OPTIMISATION OF TBM TUNNEL IN THE SHANGHAI METRO EXTENSION USING MACRO SYNTHETIC FIBRE

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SUMMARY

Shanghai metro extension is one of the most enormous TBM tunnel investigation nowadays in Republic of China. Because of the size of the investment several research connected to the project. The Customers tried to use the most economic concrete reinforcement, and joint element between the rings. The Tongji University made a real scale test about the full precast concrete tunnel ring. The test was verified with numerical models. After the clarification of the material parameters, finite element analysis was done to optimize the steel bar reinforcement in the ring, and replace it with synthetic fibres. To find the optimum joint formation different models were carried out. The effect of the different bolt types (curved or straight) was significant, just like the use of fibres. With the optimum solution the structure will be more ductile than with the original formation.

1. INTRODUCTION

The authors were engaged to optimize a traditional rebar cage reinforced concrete segmental lining by means of Finite Element Analysis (FEA) using macro synthetic fibres for the Shanghai metro extension. The aim of this study was to reduce or entirely replace the original steel reinforcement of the segmental lining, in order to make the precast production process faster and more economic.

A one-to-one full scale model of an assembled tunnel ring using the original reinforcement cages was tested at Tongji University in Shanghai, July 2013. The ring was tested to differing load levels where load and displacement were measured until failure (Liu et al, 2016). The author's first step was to calculate the real displacement characteristics of the original reinforced concrete ring, then calculate the numerically modelled version, so as to compare them. The numerical modelling undertaken has shown good correlation with the full scale physical test results. Optimization of the lining reinforcement was achieved through the addition of fibres, resulting in a substantial reduction (~50-70 %) of the steel rebar cages (Juhasz et al, 2014). After the analysis the weak points of the tunnel and the type of failure could be visualised easily. For this type of tunnel and its loading, the mechanism of failure was at the segment joints where the connecting bolts burst out from the concrete. The authors investigated

the bolted segment joints and the influence of the macro synthetic fibre on its performance (Juhasz, Nagy and Schaul, 2016).
The numerical calculations were performed by Atena Finite Element software (Cervenka, 2013), with the help of the Modified Fracture Energy Method (Juhasz, 2013). In this paper the design process and the steps of the finite element analysis will be presented.

2. ORIGINAL DESIGN AND LABORATORY TEST

2.1. Geometry and reinforcement

This typical Shanghai metro tunnel example has an inner diameter of 5500 mm, an outer diameter of 6200 mm and a wall thickness of 350 mm. One ring is made from six segments. The key and the invert segment have a different geometry and reinforcement whilst the lateral ones are identical. The invert segment has an angle of 84 degrees, the key 16 degrees, and the four sides 65 degrees.
The longitudinal length of one segment is 1200 mm. The segments were connected with 400 mm long and 30 mm diameter straight bolts at two points, so the six segments were connected at 12 points. The longitudinal bolts are similar to the circumferential. Only one ring was checked in the laboratory test so the longitudinal connections were not included in the test. The segments were hoisted at two points whereas the key segment was hoisted at a single point only. Geometry and loading configuration can be seen in Fig. 1.

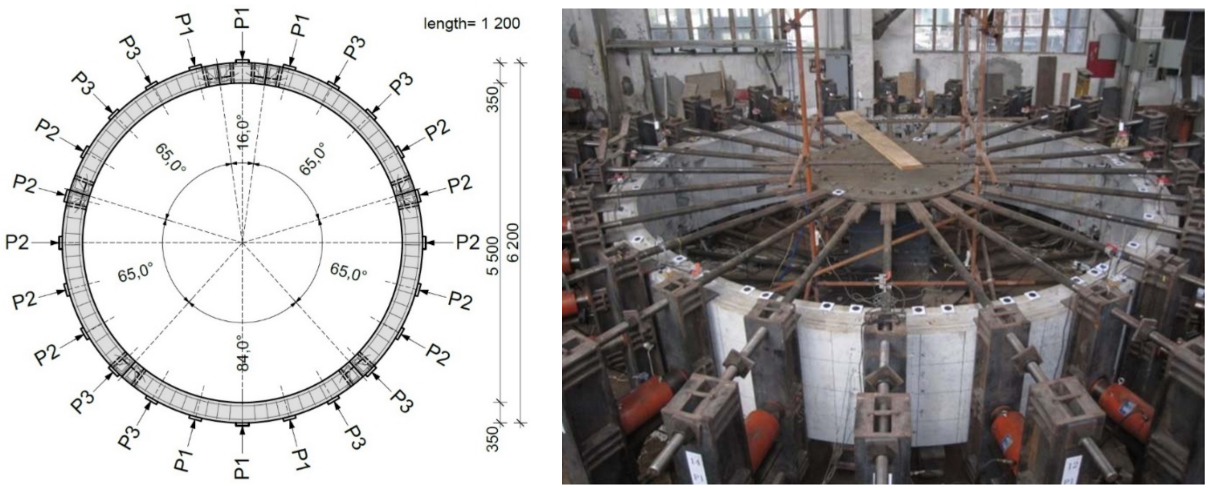

Fig. 1 Geometry, loading configuration and the real scale test

The aspect ratio of the segments, which is the developed length over the lining thickness, computes to 12.2 for the invert segment and 9.5 for the regular lateral ones. Given that a segment aspect ratio not exceeding 10 generally provides a safe opportunity for a fibre only solution, the lateral segments present no problem (Winterberg, 2012). However, the invert segment's aspect ratio is over this threshold, so it was decided to use combined steel and synthetic fibre reinforcement for the numerical studies.
The steel reinforcement, as per the original design, altogether amounts to a total of 559 kg per ring. This yields an average reinforcement ratio of 72 kg per cubic meter of concrete for the invert and side segments. This is not a very high degree of reinforcement, however, the other driver in using FRC for segmental linings is the enormous gain in productivity, giving this technology more and more momentum in countries with already high or still soaring labour costs, such as China. Replacing the complex rebar cages of a segment cuts out the time required for cutting and bending, fixing or welding, placing and checking of the position of the cage.

2.2 Materials

The general tests to characterize the materials were carried out after the full scale laboratory test. The mean concrete compressive strength was determined to be 50MPa cubic, the strain at this stress was 1.8 ‰ (0.0018). A concrete class C40/50 according to the European design standard was used, Eurocode 2 (2004), for the finite element analysis. The grade of the steel bar reinforcement was HRB335 with a yield strength of 335 MPa, using ribbed bars.

2.3 Full scale laboratory test

Tongji University in Shanghai has carried out a full scale test in their laboratory loading a full segmental ring and measuring the load and the referring displacements. The ring was loaded at 24 points, with hydraulic jacks located every 15 degrees. The load was distributed on the ring by means of transverse beams onto the segments as a line load. This closely spaced, distributed load modelled the loading from the soil under permanent condition. The load configuration and the one to one laboratory test setup can be seen in Fig. 1.

During loading the 24 loading jacks applied varying levels of load. At the invert and at the crown a load P_1 was acting at three points respectively. At the benches the load P_2 was applied as a function of P_1 and at the walls a load P_3 as a function of P_1 and P_2. Because of the different loads the structure not only experienced different central thrust force, but has undergone eccentricity as well, modelling the real conditions of the tunnel.

The loading phase had two stages. In the first stage the functions of the loads were the following:

$$P_2 = 0.65P_1 \text{ and } P_3 = \frac{P_1+P_2}{2} = 0.825P_1$$

Load P_1 was increased until P_2 reached its design value which was 292.5 kN.

In the second stage the load P_2 was unchanged, where load P_3 had the following function:

$$P_3 = \frac{P_1 + P_2}{2}$$

and P_1 was increased until its design value of 455 kN. With these functions it was able to model the loading changes as a function of the tunnel depth below surface.

The displacement was measured at 14 points of the ring. The most important positions herein were the 0, 180, and the 90, 270 degrees positions, which are measuring the horizontal and vertical displacements. From these results a load-displacement diagram was generated, showing load P_1 over the displacements at the different angles, which can be seen in Fig. 2.

3. FINITE ELEMENT ANALYSIS OF THE TUNNEL

3.1. Material tests for input of the FEA

To produce the most realistic calculation, material tests were carried out with different dosages of macro synthetic fibres, using the original concrete mix design at Tongji University. Four point beam tests were carried out on 450 mm span and the load was applied in the third points. The beam was loaded until 4 mm central displacement and the load-displacement diagram was recorded. The material tests for FRC were done with 6 and 10 kg/m^3 dosage of macro synthetic fibre.

3.2 Material models

The concrete was modelled with an advanced material model, using the combined fracture surface criteria (Cervenka, 2008). This material model can handle the different behaviour of the concrete in tension and in compression and also capable to calculate the non-linear behaviour after cracking.

The fibre reinforced concrete was modelled with the Modified Fracture Energy Method (Juhasz, 2013). The main idea is to use the concrete fracture energy (G_f) as an initial value and then increase it with an additional fracture energy (G_{ff}) from the post-crack FRC performance. The performance of the fibre was determined with inverse analysis from the existing beam tests. This method is recommended also by the ITAtech Activity Group (2015).

The concrete has a stress-strain diagram according to Eurocode 2 (2004). The crack width was calculated from the stress-crack width diagram, determined by means of inverse analysis, with the help of the characteristic length, which is a function of the size of the element and the angle of the crack within the element. This method is the only one that could realistically represent the cracks in the quasi-brittle material. This is the main advantage of this advanced material model.

Steel rebars and bolts were modelled as discrete link elements with a uniaxial ideal elastic-plastic stress-strain material model. The rebars link element was connected to every single concrete brick element which was crossed. The bolts had no connection with the concrete brick elements, however, at both ends they were held by the nuts on the concrete surface, which were only able to undergo tension.

The connection surface of two adjacent segments was connected with an interface material, which could hold compression only through friction on the surface. With this special interface material the connections of the segments were modelled, which could be open or closed for bending, where tension would be held by the connection bolts.

3.3 Numerical model of the tunnel

After defining the accurate material model the geometry was defined. Firstly, the concrete and reinforcement and then the loads and supports must be defined. The tunnel is symmetric at the horizontal and the vertical axis, so only a quarter of the full ring geometry is sufficient to model the structure with symmetrical support conditions on the symmetrical plane. This also helps to define the boundary conditions and makes the calculation faster. Finally, the monitoring points need to be defined, where the load and resulting displacements were to be measured. The loads were positioned at exactly the same locations and with the same values as in the full scale laboratory test.

4. RESULTS OF THE FINITE ELEMENT ANALYSIS

4.1 Result of the original RC solution

After running the FEA the results were checked. Most important was the load-displacement diagram, which was compared to the full scale laboratory result. It can be seen in Fig. 2 that the result of the laboratory test and the result of the FEA are similar in both characteristic and values and show the same maximum load capacity.

The maximum compressive stress of the concrete was 35.9 MPa, while the maximum crack width just before complete failure was 5.0 mm. The steel bars were grouped according to the stress-levels experienced and selection was based on the ones that could be said to be not providing any input and which could be reduced or completely omitted as a first step. According to the computed stress levels, the remaining steel bars could be reduced in diameter in accordance with the computed stress value. Full animation could be done and the entire loading process could be observed from the formation of the crack until total failure. In this way the weak points of the tunnel and the type of failure could be visualised easily. For this type of tunnel and its loading, the mechanism of failure was at the segment joints where the connecting bolts burst out from the concrete, see Fig. 2.

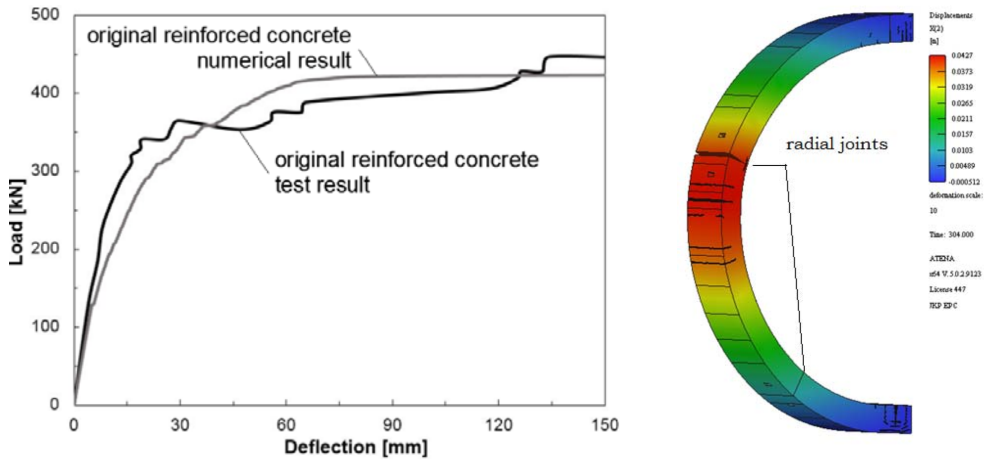

Fig. 2 Results of the laboratory test and FEA

4.2 Optimizing the segmental lining with synthetic fibre reinforcement

After the successful modelling of the original RC ring, the optimization could be started, re-calculating with reduced steel bars and added fibre. Firstly, the lowest stress-level steel bars were omitted and replaced with a moderate dosage of fibre. Then, with increasing fibre dosage, more and more steel bars were omitted. These calculation processes were laborious as adding fibre also changes the occurring deformations, thereby changing the arising eccentricity, and eventually, can change the failure mode, too. However, the ruling failure mode always was radial joint bursting at the bolt pockets.
After these calculations were made three viable solutions were proposed, which can be taken from Tab. 1.

	original solution	solution 1	solution 2	solution 3
added fibre (kg/m^3)	-	6	7	10
max. crack width (mm)	5.0	2.3	2.1	1.9
used reinforcement in one full ring	559 kg steel	344.3 kg steel (-39.8%) +46.3 kg fibre	282.4 kg steel (-49.5%) +54.0 kg fibre	140.4 kg steel (-75.0%) +77.2 kg fibre

Tab. 1 Reinforcement optimization with using synthetic fibres

Adding fibre in conjunction with steel bar reduction improved control of both crack width and crack propagation. The crack width of the original RC solution was 5.0 mm before total failure, where in solution one this was reduced to only 2.3 mm with less visible cracks. This is a reduction of crack widths of more than 50 %, which provides a substantial gain of durability.

From the calculated solutions, number two seemed to be the most viable. However, the FEA is valid only for this given situation, where for other conditions more parameters would need to be checked. The characteristic failure mode occurred at the radial joints (connection bolts and their surrounding area) so review and redesigning of this part could lead to a more optimized solution. The final recommendation is 7 kg/m^3 macro synthetic fibre in conjunction with 50 % steel rebar reduction. This solution is planned to be verified by physical laboratory testing in the near future.

5. INVESTIGATION OF THE BOLTS

5.1 Finite element model of the joints

The three main types of connectors used in tunnel segments are: curved bolts, straight bolts and dowels. The advantages and disadvantages of these connectors are studied in the publication of Delus, Jeanroy and Klug (2010). In this article the mechanics of the curved and straight bolt connection was investigated by advanced FEA. The research has two main parts: (A) modelling only the joints to determine the moment capacity; and (B) modelling the whole tunnel with the same joints to determine the loadbearing capacity of the tunnel. All joints are modelled with plain concrete (PC), fibre reinforced concrete (FRC), traditional reinforced concrete (RC) and hybrid solution (HYB: traditional steel bar reinforcement with fibre reinforcement). The reinforcement was the same like in the full round models.

The material model for the concrete elements was the same like in the previous chapter. The material model for the steel bolts is a uniaxial ideal elastic-plastic stress-strain material. Straight bolts were modelled with a 1D link element that had no connection with the concrete brick elements, however, at both ends they were held by the nuts on the concrete surface, which were only able to undergo tension. Curved bolts needed to be modelled as a 3D element with a connection surface at all side. The adjacent surfaces were linked by connection elements. These connection elements can only hold compression through friction on the surface. The bolts' tensile strength is 500 MPa, the elastic modulus is 200 GPa.

The joints were modelled like a 3 point loaded beam, supported at the two edges and loaded in the centre. This geometry layout can be tested in reality, too. The load and the central point deflection was monitored during the analysis.

The whole tunnel model and the loadings were adopted from the previous FEA of the Shanghai Metro Extension tunnel (Juhasz et al. 2014). Geometry and loading configuration of the joints can be seen in Fig. 3.

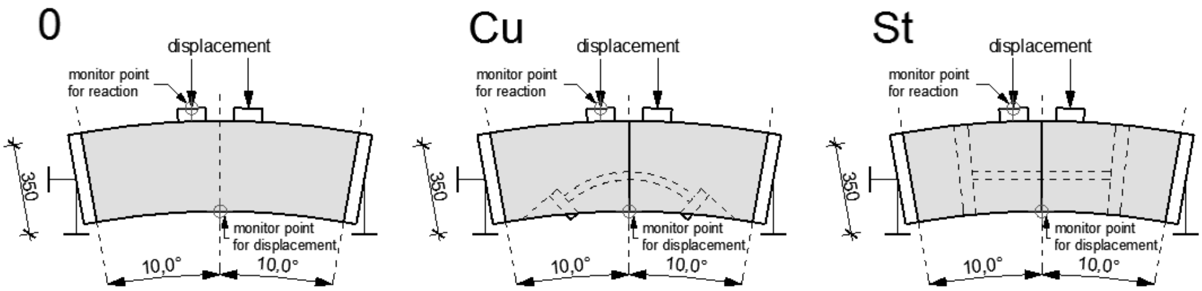

Fig. 3 Geometry and loading configuration of the joints

5.2 Results of the Finite Element Analysis's joint and tunnel model

In the joint models with plain concrete the stiffness and load bearing capacity of the connection with straight bolts was slightly higher, but the ductility (which is determined as the area under the load-displacement curve) was greater for the curved bolts. By adding fibre, the sequence has changed: the joint with curved bolts had the higher load bearing capacity and showed remarkably increased ductility. At this modelling phase, the added fibre has a bigger effect on the joint with curved bolts, although in general, the capacity and the ductility of both connection types has increased (Fig. 4a). The added fibre significantly changed the crack propagation, which could be the reason for the increase of the loadbearing capacity.

Joints with traditional reinforcement showed a smaller difference, but the tendency is the same: by adding fibre reinforcement both the load bearing capacity and the ductility has increased (Fig. 4b).

Without traditional reinforcement the tunnel lining will fail between the joints, because the joints are stronger than the middle section of a lining (segment). By changing the stiffness of the joint (straight to curved bolt) the failure point will also change, but the load bearing capacity is almost the same (Fig. 4c). The tunnel lining with curved bolts has some post crack load bearing capacity, while with straight bolts the load immediately drops. By adding fibre the load bearing capacity and ductility is greatly increased to almost the same level for both connection types. Generally, with added fibre the crack localization could be eliminated.

Adding fibre to the reinforced concrete will also increase the loadbearing capacity of the tunnel (Fig. 4d). It is noteworthy that the highest load bearing capacity was reached with straight bolts and hybrid solution, but this was not reflected in the joint tests where the capacity of the curved bolts was slightly higher. Hence, the capacity of the joints is not the only factor that will affect the global capacity of the tunnel ring.

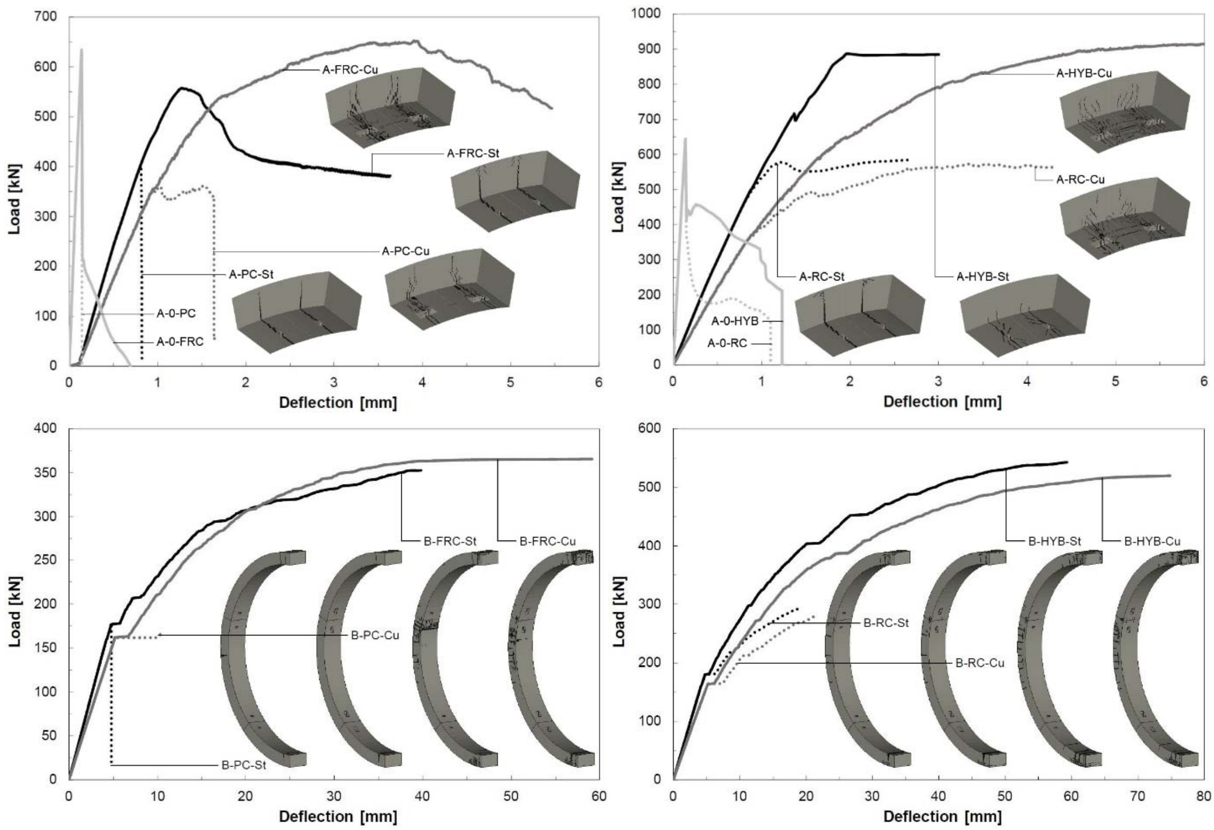

Fig 4. Results of the joint and tunnel models with different type of joint and reinforcement

6. CONCLUSION

A full scale TBM segmental tunnel ring was modelled with an advanced material model in FEA. By using the modified fracture energy method an accurate material model can be used for FRC. A typical Shanghai Metro extension TBM tunnel segmental ring was tested to full scale at the Tongji University, Shanghai, and the load-displacements results were compared with the FEA. The similarity was deemed appropriate, so the model has been justified. Low-stressed steel bars within the section were reduced and macro synthetic fibre was added to the structure. By using macro synthetic fibre reinforcement the volume of steel bars could be reduced. This, in return, leads to significant cost savings in both material and labour, as well as a reduction of the production cycle times.
Three different joint types were modelled in FEA to investigate the effect of them to the capacity of the tunnel. The present numerical research showed that there is no influence of the fibre to the stiffness of the joints. Straight bolts provide a higher stiffness of the joints than curved bolts, but less ductility. The load bearing capacity and crack propagation are significantly improved by adding macro-synthetic fibres for both plain and conventionally reinforced concrete, and for both straight and curved bolts. With advanced design of bolted joints it is possible to increase the load bearing capacity of the entire tunnel, even if the moment capacity of the joint does not reach the moment capacity of the lining (semi-rigid joint).

7. ACKNOWLEDGEMENT

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