

Finite Element Analysis of a Precast Fibre Reinforced Concrete Track Slab

Károly Péter Juhász¹ and Péter Schaul²

1. Department of Mechanics, Materials & Structures, Budapest University of Technology, Budapest 1111, Hungary

2. Department of Construction Materials and Technologies, Budapest University of Technology, Budapest 1111, Hungary

Abstract: In this article a macro synthetic fibre reinforced precast concrete track slab's design process will be presented. The analysis was done with using 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 verified 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 slabs. 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.

Key words: Fibre reinforced concrete, finite element analysis, synthetic, verification.

1. Introduction

PCAT's (PreCast Advanced Track's) unique 100 percent macro synthetic BarChip fibre reinforced precast concrete slab structure (Fig. 1) is set to revolutionise the construction and repair of the world's railways [1]. 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 (AECOM Technology Corporation) and Mott MacDonald was also involved as a consultant company. 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 verified for early ages, for de-moulding, rotating, lifting and for transport as well. The analysis was done with using advanced finite element software specialized for concrete structures, called ATENA [2]. The software uses the combined fracture surface model [3] 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 [4]. With the analysis a necessary fibre dosage was determined.

After the design AECOM prepared a real scale test for two full slabs. The slabs were placed to a concrete pool filled with compacted sand. The test was made with using an RTST (rail trackform stiffness tester) [5]. 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

Corresponding author: Karoly Peter Juhasz, head of the Czakó Adolf Laboratory, BUT, research fields: synthetic fibre reinforced concrete, numerical modelling.

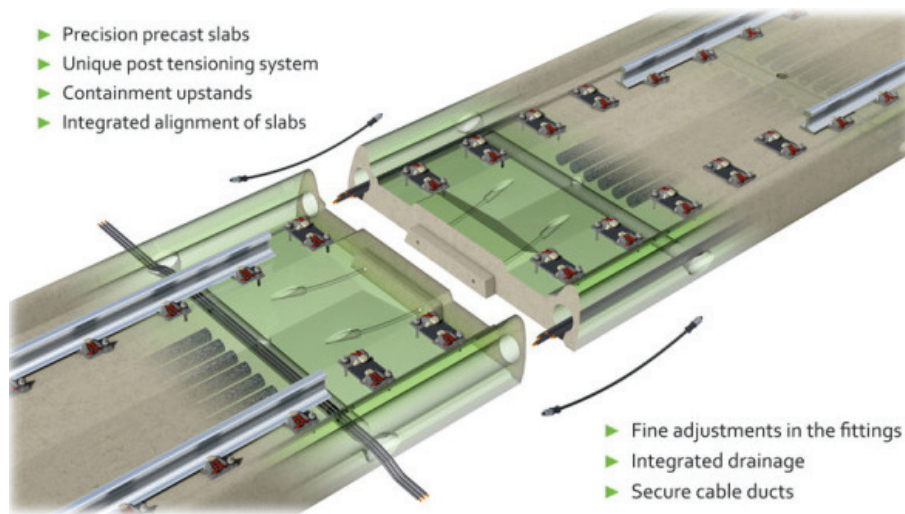


Fig. 1 The PCAT system.

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 are 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 more quickly 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 increases 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.

The slabs connect 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 types of slabs were 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 be 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 geometries was 5,000 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 advanced material model, presented in the next chapter. To determine the necessary fibre dosage both of the slab geometry was modelled. The finite element models of the structures can be seen in Fig. 2.

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 an 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 Mises 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 cases to be as close to the real behaviour as possible.

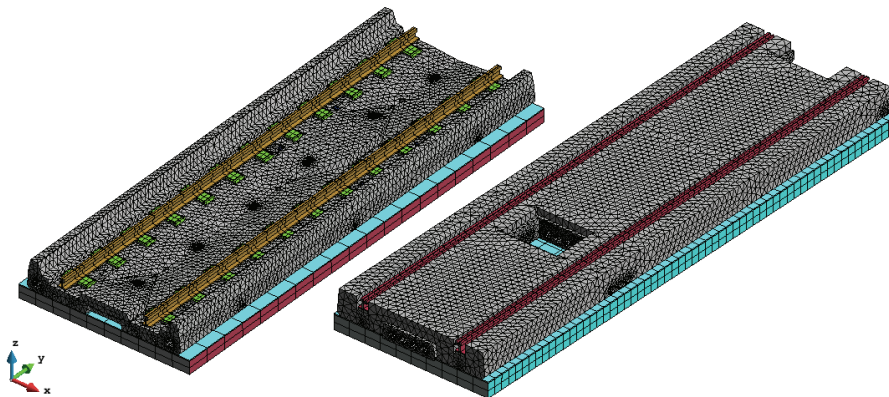


Fig. 2 Numerical models of the precast slabs.

For the slab a structured tetrahedral mesh was generated, with 3.0 cm side length. This value was reduced close to the longitudinal and transversal 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 [7] (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. Other numerous models can be used to approximate the post-cracking capacity of FRC. The model presented in the ITAtech guideline [6] was used here.

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 [4]. 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_{idu} , as can be seen in Fig. 4.

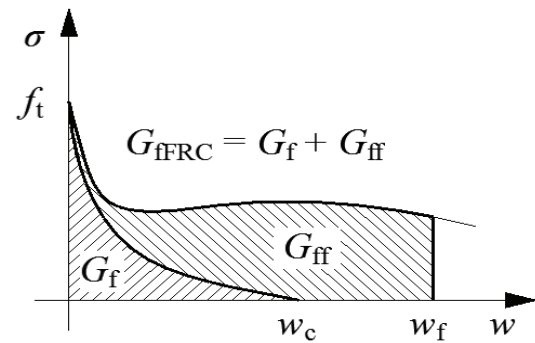


Fig. 3 Fracture energy of the FRC.

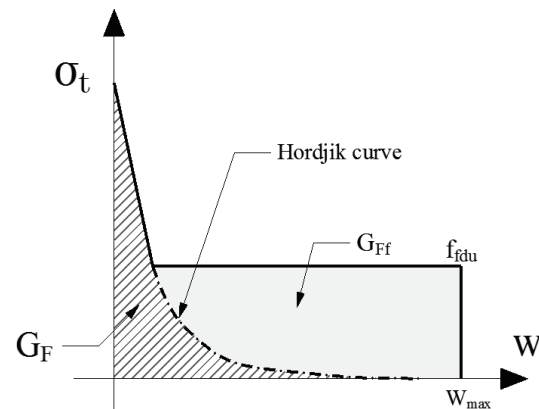


Fig. 4 Used tensile function for numerical calculation.

The concrete was modelled as a three dimensional (3D) brick element with a material model consisting of a combined fracture-plastic failure surface [3]. 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 [6]. 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 [8].

The concrete has a stress-strain diagram according to Eurocode 2 [9]. 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 effects will occur to the track slab. 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 means 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 occurred: the demoulding was made upside down, but the racking of the slabs was in the other direction. In these two load cases also the lifting and rotating elements were checked. The next situation was the storing load case. In this case the weight of three elements was 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 was 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 ULS (ultimate limit state) the principal stresses, in SLS (serviceability limit state) the crack widths and the vertical displacements were checked. During the calculation the unequal rail loading was also taken 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 was calculated back from the estimated lifetime of the structure and the average daily traffic. The finite element software calculates two additional fatigue strain for the maximal fracturing strain [10], one handles 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 (Fig. 5). In ULS



Fig. 5 The PCAT slab.

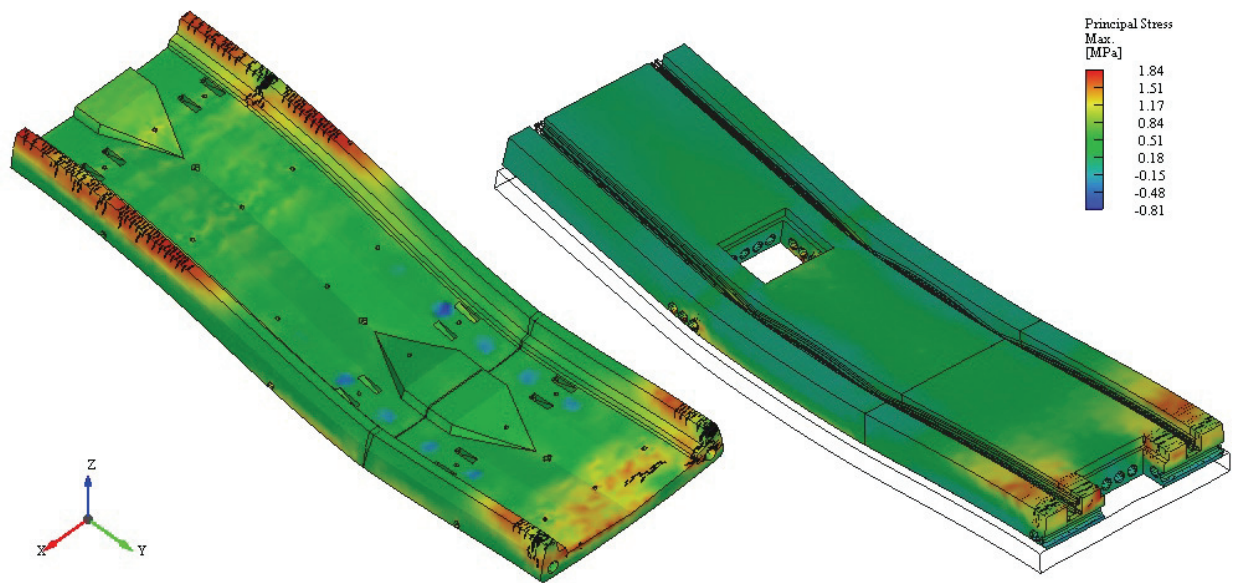


Fig. 6 Principal stresses and cracks in deformed Atena model.

the target was that the structure bears 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 cases met with the requirements in every loading position and design situation.

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 cracks appeared in the surface of the structure, but without failure, and in SLS almost no visible crack appeared on the structure (Fig. 6).

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 tonnes axle loads. For the testing it was proposed after the first suit of loading at 8 tonnes the load was increased in 4

tonnes increments up to 24 tonnes, subject to slab performance during the testing.

The loading of the slab was carried out using the RTST (Fig. 7) 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 was positioned above the concrete slab surface to record the deflection in microns.

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 slabs with the mentioned detail as well. The soil parameters in the



Fig. 7 The RTST testing (AECOM PCAT Test report).

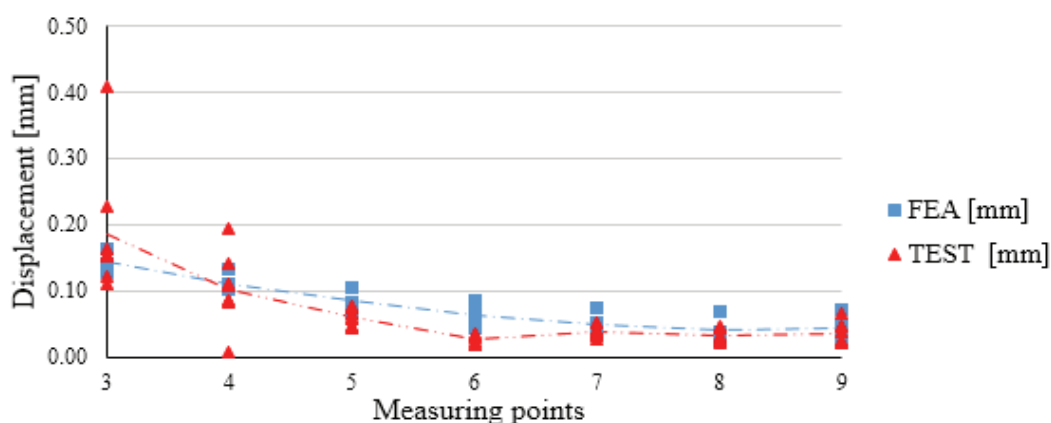


Fig. 8 Results of RTST and FEA.

finite element model were chosen 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 points, 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 were 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 determines the very poor subgrade stiffness in this area. The results of the test and the FEA can be seen in Fig. 8.

7. Conclusions

A new, highly optimized only macro synthetic fibre reinforced concrete track slab was developed by the PCTA Ltd. The slab because of 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 the 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 years lifecycle. To verify the finite element model a real scale test was carried out by AECOM. The test represents the real behaviour of the slab under train load. A finite element model was made to represent the test. In both examinations the vertical displacements of the slab were measured. The results were close to each other in every design case, and also the finite element analysis was capable to show where the soil stiffness was inappropriate.

Further researches will be carried out in the future, where a mock up line will be built by using the PCAT system.

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