CATALAN CUNNING

Some very small steel fibres have had a massive impact on the construction of Barcelona metro's new Line 9. **Alexandra Wynne** reports.

Barcelona is crying out for a new metro line. For a start, access to this cosmopolitan European hub's airport is awkward with infrequent trains.

Much worse is the daily grind faced by the city's inhabitants trying to get around – very few journeys can bypass the congestion as existing metro lines bring traffic from the suburbs straight to the city centre.

The new Line 9 will help to solve all this. Acting as a cross city express, the 48km route will span the width of the city and include spurs at each end – all to help maximise interchanges with existing metro lines, the airport and the high-speed railway.

The project is the largest ever carried out by the Catalonian government, with funding supplemented by national and European banks.

When the line is complete, double deck, driverless trains are expected to carry around 1M passengers a year across the city.

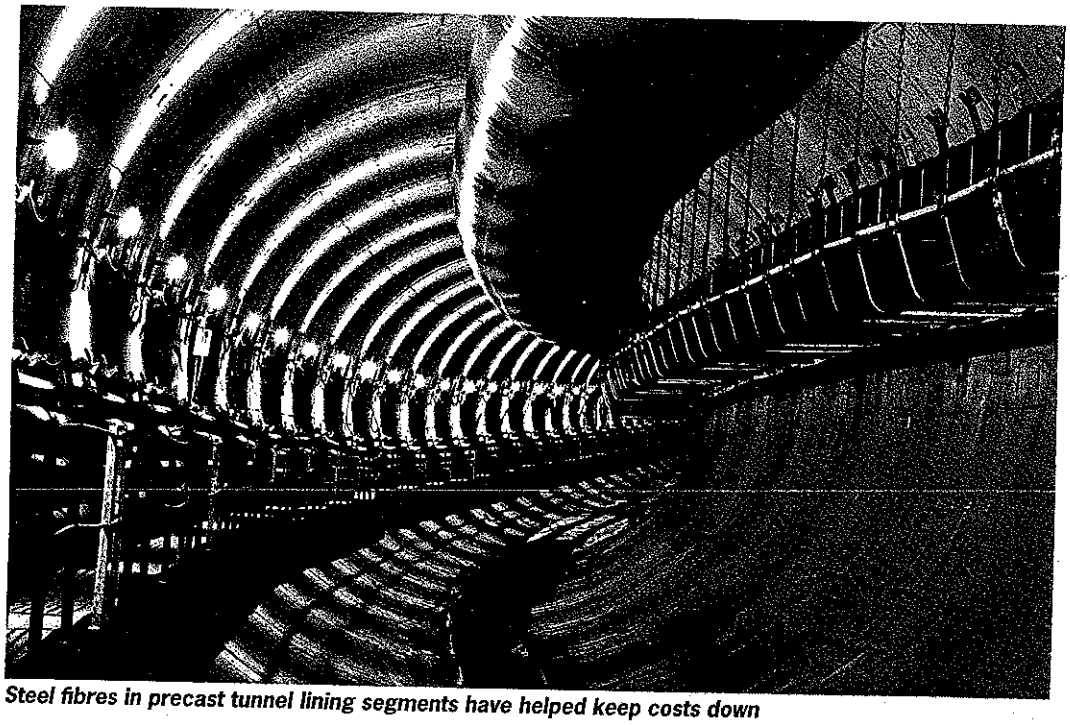
A massive 42km of the route is in tunnel – and a deep tunnel at that. Original plans meant the depth would range from around 35m to 60m. But a tunnel collapse during construction of the metro's Line 5 around six years ago created unease about Line 9, which was already under way, leading to the decision to deepen the tunnel in that area to 90m.

It is not just the scope that has changed. Costs early on were put at around €1.75bn, but latest estimates suggest that the final figure will be closer to €6.5bn.

Part of the reason for the design change and the increase in costs has been the ground conditions.

The geotechnical profile of the route changes from competent granite to softer clays, sands and gravels with many variations in between. The route also runs beneath the two rivers in the city. An added bonus is that the profile changes, often suddenly, between the extremes.

"Barcelona's geology is complex with areas of sedimentary rocks such as slates, limestone and microconglomerates giving way to granites and some metamorphic rocks," said tunnelling specialist Nicola Della Valle when he was seconded to consultant Paymacotas to supervise the deep tunnelled section.



Steel fibres in precast tunnel lining segments have helped keep costs down

About 70% of the Line 9 tunnels will have a diameter of 12m – some sections require a smaller 9m diameter, particularly where the route passes through a narrow layer of impermeable ground between water-bearing strata. Around 95% will be built using five tunnel boring machines (TBMs) with 5% done using excavation techniques.

Four Herrenknecht TBMs and one from French firm NFM Technologies will carry out the extensive bored tunnelling work.

Problems with the geology also mean excessive wear on the TBM cutting heads, which also require frequent repair – more frequent than is desired as getting a cutting head out of the tunnel is time consuming and complex.

It would be understandable if these experiences made construction bosses reluctant to adopt innovative techniques on the project.

But specialist materials supplier and manufacturer Maccaferri has opened up the scheme to a materials- and cost-saving process.

The client is Gestió d'Infraestructures, the promoter appointed by the Generalitat de Catalunya (Catalonian government) and key construction consortiums are UTE Gorg and UTE Linia 9, which are working together across much of the project (*see box*).

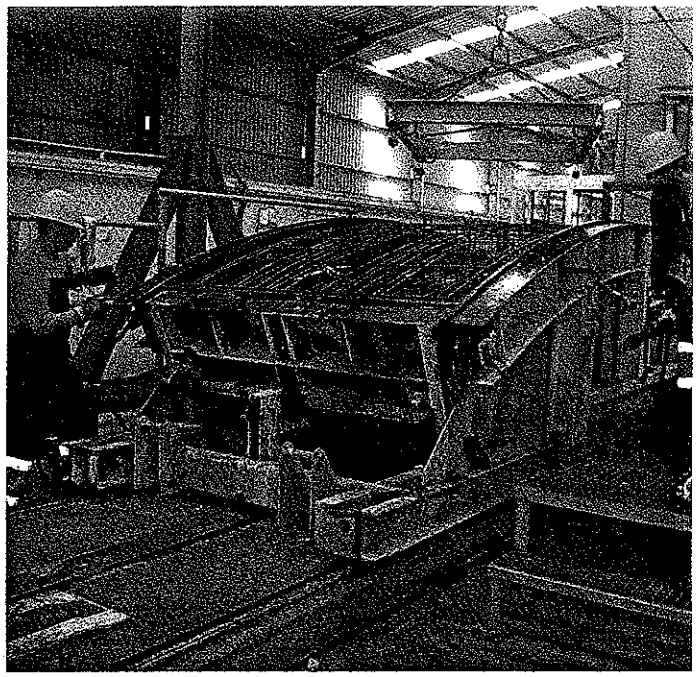
A new approach was considered for the precast concrete tunnel lining elements. These are 1.8m wide and 350mm thick to fit neatly into the 12.1m excavated diameter of the tunnel. Seven 4.56m long segments plus a single keystone make up the entire ring.

> "We decided to go slowly towards the use of fibres in a structural application."
> **Bernard Bergé, Maccaferri**

The original design relied on a heavy duty 120kg/m³ of traditional steel reinforcement to be cast into the concrete as a fabricated cage.

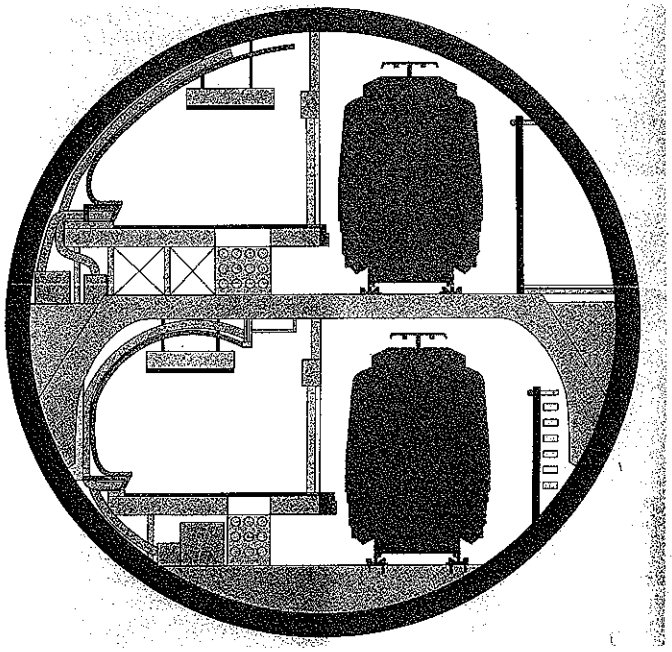
With a constant awareness of steel prices, engineers from different consortiums studied the design and agreed to a plan to try using 30kg/m³ of Maccaferri Wirrand FF1 steel reinforcement fibres to see how they could reduce the amount of rebar required. The lining must withstand pressure of over 15,000t exerted by the TBMs as they work their way along the alignment.

Despite more than 25 years' experience of using steel fibre reinforcement, this was the first occasion Maccaferri had specified them for precast concrete tunnel segments. "We decided to go slowly towards



Tunnel segments are cast at Balaguer in northern Spain

Reinforcement fibres are fed into the mix



Tunnels of between 9m and 12m make room for a single track, double deck layout to accommodate the driverless trains

pursuing the use of the fibres in a structural application," says Maccaferri international fibres manager Bernard Bergé.

The fibres are around the length of a paperclip and help create a more ductile and crack-resistant concrete. In effect, if a crack wants to form in the concrete the fibres act to hold it together.

Using fibres also speeds up the casting process. The elements are cast off site at a facility in Balaguer around 130km from Barcelona. It is equipped with feeders which automatically measure and mix the right quota of fibres into the concrete.

Reducing the amount of rebar needed also reduces the amount of labour-intensive rebar cage building for the elements, saving money.

As well as steel fibres, the precast elements include very fine polymer fibres. These enhance the fire-resistance of the precast elements. The polymer fibres melt when exposed to fierce heat, leaving behind microscopic tubular voids within the concrete, into which latent moisture can evaporate. This moisture would otherwise build up within the concrete and cause spalling.

Despite the success of the steel fibres, and their recent adoption into the Spanish building code for their structural properties, Maccaferri did not stop there.

Part way through the supply contract, it devised a new steel reinforcing fibre, FF3. This fibre has a diameter of only 0.75mm – compared with FF1's 1mm – but can contribute a greater structural strength with less volume of steel again.

At only 25kg/m³ the FF3 fibres provided the same structural performance as 30kg/m³ of the FF1. Using the new fibre enabled contractors to reduce the amount of steel rebar used to just 54kg/m³ – less than half the original specified amount.

Still intrigued by the new application, and following interest from the contractors, Maccaferri ordered further trials at the University of Bergamo in Italy to see how far the steel fibres could go in replacing the traditional rebar.

They decided to test the strength of hypothetically replacing the entire volume of rebar with 60kg/m³ of steel fibres.

Testing focused on a number of measurements including finite element analysis to assess stresses during stocking, handling and installation of the precast units and a full-scale insitu assessment of 20 linear metres of tunnel.

The conclusions offered a pleasant surprise, proving that the fibres could satisfy the structural steel requirements of the project with no need for any rebar.

However, despite their keenness to embrace innovation, the consortiums felt using 60kg/m³ and no reinforcement took them too far out of their comfort zone.

"We did the tests and it was perfect," says Bergé. "But they simply didn't want to take that risk. You can understand – it's a large tunnel, you cannot go from zero fibres and all steel bars to having only fibres for final structural strength that quickly."

Regardless, the project is relying on a hefty amount of steel fibres from Maccaferri – predictions are that by the end of the scheme somewhere around 15,000t will have been used.

While a small section of the line has now opened, delays on the project have put latest estimates of the complete opening date at 2013 to 2014, when one of the world's longest and deepest metros gets to show off in all its deep-tunnelled glory.

KEY CONSORTIUMS

UTE Linia 9
FCC Construcción
Ferrovial Agroman
OHL
Copisa
Copcisa

UTE Gorg
Dragados
Accione
Comsa
Acsa-Sorigué

KEY FACTS

Frequency of trains in central section 2.4mins
Total length 47.8km
Stations 52
Expected traffic Over 1M journeys annually