NUMERICAL MODELLING OF A PRECAST FIBRE REINFORCED CONCRETE TRACK SLAB

Károly Péter Juhász
JKP Static Ltd.
Reitter Ferenc str. 73, Budapest, Hungary

Péter Schaul
JKP Static Ltd.
Reitter Ferenc str. 73, Budapest, Hungary

John Hammond
Precast Advanced Track Ltd.
King Street, Knutsford, United Kingdom

SUMMARY

In this article a macro synthetic fibre reinforced precast concrete trackslab's design process will be presented. The analysis was done with using an advanced finite element software called ATENA (Cervenka et al 2013). Beside the static loads, the precast slab was also checked for dynamic and fatigue loads. The structure was verify for early ages, for de-moulding, rotating, lifting and for transport as well. With the analysis a necessary fibre dosage was determined. After the design AECOM prepared a real scale test for two full slab. During the test the displacements were measured on different places with using Geophones. Finite element model of the test was made with all the details of the real scale test. The results from the tests and from the finite element models were close to each other in every checked case.

1. INTRODUCTION

PreCast Advanced Track's (PCAT) unique 100 per cent macro synthetic BarChip fibre reinforced precast concrete slab structure is set to revolutionise the construction and repair of the world's railways (Hammond, 2016). The system was developed by the PreCast Advanced Track Company, and the JKP Static ltd was charged with the finite element modelling of the structure. During the design process AECOM and Mott MacDonald were also involved as a consultant company. To different geometries were checked, one for off- streets and the other is for streets, which means the traffic can cross the slab as well. To see the exact behaviour of the full structure, one and a half slab was modelled with the connection cables. The analysis was done with different soil parameters, to see the effect of the unequal subgrade as well. The slab was checked for different loads and load cases, to find the worst effect during the lifetime. Beside the static loads, the structure was also checked for dynamic and fatigue loads. The structure was verify for early ages, for de-moulding, rotating, lifting and for transport as well. The analysis was done with using an advanced finite element software specialized for concrete structures, called ATENA (Cervenka et al 2013). The software uses the combined fracture surface model (Cervenka and Papanikolaou, 2008) to model the different behaviour of the concrete in compression and in tension. The fibre reinforced concrete material was modelled with the Modified Fracture Energy Method (Juhász, 2013). With the analysis a necessary fibre dosage was determined. After the design AECOM prepared a real scale test for two full slab. The slabs were placed to a concrete pool filled with compacted sand. The test was made with using a Rail Trackform Stiffness Tester (RTST) (Govan et al, 2015). During the test the displacements were measured on different places with using Geophones. Finite element model of the test was made with all the details of the real scale test. The results from the tests and from the finite element models were close to each other in every checked case.

In this article the design process and the steps of the finite element analysis will be presented.

2. THE PCAT SYSTEM

PCAT is a new concept in railway construction which can challenge the traditional engineering method of supporting railway tracks on ballast. Whilst ballasted tracks have some advantages, they also have significant drawbacks that can be overcome by adopting slab track systems. PCAT's innovative lightweight slab structure represents a world first for precast track slabs as it is manufactured entirely from BarChip 48 macro synthetic fibre reinforced concrete, without steel reinforcement being required. This ensures that if the concrete cracks there is no steel to corrode, providing a long life structure, as fibres continue right to the edge of the structure this enhances durability and resistance to accidental damage. It also reduces maintenance, material costs and the fibre reinforcement is safer to handle than steel during manufacture. The PCAT slab design is based on a channel beam upper profile which provides a high modulus slab structure, this maximises the slab strength and minimises the stiffness needed for the track foundation. This allows PCAT tracks to be constructed quicker than conventional track. It also means PCAT is particularly suitable for adoption where poor or variable ground support and flooding conditions exist.

The PCAT distinctive deep edge beam is designed to be formed higher than the adjacent rail without conflicting with the train underside gauge. This has the potential to reduce rail and wheel contact noise by obstructing the sideways bypass of noise. The high strength of the edge beam is likely to be adequate to prevent a derailed train from coming off the PCAT slab track structure and thus increase track safety. The upper slab profile collects surface water and conveys this to drainage outlets via the transverse and longitudinal ducting system accommodated within the slab. This disperses water away from the track foundation and increases the resilience of the track, preventing damage to the associated earthwork structures. The ducts can accommodate track cables and services in a secure environment which prevents theft and damage.

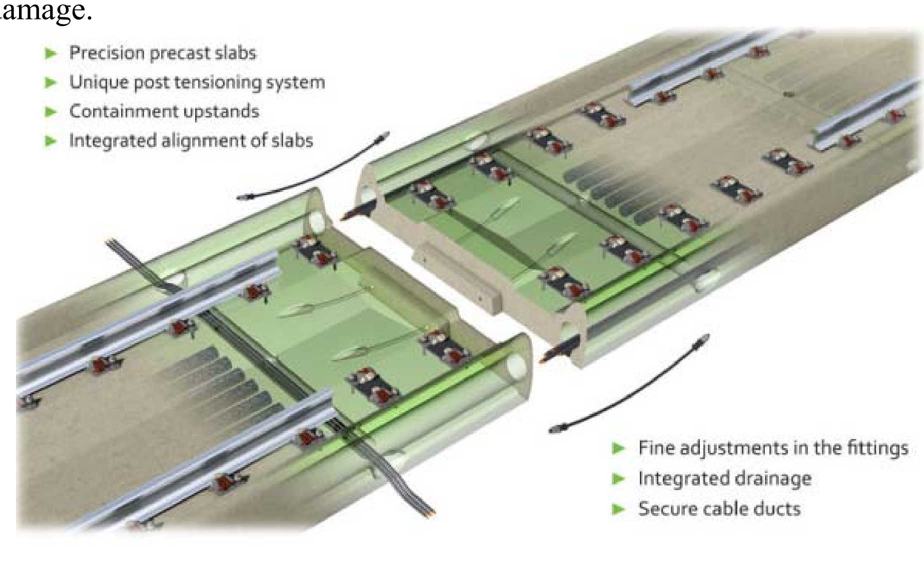

Fig. 1 The PCAT system

The slabs connecting to each other with a dry male –female joint (came from the geometry) and with curved connection cables as well. This is designed to permit a rapid laying and joining process to form the monolithic structure. Curved steel connectors between adjacent units are easily inserted and tensioned from the slab surface as erection proceeds. This allows rapid installation to take place from the occupied track to provide the monolithic structure, even in tunnels with restricted space. Uniquely, if needed, PCAT slabs can be simply decoupled, levels adjusted or slabs removed and replaced without affecting the track structure. Two type of slabs was developed to serve all the needs. One is the mentioned standard slab (off-street slab) with the side beams, which is highly optimised and can easily installed. The other one is a more robust structure, but with a straight upper surface and with hidden rails (on-street slab). This type of the slab can be used in streets as well, thanks to the sunk rails the traffic can easily cross the slab. The full length of both geometry was 5000 mm, the minimum thickness of the off-street slab was 150 mm and the thickness under the rails in case of on-street slab was 200 mm.
The slabs were designed for 120 year lifetime.

3. STRUCTURAL DESIGN – NUMERICAL MODELLING

3.1. Finite element model of the structure

The numerical modelling of the PCAT slabs were done in a Finite Element Software called ATENA. This software specialized for concrete structures, with and advanced material model, presented in the next chapter. To determine the necessary fibre dosage both of the slab geometry were modelled. The finite element models of the structures can be seen in Fig. 2.

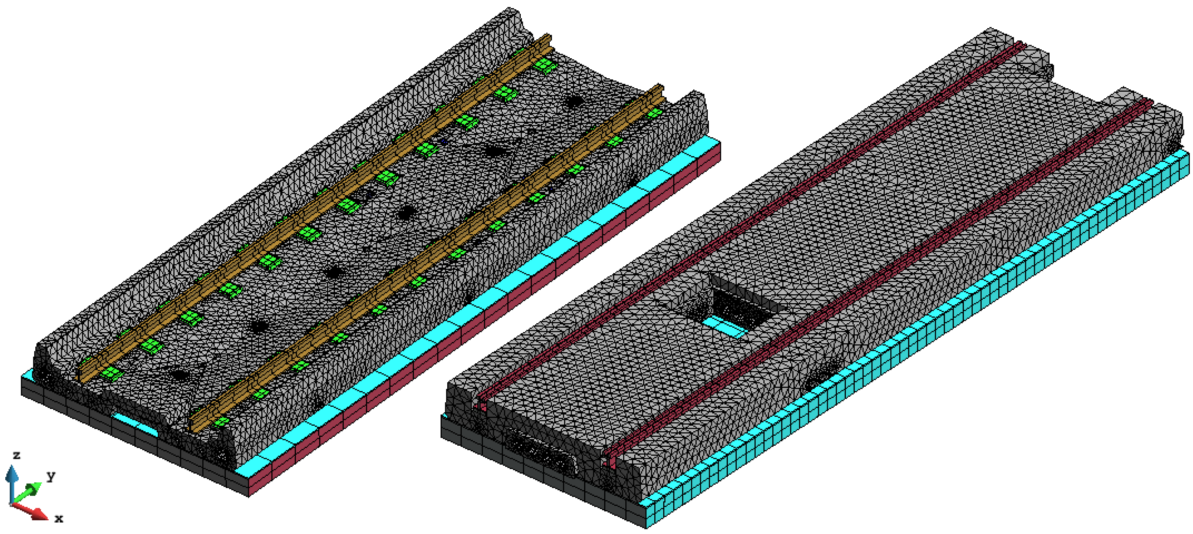

Fig. 2 Numerical models of the precast slabs

To ensure the connection between the model and the real structure's behaviour, all the details were modelled including the connection ducts, the injection holes, the rail slippers and the rails with their exact geometry. In the models one and a half slab was modelled to be able to investigate the behaviour of the joints. For the connecting surface an interface material was determined, which could bear only compression stresses. It occurs that the slabs during the loading process could open along the connection surface, and the ducts bear the tension stresses. Under the slabs a bedding layer and a HBM (Hydraulically Bound Mixture) layer was modelled. For the subgrade non-linear springs were used. To investigate the effect of the

soil parameters all the models were checked for a higher (350 MPa) and a lower (175 MPa) HBM layer as well.
In the model various material models were used for the different structural elements. For the concrete slab and advanced concrete material was used (see the details in the next chapter). For modelling the subbase and the subgrade linear elastic materials were used with different elastic modulus. The same material model was used for slippers as well. For the steel elements, such as rails and connection cables a Von Misses material model was used which can handle the yield of the steel elements. Two different interface elements were used, one to model the friction between the concrete slab and the steel duct, and one to model the transfer of the compression forces between the two slabs. The parameters were determined in both case to be as close to the real behaviour as possible.
For the slab a structured tetrahedral mesh were generated, with 3.0 cm side length. This value was reduced close to the longitudinal and transvers holes, injection holes and pits. For subgrade, rails, slippers and ducts brick elements were used to speed up the running time of the model.

3.2. Material model of concrete and FRC

The concrete was modelled using an advanced material model, which means using combined failure surfaces. With this material model the different behaviour (elastic-plastic or brittle, compressive and tensile strength, fracture energy) of concrete in tension and compression can be modelled. There are many such models available in the literature, the most commonly used are: Von-Mises and Rankine; Drucker- Prager and Rankine; and Menétrey-William and Rankine (Rankine cube is at the tension side). However, it is important to note that these models only define the peak strength of the material, not the post-cracking response. Numerous other models can be used to approximate the post-cracking capacity of FRC. The model presented in the ITAtech guideline (ITAtech Activity Group Support, 2015) was used here.

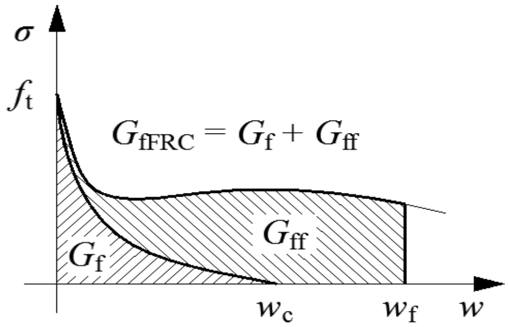

Fig. 3 Fracture energy of the FRC

When stresses exceed the tensile strength of the concrete it will crack. There will be residual stress at the crack surface that depends on the crack width opening distance. This stress is associated with an energy, called fracture energy (G_f). This energy is influenced by the aggregate type (round or crushed), size, and its bond to cement mortar. Fibres increase this fracture energy (G_{ff}), thereby making the concrete a more ductile material. This approach is called the modified fracture energy method (Juhasz, 2013). The most important criterion for the selection of the FRC material model is to be able to model this increased fracture energy (G_{fFRC}) and select a value that is appropriate to the FRC used for a design (see Fig. 3). For our models the additional fracture energy was modelled with a constant residual strength, f_{fdu}, as can be seen in Fig. 4.

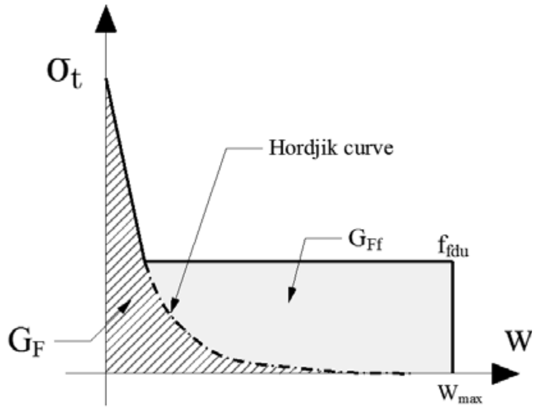

Fig. 4 Used tensile function for numerical calculation

The concrete was modelled as a three dimensional (3D) brick element with a material model consisting of a combined fracture-plastic failure surface (Cervenka and Papanikolaou, 2008). Tension is handled herein by a fracture model, based on the classical orthotropic smeared crack formulation and the crack band approach. It employs the Rankine cube failure criterion, and it can be used as a rotated or a fixed crack model. The plasticity model for concrete in compression uses the William-Menétrey failure surface (Menétrey and William, 1995). Changing aggregate interlock is taken into account by a reduction of the shear modulus with growing strain, along the crack plane, according to the law derived by Kolmar (1986).
The concrete has a stress-strain diagram according to Eurocode 2 (Eurocode, 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.

3.3. Design and load cases

To check all the possible effect on the slabs, different loading scenarios were carried out in the finite element software. During the lifecycle various effect will occur to the trackslab. Because the slab is pre-casted the first effect comes from the demoulding of the element. In this case a time dependent material model was used, which mean the material parameters changed during the analysis follow the hardening of the concrete. With this analysis the optimum demoulding time can estimate as well. To demoulding a lifting and a tearing force was added to the early age concrete slab. After this, but also in early ages, a rotation effect was occurred: the demoulding was made upside down, but the racking of the slabs were in the other direction. In this two load case also the lifting and rotating elements were checked. The next situation was the storing load case. In this case the weight of three elements were added to the slab, simulating the effect of the racking.
The highlighted design target was to check the ultimate and the serviceability limit states under the train load. The geometry of the trains were added. To examine the worst loading case, and to model the passage of the train, seven different loading scenarios were carried out in different positions. In Ultimate Limit State (ULS) the principal stresses, in Serviceability limit State (SLS) the crack widths and the vertical displacements were checked. During the calculation the unequal rail loading was also take into consideration.
To be able to calculate the effect of the cyclic loading fatigue analysis was done also for all the loading positions. The number of the cycles were calculated back from the estimated lifetime of the structure and the average daily traffic. The finite element software calculate

two additional fatigue strain for the maximal fracturing strain (Pryl et al. 2010), one handle the tensile strength reduction during the cyclic load (according to the Wöhler curve), and the other takes into consideration the crack opening effect during the cyclic load.

4. RESULTS

The structure complies with all the design requirements both in ULS and in SLS. In ULS the target was that the structure bear the loads with safety factors and with design material parameter values without the failure of the structure. In SLS the aim was that the crack widths should be less than the value according to Eurocode 2 (0.2 mm). Both design case met with the requirements in every loading position and design situation.

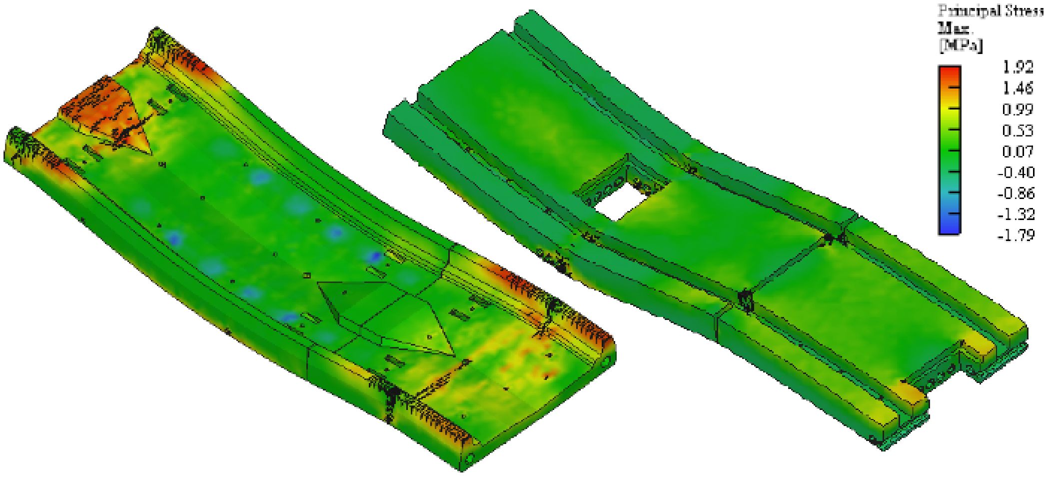

Fig. 5 Principal stresses and cracks in deformed Atena model

The slabs deformation was realistic, it followed the expectation under the different loads. The connection between the two slabs worked well. It also can be seen that the structure is highly optimized, in ULS several crack appeared in the surface of the structure, but without failure, and in SLS almost no visible crack appeared on the structure.

5. REAL SCALE TEST WITH RTST

At the AECOM Pavement Test Facility in Nottingham was installed the PCAT slab within their test pit to measure the deflection of the slab along the structure using an applied load at different series of locations. The position of the load was replicated the arrangement used in the FEM simulation. The PCAT off-street slab has been designed for 12 tonne axle loads. For the testing it was proposed after the first suit of loading at 8 tonne the load was increased in 4 tonne increments up to 24 tonne, subject to slab performance during the testing.
The loading of the slab was carried out using the Rail Trackform Stiffness Tester (RTST) (Fig. 6) which has been developed by AECOM to replicate the loading requirements of high-speed or heavy-haul lines through the use of an increased range of pulse-loading conditions. The weight is fully enclosed within the machine, which greatly reduces operator risk. The RTST apparatus is mounted on a transport frame that can moved along on rubber-caterpillar tracks whilst off track and then switch to rail wheels. On ballasted track geophones measure the deflection response of the ballast, sub-ballast, formation and subgrade enabling the assessment of layer stiffness. During testing of the PCAT slab an array of 9 geophones were positioned above the concrete slab surface to record the deflection in microns.

Fig. 6 The RTST testing (AECOM PCAT Test report)

6. VERIFICATION

To ensure the numerical model's property, a finite element analysis was made about the RTST test. The model contained the whole test setup: the concrete pit, the compacted soil, and the two slab with the mentioned detail as well. The soil parameters in the finite element model were choose according to the used values in the laboratory test. The effect of the RTST was added to the slab with using a steel plate which corresponds to the loading beam's foot. The materials and the material models were the same like in the previous analysis. The measured value in the finite element model was the vertical deflection. It was measured in 9 different point, where in the test the geophones were. The position of the loading plate in the finite element model followed the RTST machines position in the test.
The results in every loading case were close to each other. The finite element analysis followed well the reality, the differences between the measured deflections in the model and in the test was less than 0.1 mm. Only one loading scenario was where the difference was higher, where the load was over the female joint. This was in contribution with the AECOM report which determine a very poor subgrade stiffness in this area. The results of the test and the FEA can be seen in Fig. 7.

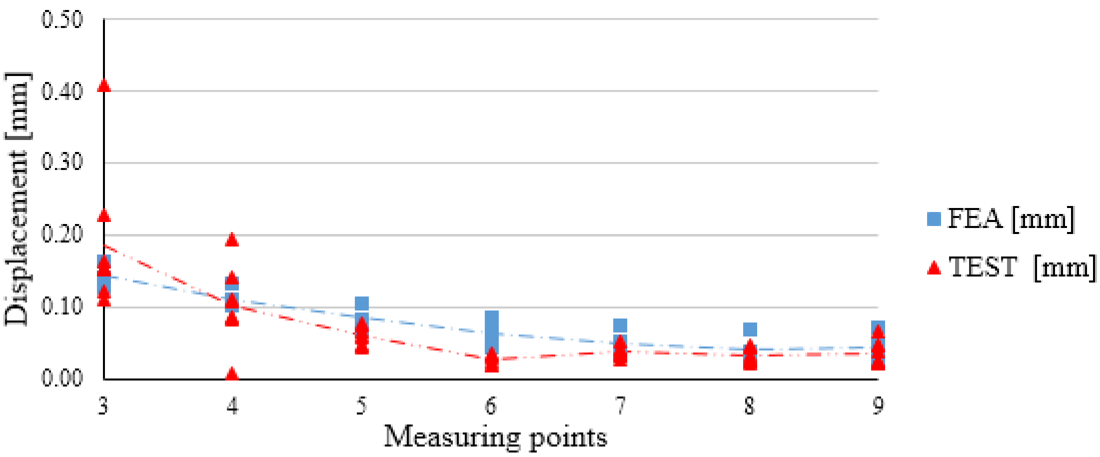

Fig. 7 Results of RTST and FEA

7. CONCLUSION

A new, highly optimized only macro synthetic fibre reinforced concrete trackslab was developed by the PreCast Advanced Track ltd. The slab because its precast nature can be easily installed, and the reparation can be also quick. To determine the optimum fibre dosage finite element analyses were done, with a concrete specific finite element software, ATENA. The results showed that the structure can bear the load in every ULS design case, and the crack widths in SLS are always under the limit according to the Eurocode. The analysis showed also, that the structure will work well after the 120 year lifecycle. To verify the finite element model a real scale test was carried out by AECOM. The test represent the real behaviour of the slab under train load. A finite element model was made to represent the test. In both examination the vertical displacements of the slab were measured. The results were close to each other in every design cases, and also the finite element analysis was capable to show where the soil stiffness was inappropriate.
Further researches will carried out in the future, where a mock up line will build by using the PCAT system.

8. ACKNOWLEDGEMENT

The research was supported by the FibreLab, co-founded by the Nemz_15-1-2016-0026 Programme and the European Union Horizon 2020 Framework.

9. REFERENCES

Cervenka, J. and Papanikolaou, V.K. (2008), ”Three dimensional combined fracture-plastic material model for concrete” International Journal of Plasticity (24): 2192-2220

Cervenka, V., Jendele, L., Cervenka, J. (2013), “ATENA Program Documentation: Part 1 Theory” Cervenka Consulting s.r.o., Prague, 318 p.

EUROCODE EN 1992. (2004), “European Code for design of concrete structures”, European Committee for Standardization

Govan C., Sharpe P., Brough M. (2015), “The Rail Trackform Stiffness Tester – Development and early trials to assess stiffness characterisation of novel trackforms”. Railway Engineering, Edinburgh

Kolmar, W. (1986), “Beschreibung der Kraftuebertragung über Risse in nichtlinearen Finite-Element-Berechnungen von Stahlbetontragwerken“, Dissertation, T.H. Darmstadt.

Hammond J. (2016), “Construction and reinforcement” in Railing Professional October 2016 Issue pp. 162-163.

ITAtech Activity Group Support (2015), ”ITAtech Design Guidance For Precast Fibre Reinforced Concrete Segments” ITAtech Report n7, draft

Juhász, K.P. (2013), “Modified fracture energy method for fibre reinforced concrete”, in: Proceedings of Fibre Concrete 2013: Technology, Design, Application. Prague, Czech Republic 2013, pp. 89-90.

Menétrey, P., William K.J. (1995), “Triaxial Failure Criterion for Concrete and Its Generalization”, ACI Structural Journal 92(3). pp 311-318.

Pryl D., Cervenka J., Pukl R. (2010), “Material model for finite element modelling of fatigue crack growth in concrete” Procedia Engineering 2 pp. 203–212