VMT's 3-D laser tracker system is used to check segments are within tolerance

State of the art segments: Lining the Lee Tunnel

Precast segment manufacture for London's deepest ever tunnel, Thames Water's 6.8km long, 7.8m diameter, Lee Tunnel sewer project, is now up to full speed. Amanda Foley recently visited Morgan Sindall's production facility, at Ridham Dock, in Kent, to find out more about this state-of-the-art tunnel lining

SINCE BAZALGETTE'S revolutionary sewer network was built in the 1800s London's population has quadrupled. The system now operates at double its designed capacity and struggles to cope if as little as 2mm of rainfall occurs. This means that every year around 39 million tonnes of untreated sewage is discharged, via 57 combined sewer overflows (CSOs), into the Lee and Thames rivers. These overflows have a substantial impact on river ecology and pose a significant health risk to those living and working on the rivers.

Tideway and the Lee Tunnel

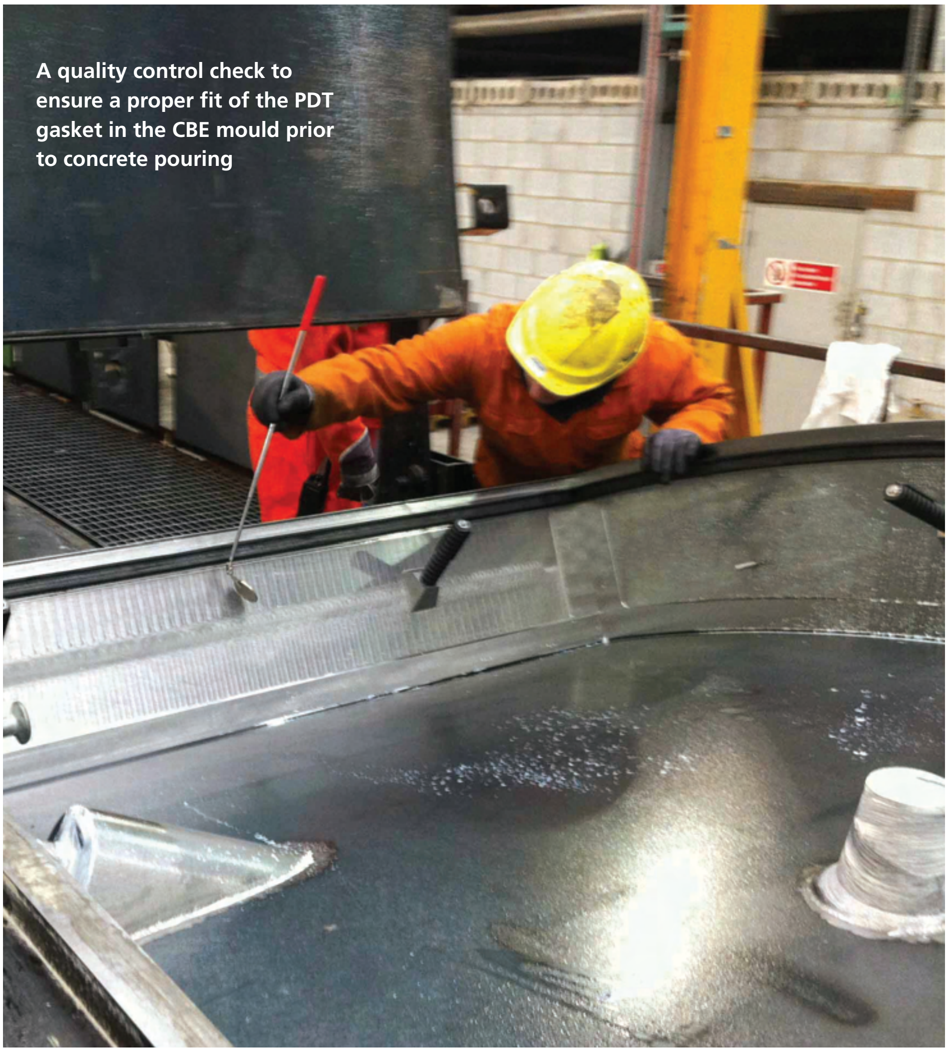
In order to combat the problem, the US$1bn (£635M) Lee Tunnel is the first of two major tunnel projects being undertaken by client Thames Water as part of the Thames Tideway scheme, which also includes the US$5.9bn (£3.6bn) Thames Tunnel. Once completed, in 2014, the Lee Tunnel will divert CSOs away from London's largest outfall at Abbey Mills, in Stratford, and convey them to the upgraded Beckton Sewage Works for treatment. This will eliminate 40% of the current overflows into the Thames via its tributary the River Lee.

Morgan Sindall/VINCI Construction Grands Projets/Bachy Soletanche (MVB) Joint Venture was awarded the US$652M (£400M) design-build contract for the tunnel and its four associated large diameter shafts in January 2010. Come early next year, the JV will launch an 8.8m diameter Herrenknecht Mixshield from the 82m deep Beckton Drive Shaft on a 6.8km westward drive to a reception shaft located at the Abbey Mills pumping station.

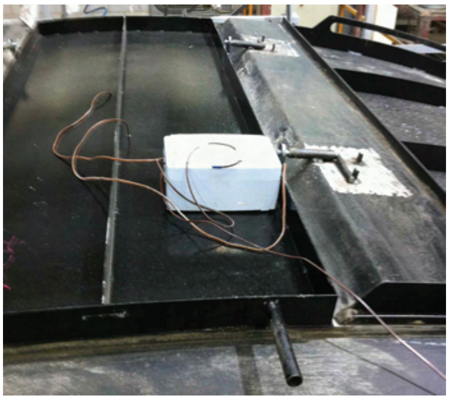
Design-build proposals for the project were based on a preliminary design completed by Aecom and specifications drawn up on behalf of Thames Water by Tideway's Programme Manager, the CH2M Hill-Halcrow partnership.

Running at depths of up to 75m, within the Upper Chalk aquifer, the Lee Tunnel will be London's deepest to date and a principle challenge on the project will be dealing with anticipated water pressures of up to 8 bar. Taking into account the loadings, pressure and long-term durability requirements that will be placed on the tunnel during its life, one of the UK's most state-of-the-art precast segmental linings has been specified for the project.

Designed by MVB's engineer, Morgan Sindall Underground Professional Services (UnPS), the 1.7m wide, 350mm thick, seven segment + key universal tapered ring is currently under production at Morgan Sindall's permanent precast factory, at Ridham Dock, in Kent. A number of emerging technologies – such as steel fibre reinforcement, cast-in EPDM gaskets, 3D laser checking of cast segments



A quality control check to ensure a proper fit of the PDT gasket in the CBE mould prior to concrete pouring



The START (STrength Assessment in Real Time) maturity monitoring system

for quality control and a unique maturity monitoring system – have all been brought together for the first time during segment fabrication for this project. Although the factory's two year long, 32,500 segment, manufacturing run has only just got up to full speed, the results are promising and set to take the production of precast tunnel linings another step forward in the UK.

Casting excellence

For the well-established Ridham Precast factory – which has been has been turning out high-quality tunnel lining segments since it opened 10-years ago – one of the most unique things about the Lee segment design is the adoption of cast-in gaskets. "It's a big step in the right direction as far as we're concerned," says Mick Town, Manager of Ridham Precast. "It gives us a far better quality fit of gasket."

Having gone from a bit of glue and a bit of hope, to securely anchored gaskets that sit perfectly square at the corners, the superior quality of the overall unit is visually apparent. The elimination of gluing also reduces labour and removes solvents from the factory, which improves the working environment. "The glue isn't a major health hazard, but there's always that lingering smell in the factory, which isn't good, and it's a dirty job as well," says Town.

"There's also the fact you don't have to re-work the gaskets," says Ridham's Engineering Manager, Dave Hicks. "With glued gaskets you always run the risk that the glue will delaminate if they're stored for a long time. Then you have to re-work them before they can go out. With cast-in gaskets that issue is eliminated completely, which is a big plus."

The idea of cast-in tunnel gaskets has been around for some time, but was brought on by seal specialist Phoenix Dichtungstechnik (now known as PDT). "We saw what they had done with Ceresola moulds in Moscow," says Town. "It was only a very short tunnel, but it looked like a great idea. So we got PDT talking to CBE our regular mould supplier and between them they devised the system here, which is great."

"The interesting thing is, when I was in Switzerland running the CUC training school, we did a course in segment production and we demonstrated with a Ceresola mould, a Phoenix cast-in gasket and steel fibre self-compacting concrete," says Charles Allen, a consultant working alongside Programme Management partner CH2MHill. "That was 10 years ago and it's taken that long for cast-in gaskets to take off. This will be the longest tunnel in the world to use the system."

There isn't a great deal in cost difference between the two systems, as cast-in gaskets are slightly more expensive than traditional

Lee's segments employ 30kg/m^3 of Dramix steel fibre reinforcement

gaskets, but this is offset against reduced labour costs. "It's the quality of the unit which is the major difference though," says Town. "So far it's looking very, very, promising."

Ridham is using 40 CBE moulds, on one of its two fully PLC-automated carousels, to produce an average of 60 segments (or 7.5 rings) per day for the Lee Tunnel, which is the maximum physically possible on a single shift. Following mould cleaning and placement of inserts, the custom PDT gaskets are push fitted into the mould's gasket slots and given a final quality check prior to concrete pouring. Grade

C50/60 concrete, with granite aggregates and 30kg/m^3 of Dramix steel fibre, is volumetrically poured into the moulds and hand finished prior to being placed in the curing tunnel.

The segments are de-moulded after about five hours curing, at a minimum strength of 11MPa, therefore an early concern was that the gaskets would get pulled out of the young concrete whilst opening the moulds.

However, PDT and CBE got together and examined the retention force required for the gasket. "It's a bit of a trade off," explains Hicks, "the gasket has to fit in easily, as we're working so quickly, but it also has to withstand pouring, vibration and stripping from the mould." Trials paid off however and this hasn't been an issue at all. "It is a little more difficult to clean the mould than it would be if you had a normal gasket groove, because it's more of a compact shape," says Town. "But the benefits far outweigh that as far as we're concerned."

Superior durability

Lee will be the largest diameter tunnel in the UK to use steel fibre reinforcement to date, but this is nothing new for Ridham Precast. They have been working with fibres for over 10 years, since the factory was first set up to produce segments for Heathrow's Terminal 5 tunnels. The benefits of using steel fibres are significant, resulting in reduced manufacturing costs, improved durability and crack resistance, and less damage during handling. "When it comes to cost, durability and handling, fibres win hands-down," says Town. Fibres also represent a significant reduction in the overall amount of steel used on the project. Traditional rebar reinforced segments will typically incorporate anywhere between 80kg to 120kg of steel rebar, whereas an equivalent steel fibre segment is likely to contain 30kg to 35kg of steel. There is also labour to consider. "We need at least two or three men on the

production line if we're fitting cages and then there's an additional QC process," says Hicks. "With steel fibres you just fill the hopper and you're done for the day."

The Lee Tunnel's segments were designed utilising UnPS's extensive experience in steel fibre reinforced concrete linings (reaching back to the Heathrow Baggage Tunnel in 1994), however due to the lack of design codes for steel fibre reinforcement, the design was validated by full scale physical modelling at the Building Research Establishment, in Watford.

Although not a major risk, fires have been known to occur in tunnels under construction. Therefore, in addition to 30kg/m^3 of Dramix steel fibres, Lee's segments also incorporate 1kg/m^3 of Adfil polypropylene fibres to mitigate against spalling in case of fire.

Systematic checking

Another first for the UK is the requirement that Lee's segments be checked daily using a 3D laser tracker system. "The VMT system was a major investment for us," says Hicks. "But we can see the benefits." Up until now, Ridham has always manually checked its moulds by micrometer, now instead they are checking segments using the laser tracker. "Because you're checking the end product, rather than what's producing the end product, it's a much better QC approach in my view," says Hicks.

With a trapezoidal tapered segment, for example, it is virtually impossible to manually check the tolerance of a segment, as there are no straight reference faces to work from. "You're starting with nothing. But a 3D system doesn't care, it's got a 3D model, it knows what the shape the segment should be and it compares what it sees against the model and tells you whether its good or not," says Hicks.

Checking segments also means production isn't affected as it was before. "If a segment is beginning to go out of tolerance, there are trigger levels built into the laser tracker system's software," says Allen. "As soon as those trigger levels are reached, you pull the mould off the line and reset it – or re-engineer it if necessary – then check it again and put it back on the line. So it's far less disruptive."

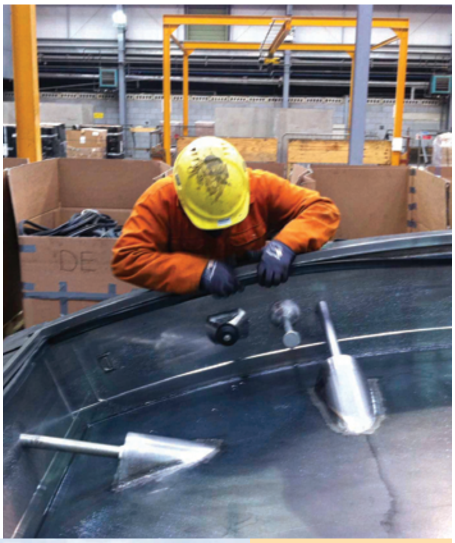
"With everything being done off-line, we can also check a lot more regularly, so the risk to us as a manufacturer is lot less," explains Hicks. "If one segment is out of tolerance, everything has to be quarantined and re-checked back to the last known in-tolerance segment. Previously we were checking moulds every 100 uses, which meant 100 segments would have to be quarantined. Now we are checking daily, our quarantine exposure risk has almost been halved, to 60 segments."

The learning curve for the laser tracker system has been relatively short and Ridham partly puts this down to the training received from VMT. "The laser tracker checking is a lot quicker to use than we thought it was going to be, significantly quicker than manual checking," says Hicks. The level of precision skill required is also less. "I don't want to dumb down what the guys are doing now, because there's a lot of computer manipulation required to operate the laser tracker system, but the skill needed for manual measuring is gone," explains Hicks. "We've produced 50 rings now and, although we certainly haven't laser checked every segment, the guys are very capable now."

Prior to shipping, the Lee moulds were laser

The Lee Tunnel's segment moulds are opened following five hours in the curing tunnel. Early concerns that the segment's cast-in gaskets would be pulled from the young concrete, rather than mould, have proved unfounded

tracker checked by the manufacturer, normally these moulds would have been checked again manually when they arrived at the factory. "This time we used the laser tracker to check the moulds, which actually highlighted some anomalies we wouldn't have seen otherwise," says Hicks. "Some of the moulds had acquired a very slight twist, which is almost impossible to see if you're checking mechanically, but very easy to see when you're checking with a 3D model. So we had to shim the corners of the moulds to make sure we were taking the torsion out. It wouldn't have been a major issue for the ring build, but it would have meant the rings wouldn't have been perfectly straight. Now we can assure they are."



Above: PDT's gaskets are a push fit into the gasket recess of the CBE moulds

Left: The yard at the Ridham Precast facility begins to fill up with stacks of rings for the Lee Tunnel

Quality procedures

Every segment that is produced at Ridham Precast is assigned a unique reference identification code by the factory's automated control system. This code can be used to identify all the specific components contained within each segment, as well as detailed information on vibration and curing.

"The fact that it's a stuck on label with a barcode is just an easy way of automating the scanning process," says Hicks. "Everything is linked back to our main production database, along with all the references and information held about each segment, which gives us complete traceability." This also means that once the segments are in the tunnel, the same barcode can be scanned at the point of installation and used to build a 3D model of where every segment is, which is what is being planned on Lee. "It's not expensive to run and it's a good system," says Town.

Ridham uses Radio Frequency Identification (RFID) for tracking pallets around its carousel. "So we know what pallet is where and what mould is on there, what concrete is required and various other data," explains Hicks.

There has been talk on other projects around the world of using RFID for traceability within segments. However, Hicks explains this technology is incompatible with steel fibre reinforced concrete. This is due to the fact that RFID needs a non-metallic path between the transmitter and the receiver, so if you have steel fibres in or around an RFID tag they act like a Faraday cage and the radio signal can't get through. "If you can't communicate with the tag, then it's just a bit of plastic," says Hicks. "I don't think people have physically thought through how they're going to do it. Even using a rebar cage you would need a minimum 50mm standoff, otherwise the steel is going to affect the signal."

By contrast, Ridham's barcode system provides simple, well-understood, robust technology. "Even iPhones have got a barcode scanner application, so you could operate the system with a phone if you wanted to," says Hicks.

Maturity Monitoring System

The START (STrength Assessment in Real Time) maturity monitoring system, developed by OtB Concrete, is being used for the first time in precast segment production on this project. "By casting thermocouples into segments, the time/temperature profile that the concrete is receiving can be monitored and recorded by the system," explains Hicks. From this accurate strength gain predictions can be made, which will be used for de-moulding control, to make sure the segments are up to strength prior to de-moulding. "It's in the very early stages, as we've only just started using it, but the theory is all very good," says Town.

There are a number of benefits to the START system. First of all, the project has a specified maximum curing temperature of 60°C, "so we have to show that we're not exceeding that," says Hicks. "We're also looking to achieve a minimum in-situ strength of 11MPa before we can de-mould safely. If we can achieve that minimum strength when the weather is warmer by putting less energy into our curing tunnel that saves us money."

Historically, this has been done based on experience, rather than science. "If it's 20°C outside, then we know we can reduce the curing tunnel temperature by 5°C," explains Hicks. "If it goes up to 25°C we might be able to knock a couple more degrees off. So we're hoping that this system will give us a real time analysis of our curing process and allow us to adjust our curing temperatures accordingly on a more frequent basis."

Hopefully, in the long-term this will provide significant savings in energy, particularly in the summer months, producing a more sustainable product via reduced CO_2 emissions.. "Over the last few years, we've been actively looking at how we can reduce our energy usage – looking at admixtures and lots of other things – this is another way of employing technology to reduce costs. It's only when you ramp up to full production that this comes into it's own and we have to have enough data to be sure what we're predicting is what we're getting. But the potential is very good," says Hicks.

It is difficult to know what the savings for Ridham might be at present, but with the price of diesel in the UK being what it is and likely to go up even further, fuel cost is becoming an increasingly important issue for the factory. "Energy use is a very significant overhead within our production and a large percentage of that is the diesel required to generate steam for the curing tunnel," says Hicks. "It's also not a linear relationship. A relatively small change in temperature in the curing tunnel results in something between a square and a cube relationship to the amount of diesel we're using. So if we change the temperature by 2%, we can make 5-8% savings in fuel. So the potential is large."

The system won't affect curing times as such, but then production quantities are not limited by time anyway. "We physically can't really move segments around our carousel any quicker than we are at present," says Town. This is obvious as soon as you walk into the factory, where Ridham's production team are working flat out, particularly on the finishing stations, just to get the segments completed in 10-minute cycles. "They'll get it down to about 8 minutes in the next few weeks, but that's the limit," says Town.