrated into the lifting sockets in the segments, but the designers couldn't be sure that the valve wouldn't get clogged or impeded in some other way.

"In time the Combisegment application would have been feasible, but at the time of lining selection we just did not have that level of confidence that it would work correctly," says Piek.

So, eventually, the best method – largely down to risk profile – was the tried-and-tested two-pass system of a fiberglass pipe grouted inside a concrete tunnel lining.

Doha – proving HDPE Linings

If you want an example of aggressive wastewater, the Doha South Sewer Infrastructure Project (formerly IDRIS) is a good place to start. With wastewater



temperatures of around 30 degrees C, shallow gradients and turbulence in shafts during peak flows, the lining for this tunnel must be robust.

The 16km, deep tunnel sewer is divided into three sections – Eastern, Northern and Western – and will convey wastewater flows to the existing Doha South sewage treatment works.

The standard approach for the sewer would be to use a primary segmental lining and secondary cast-in-situ concrete lining. The secondary lining would have and HDPE or PVC lining cast into it.

At the preliminary design stage owner Ashghal and its programme management consultant Jacobs considered the traditional two-pass approach as well as polymer concrete segments. "The client had some previous experience of polymer concrete pipes," says Jacobs' design and quality lead in Doha, Anna Olliver.

However, there was not enough experience of using polymer concrete in segments, says Olliver, and there were concerns over manufacturing issues. There was also uncertainty over whether there would be enough capacity locally to supply them.

Though the project was tendered on the two-pass system, contractor Bouygues Travaux Publics and Urbacon Trading & Contracting Joint Venture (BUJV) came up with a one-pass solution that offered Ashghal significant

savings. Because of the time savings due to the omission of a secondary lining construction, the project could be completed using two TBMs rather than four in the same time period.

The first thought was to use Herrenknecht Combisegments, but tests required to prove the longevity of the gasket material on the segment liners could not be completed in time. BUJV's solution was to cast HDPE into the segments and weld the HDPE on site.

Checking for cracks beneath the HDPE was a challenge. Non-destructive testing did not give high enough resolution. However, the additional sacrificial thickness also provided a greater resistance to cracking.

"With this sacrificial concrete came extra redundancy," she says. "Full-scale testing showed that the segment could take 250 percent of the stress force that they were designed for which is quite remarkable." This could be due to the anchored HDPE making the segments stronger, says Olliver, although this is an area that requires additional research.

Examination of segments at junctions before removing them and testing of any damaged segments at the factory has also helped to reassure Jacobs and Ashghal that the segments are robust.

One of the operations which improved through the installation

Using a zero-g arm to support the welding gear left the operatives free to focus on the quality of the welds. A thin wire was embedded in each of the welds and spark tested afterwards to ensure water tightness.

Credit:
Kumar Gaurav Singh



of the three branches of the sewer was the welding process, says Olliver. Welders used zero-gravity arms to support the tools; they had around 250km of welds to carry out in two phases: the upper part of the tunnel immediately behind the TBM and the invert once everything was cleared out.

Each of the three branches has a different coloured HDPE lining: pink, yellow and blue. This will allow the location of any damage in the future to be narrowed down, explains Olliver. Holes in the lining made during construction were easily repaired by welding little patches on.

Olliver admits that she was sceptical about this one-pass method at the beginning of the project, but now she is positive: "I am really won over," she says. "From our experience with the two-pass lining, there can be challenges with the quality and with health and safety during installation. You keep finding defect after defect. I feel that we have saved the client a lot of problems in the future by doing it this way."

Auckland Central Interceptor – investigating MIC-resistant concrete

In planning the 13km-long Central Interceptor in Auckland, New Zealand, client Watercare decided to embark on a two-year research programme to find the right materials. Its aim was to specify a one-pass tunnel lining using a material that would be resistant to microbiological-induced corrosion (MIC).

Materials including Calcium Aluminate Cement (CAC) and geopolymers were tested and looked promising, but conclusive test results didn't arrive in time to specify this for the tunnel segments.

"Originally Watercare considered the use of an acid-resistant single-pass lining for the tunnel segments, but this approach was modified due to lack of track history with the materials proposed, and the timing of the laboratory verification with respect to the procurement deadlines," says Watercare's engineering manager for the Central Interceptor Project,

Stephen Grace.

Watercare's performance specification still calls for a single-pass segmental concrete lining, but one with an embedded HDPE liner, similar to those used in Doha. "In addition to schedule, cost and safety benefits, it is expected that this will result in a better-quality product due to the controlled conditions in a precast factory compared with placing concrete deep underground," says Grace, "though the potential for handling damage is increased and will need to be managed."

However, MIC-resistant, or acid-resistant, concrete has been specified for some of the shaft linings following test results that came in post-tender, says Grace. As well as subjecting the concrete to acid bath, biogenic and petrographic testing, Watercare has put concrete samples in high corrosion areas of the sewer networks.

"Biogenic testing culminated with destructive compressive strength testing to confirm the residual strength of the samples," says Grace. "This has given

On the Doha South Sewer Infrastructure Project contractor Bouygues Travaux Publics and Urbacon Trading & Contracting Joint Venture (BUJV) is using a one-pass solution of segments with HDPE cast into them, welded once in place.

Credit: Mark Marshall

Watercare confidence to specify the appropriate materials for each shaft." Risk assessments which look at likely corrosion rates and ease of access for maintenance have guided Watercare's decision-making on which shafts to use the MIC-resistant concrete in.

As for the tunnel segments, they will have an additional, sacrificial thickness, as in Doha. The northern section of the tunnel will have segments that are reinforced only with steel fibre, whereas the Southern section segments will have rebar in them too, says Grace, to cope with the ground conditions and the depth of cover under the harbour crossing.

Thames Tideway – segmental secondary lining

The Thames Tideway in London is a 25km-long tunnel which roughly follows the route of the Thames River and will collect the water flows that the city's Victorian system can no longer cope with. It is divided into three sections – East, Central and West – that roughly coincide with different geological conditions. The East and Central sections are investigating a novel steel fibre-reinforced concrete (SFRC) segmental solution for the secondary lining.

The other design, which is being pursued by the West contract, sees a cast-in-situ secondary SFRC lining, with crack width control capacity and load-sharing between the two linings. The alternative design approach requires the segmental secondary lining to sustain the internal pressure and the primary segmental lining to provide

confinement during surge events and take 100 percent of the hydrostatic and ground loads.

The potential benefits of the secondary segmental lining system compared to the conventional method would be to reduce cost, improve the construction schedule, reduce environmental impacts and reduce rework, according to Matt Jones, director of water, ports and power at Aecom, writing in Water Projects Online at the end of last year. Currently work is underway to trial the process with an erector built by Herrenknecht.

Aecom, working for JV contractor Ferrovial Laing O'Rourke (FLO) on the Central section has devised a construction sequence which allows the connection of the side tunnels and the main tunnel without propping internally. This method, a version of which was first used on the Victoria Station Upgrade project for London Underground would allow the secondary lining works to progress unhindered, delivering programme improvements.

DTSS Phase II - Belt and Braces

Singapore's national water agency, PUB, is taking no chances on the design of the tunnel lining for DTSS Phase II, a deep, 50km-long gravity-fed wastewater tunnel. The primary lining will be a standard segmental lining, while the secondary will be made of MIC-resistant concrete with a HDPE lining cast into it. Allen calls this a "belt-and-braces" approach.

Each of the contractors working on the five design-build contracts that make up DTSS II must now

come up with a concrete for the secondary lining that meets the specification. This is no mean feat, says Allen who is working with designer Arup for Penta-Ocean/Koh Brothers JV on contract T-08 of the programme.

"All contractors are having to embark upon large R&D programs for this," he says. "No concrete is completely MIC resistant. The sulphuric acid arising from the anaerobic conversion of sulphides in the sewage has a pH of the order 1.0. No Portland Cement-based concrete can resist this."

Contractors are likely to be testing various blends of OPC, PFA, GGBFS, silica fume, limestone powder and metakaolin in their mixes, together with CAC and geopolymer concretes.

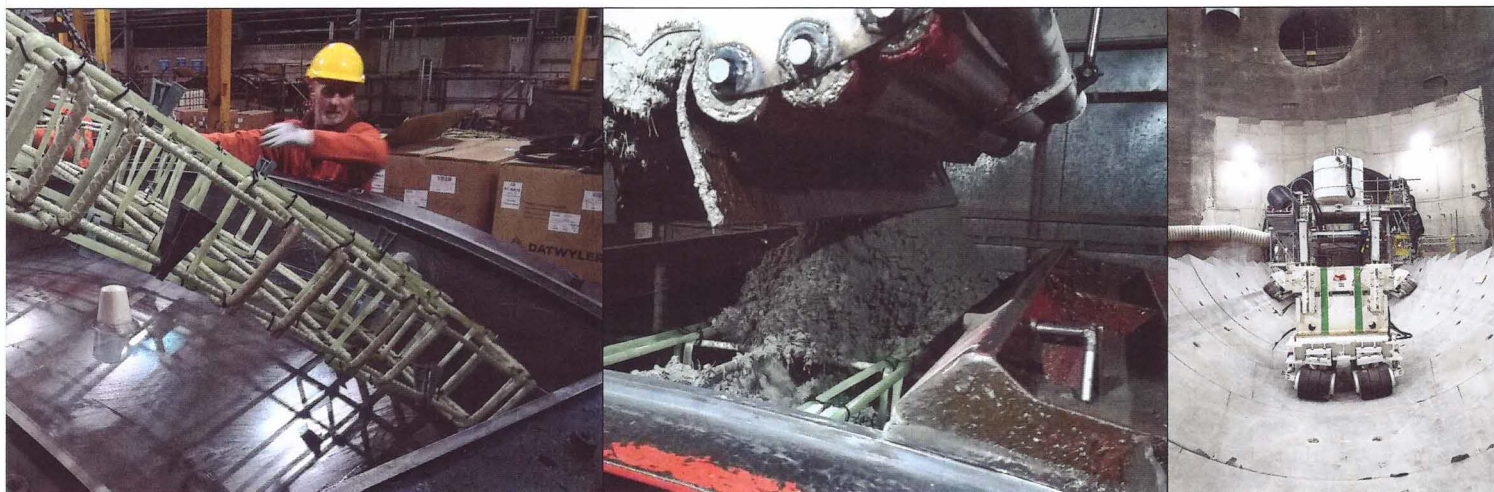
"In simple terms, the best way to reduce biogenic corrosion is to reduce the calcium contents of the concrete," says Allen. "CAC concrete and geopolymer concrete are showing the best MIC resistance in the one-year test results from Watercare for the Auckland Central Interceptor Tunnel."

One of the biggest challenges is that no standards exist for biogenic corrosion, says Allen. Only three laboratories have developed biogenic corrosion tests: KIWA and Fraunhofer Institute in Germany and the Advanced Water Management Centre at the University of Queensland.

The future: one-pass segmental linings?

If materials technology were to deliver a failsafe MIC-resistant concrete, one-pass segmental linings for wastewater tunnels

The Thames Tideway (West) tunnel segments casting and installation on the job site



would offer a raft of benefits. Programmes could be shorter, the Carbon footprint smaller and the capital cost lower.

Sotiris Psomas, senior technical director at Cowi, who has worked on the design of the Lee Tunnel and the Tideway Tunnel believes that in the UK a single lining of high-quality SFRC could already meet the design life. "Although having a secondary lining provides some additional redundancy from a durability point of view, I believe – and other people believe – that we would be able to achieve the design life and the required performance requirements with a single one-pass lining," he says.

The simplest way to add redundancy into a single-pass segmental lining would be to increase the thickness to accommodate section loss due to abrasion or corrosion. It would also require the segmental ring to be installed to tight tolerances with an assured method of tailskin grouting. This approach was proposed as an alternative design on a large infrastructure project recently, says Psomas, but at the time was rejected as more work would have been needed to justify it as a workable solution.

There's also an argument to say that the final product could be of higher quality with single-pass. Piek makes the point that where a secondary lining of any sort is installed, it is at the end of a project when a contractor may be low on budget and low on supervision:

"The pipe install might be done by the general contractor or a sub, but in almost all cases the backfill grouting operations will be subbed out. These are fixed-price, production-oriented people who at the end of the job are trusted with arguably the most important aspect of the project."

One of the positive aspects of the Doha project was that the final product was there, visible early in the project, says Olliver. "Once you have removed the TBM and utilities, that is the tunnel, the final product. This was definitely positive in terms of workflow for the contractor but also for the client, we could show them that this is what the tunnel would look like."

Geopolymer concrete looks like a good option for a single-pass lining but it has yet to be used in tunnel segments, though it has been used in shafts and manholes. Some projects are considering this option, reports Richard Cubeta, MD of SolidCast Polymer Technology, who hopes to have more news within the next 18 months.

A brand-new solution which could make the long-term durability of single-pass linings more durable is the use of alternative reinforcement. Manufacturer ATP Construction Composites has been working

on the developments of a hybrid segment reinforced with Glass Fibre Reinforced Plastic (GFRP) bars and steel fibres (see box), some of which are being installed as a trial at Tideway West.

Though tried-and-tested is sometimes the best option, some wastewater projects are driving change and innovation in lining systems and technologies. In-built monitoring and remote monitoring using remotely-operated vehicles or even robots will shed more light on how linings are performing. And that will allow further changes and advances to be made.

Sewage tunnel corrosion – how does that work?

What causes corrosion of concrete sewer pipes?

They are corroded by acids produced in the wastewater from chemical and microbial processes. Microbial induced corrosion (MIC) is the main villain.

How is the acid produced?

Anaerobic sulphate bacteria which live in the biofilm layers on the submerged sewer walls combine organic matter and sulphates to make hydrogen sulphide and carbon dioxide.

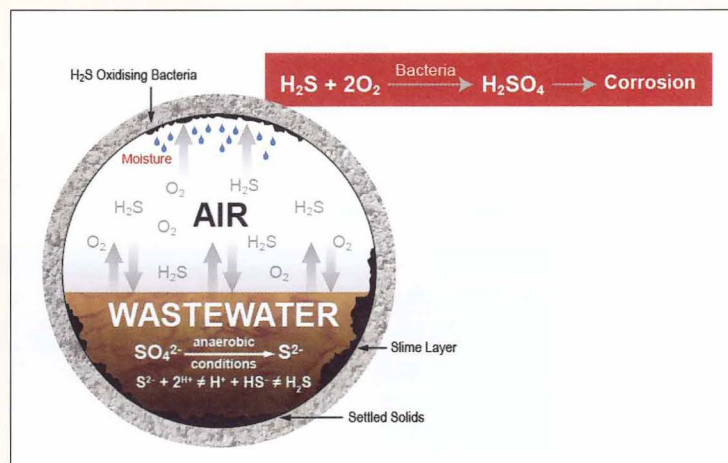
Some of the hydrogen sulphide makes it out of the biofilm and the wastewater to the air above the wastewater. It then dissolves in moisture on the inside of the exposed part of the tunnel to form sulphuric acid.

Does corrosion take place at a steady rate?

No. At first the surface of the concrete will be too alkaline for bacterial or fungal colonisation. They only start living on the surface once chemical corrosion has lowered the pH of the concrete. Loss of concrete only occurs once the surface reaches a pH of around 6.

What impacts on the rate of corrosion?

Higher concentrations of hydrogen sulphide in the headspace, higher temperatures in the air in the headspace and more moisture on the exposed tunnel walls all increase the rates of corrosion.



New hybrid promises smaller crack widths

On the West section of London's Tideway tunnel, a brand-new type of hybrid tunnel segment will be under trial: one that is reinforced with a combination of steel fibres and glass fibre reinforced plastic (GFRP) rods.

Full-scale tests carried out by Professor Alberto Meda at the University of Rome Tor Vergata have already shown that segments reinforced with high-strength steel fibres and GFRP experience significantly smaller cracks when subjected to bending moments and thrust forces.

In bending tests, on metro tunnel-sized segments, the SFRC-GFRP segments reached a peak load 63 percent higher than the SFRC ones and the crack widths for the hybrid version were 60 percent narrower than the fibre-only ones. For point-load tests, crack widths were reduced by 37.5 percent under a load equivalent to the TBM shove load.

In a paper given to the Joint ACI-fib-RILEM International Workshop, Meda comments that these hybrid segments could be useful in situations where bending moments are higher. This could be at cross-passage locations or where cover is shallow.

Professor Colin Eddie, managing director at CECL-Global and a consultant to fibre manufacturer Bekaert Maccaferri, believes that the hybrid solution could help counter the biggest threat to the long-term serviceability of tunnels: cracking due to the TBM thrust force.

A study carried out by a major infrastructure programme revealed that the average rate of damage on any segmental lining tunnel is that one segment will be cracked every six rings, says Eddie. "They are cracked 99% of the time during shoving, the transient load case," he says. "Often, it's the rings on the outside of the curve that are damaged."

Even a small lip of 1mm between segments can cause

uneven forces and hence cracking, says Eddie. Cracks close up once the thrust force is removed and the rings are acting in compression, but the bigger the crack, the less it closes up.

"Putting steel bar into underground structures is bonkers because if there are any cracks, it's difficult to demonstrate any design life," says Eddie. "Instead, we can put GFRP in the zone where it's doing the most work, that is in the perimeter of the gauge."

Meda's research was sponsored by GFRP rod manufacturer ATP Construction Composites and Bekaert Maccaferri. ATP has been making composite products for tunnelling for 30 years and its GFRP bars already go into many soft eyes. A patented technological breakthrough – the ability to manufacture a hook or stirrup in one piece – is what enables the segments to withstand high bending moments.

Prior to the hybrid tests, ATP had already carried out comparative testing between steel bar reinforcement and GFRP with the help of European funding. Broadly, these tests showed that the GFRP performed similarly to steel – exhibiting measurable ductility – but cracked at lower ultimate loads. It is the combination with steel fibres, specifically Bekaert Dramix 4D 80/60BG which show strain-hardening behaviour and

crack width control, that has turned this technology into a really promising one, says ATP's general manager Nello Giamundo.

Hybrid segments will be used on the West contract for the Tideway wastewater tunnel in London, albeit in a temporary situation. Around 80 rings will be used at the launch and at junctions with side tunnels.

One factor blocking the uptake of the hybrid fibre and GFRP technology is the lack of codes. In the UK CIRIA has recently published a guide, but this is more relevant to structural applications such as bridges, with factors of safety for permanent rather than temporary (shove force) loads.

"The important thing now is to work on some standards," says Giamundo. "We have already developed a guideline, but that is just a start."

Meanwhile, design assisted by testing is permitted in Europe, says Eddie, under EN 1990: "We would argue that the tests that have already been done are a starting point. The performance of these materials is quite predictable."

ATP is also undertaking fire tests. The SFRC-GFRP material looks promising when looking at the fire loading required for rail and metro tunnels. The next step will be to carry out tests for the more onerous performance demanded for road tunnels.

Using a hybrid of high-strength steel fibres and glass fibre-reinforced plastic rods to reinforce tunnel segments leads to better crack control than using steel fibre reinforced concrete only

