13th Central European Congress on Concrete Engineering
Next Generation of Concrete Engineering for Post-Pandemic Europe
13-14th September 2022

Károly Péter JUHÁSZ[1]
Péter SCHAUL[2]

Opportunities for synthetic fibre reinforcement in concrete structures

Abstract: In the past decade macro synthetic fibre reinforcement has become widely used in concrete structures, such as tramlines, tunnels and industrial floors. By using synthetic fibres as reinforcement in concrete structures, the casting time and labour work will decrease, while the ductility will increase. In addition, the durability will also be higher when using synthetic fibres, while the carbon footprint is much less compared to steel fibre reinforcement. In most cases the steel reinforcement can be omitted entirely from the structure using macro synthetic fibres. These uniformly distributed fibres in concrete can increase the residual flexural strength of the concrete independently from the location. This makes it possible to use fibres in cast in situ elements, like tramlines, shotcretes and industrial floors. Beside the cast in place solution the use of synthetic fibres in precast concrete elements started to spread, mainly because of the same benefits of shortening construction time. These elements also needed to be designed for temporary situations, such as demoulding, lifting, transporting and placing on site. The typical uses for precast FRC elements are tunnel segments and precast tramline elements. The calculation process of these structures always has to comprise the static load, the dynamic load and if the effect exist, cyclic loading (i.e. fatigue). These effects can be handled using advanced finite element analysis software, which is specialized for concrete and fibre reinforced concrete structures. In this paper the opportunities of using macro synthetic fibres and designing the fibre reinforced concrete structures will be presented with worldwide references.

1. Content of the paper

The use of fibre-reinforced concrete is becoming increasingly possible for a growing number of structures. Rising steel price and labour costs, along with scarce supplies are increasing the use of synthetic fibres in the market, allowing faster construction and cost reduction in structures made with them. Macro synthetic fibres can also be used in tramway, tunnel or industrial floor structures. This paper describes the potential applications of fibres in these structures, realised examples with their calculation methods and details.

While it may seem simpler to persist with the traditional steel bar reinforced concrete solution, one of the biggest issues of the day is the environmental footprint – how much carbon dioxide is released into the air when a product is manufactured. Without detailed calculation and analysis, roughly 50-70% less CO_2 is released into the air when using macro synthetic fibre. Unfortunately, the environmental footprint of the cement is also high, so this can only be reduced by reducing the amount of concrete itself. However, when using synthetic macrofibres, corrosion problems can be completely eliminated, there is no need to provide cover for the reinforcement, and savings can be made on the quantity of concrete. Moreover, by using fibres made from recycled plastics for the fibres used in FRC, another step can be taken in protecting the environment.

A very significant way to decrease our planet's plastic pollution could be to use these recycled plastics in construction materials for the building industry. The decomposition time of a yoghurt container does not need to be 450 years, but a building structure should be worth 50 years. This contradiction could be resolved by choosing materials for our building structures that are more durable and recyclable. From

[1] PhD. Eng., JKP Static Ltd., Hungary, office@jkp.hu
[2] MSc. Eng., JKP Static Ltd., Hungary, peter.schaul@jkp.hu

an environmental point of view, the choice of synthetic macro fibres is obvious, and the development and standardisation of these materials is therefore a major priority.

2. Track slabs with synthetic fibre reinforcement

Today the construction of modern concrete slab track plays a prominent role in the construction industry. Besides keeping in mind having an economic solution, more emphasis is placed on its durability and its resistance to environmental factors such as moisture, de-icing salts etc. The economic solution can be achieved primarily by decreasing the thickness of the slab and shortening the construction time. Durability can be significantly increased by designing for fatigue and by using materials that are resistant to these environmental factors. Because of this macro synthetic fibres are being used more often for the reinforcement of the concrete for both cast in place and precast structures.

Corrosion resistance is the greatest benefit of macro synthetic fibre where durability can be assured. Synthetic fibres also behave better under dynamic loads than steel fibres, therefore their use for tramline or railway track slab is very favourable. Added to this are the economic advantages such as a reduction in labour personnel who would traditionally set and tie the steel reinforcement into place.

The first macro synthetic fibre reinforced track slab was constructed in Japan in 2002: Elasto Ballast track railway. The goal of using macro synthetic fibre was, beside from the reduction of the vibration and noise, to increase the speed of the construction process. The first synthetic fibre reinforced track slab in Europe was the Docklands Light Railway near London in 2004 [1].

2.1 Cast in place tramlines

One of the most common structures for tramlines is the cast in place track slab. There are several proprietary track slab configurations commonly using either the poured in place track slab or the track slab prepared using a slipformed concrete machine. In the first case; after installing the formwork, the slab is filled with macro synthetic fibre reinforced concrete, and the joints are installed after each section of the track slab is poured. Each pour is then mostly connected with steel dowels. In the second case the machine continuously places the macro synthetic fibre reinforced concrete using the moving formwork. In this case the joints are made by saw cutting the slab, which reduces the likelihood of any crack formation.

In 2010 and 2011, during the extension and reconstruction process of the A and C sections of tramline Nr. 1 in Szeged, Hungary (fig. 1) in areas of the so-called loops which was a major tram intersection, it was necessary to have concrete track slabs that contained no steel reinforcement. Therefore, it was an idea to use macro synthetic fibre reinforced concrete in these sections. At that time, only synthetic microfibers had been used for concrete reinforcement in Hungary, the effects of which are mostly seen in the case of fresh concrete: through reducing the rate of plastic shrinkage cracking. However, in hardened concrete only macro synthetic fibres have any structural impact. While exploring foreign technologies, it was found a suitable building material for this purpose was a Japanese-developed macro synthetic fibre. During the design process it turned out that traditional reinforcement could entirely be replaced by the use of this macro synthetic fibre in this application. After a technical and financial analysis it also became clear to the general contractor that the desired structure could be built more economically and faster, furthermore: not only could it be applied in the critical sections where no steel reinforcement was allowed, but also it could be used in the other sections of the tram tracks. Based on the above, a unanimous consensus was reached by the Client, the General Contractor and the Designer to try out the new technology. The new technology was designed for and initially tested on non-critical track areas (RAFS-CDM) such as at road junctions, turn-outs, current tracks, bus bays and vibration damping tram tracks.

During the design process the dynamic loads of trams and buses were taken into account, then the load-bearing capacity, serviceability and fatigue limits were checked in accordance with Eurocode [2]. Finite element analysis was made on the basis of the recorded material model recommended by RILEM TC 162-TDF [3]. According to the calculations the tramway met the standard loads and load combinations.

Fig. 1. Tram line in Szeged, Hungary

The Szeged tramway project was a huge success. After the system proved to be fully functional several other tram tracks were constructed using very similar solutions and using macro synthetic fibres. These tram tracks were constructed in St. Petersburg, Russia, and in Tallinn, Estonia. In Hungary the success also continued and led to the partial reconstruction of Budapest tramlines Nr. 18 and Nr. 1, as well as the complete track reconstruction of the Nr. 3 tramline using this solution.

2.2 Precast concrete tramlines: PCAT system

Another important trend in tramline structures is the precast concrete track slabs. These elements are made in precast concrete factories and transported to site. These elements will be subjected to additional loads besides their final load cases (as was the main design criteria above) such as early age demoulding, rotation, lifting, stacking, transporting and installation on site. Usually these elements are made from concrete with higher compressive strengths i.e. C40/50 as compared to the cast in place slabs i.e. from C25/30. Generally, the precast elements have a higher dosage of macro synthetic fibre than the track slabs that are cast in place.

One of the most succesful design references is the PCAT system. PreCast Advanced Track's (PCAT) [4] unique 100 per cent macro synthetic fibre reinforced precast concrete slab structure is set to revolutionise the construction and repair of the world's railways [5]. PCAT's innovative lightweight slab structure represents a world first for precast track slabs as it is manufactured entirely from 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 and so 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 which maximise the slab's strength and minimises the stiffness needed for the track foundation (fig. 2). This allows PCAT tracks to be constructed quicker than conventional track.

The slabs connect to each other with a dry male-female joint for initial alignment and then with curved bolt connections (fig. 3). This is designed to permit the 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 newly laid track 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 rest of the track structure.

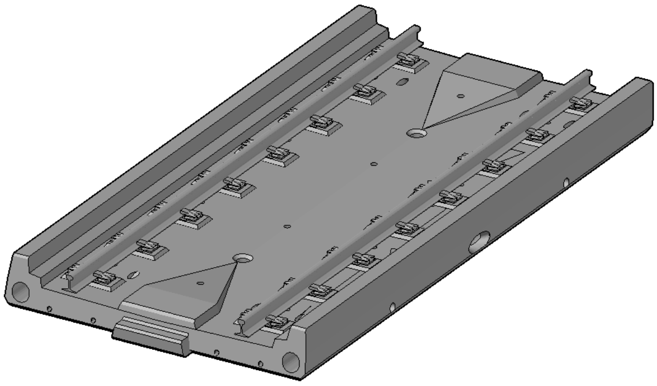

Fig. 2. Geometry of off-street PCAT

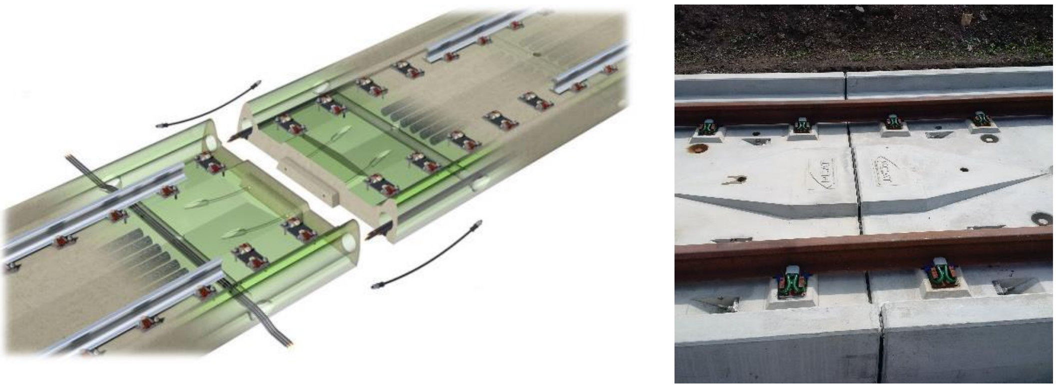

Fig. 3. Joint of PCAT, left: [4], right: photo by the author

Two types of slabs were developed to serve all potential installation requirements. One is the aforementioned 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) (fig. 4). This type of the slab can be used in streets and thanks to the sunken rails, the traffic can easily cross the slab. The maximum length of both types is 5000 mm, the minimum thickness of the off-street slab is 150 mm and the thickness under the rails in case of on-street slab is 200 mm. The slabs were designed for a 120-year design life.

2.3 Finite element model of the structure

The numerical modelling of the PCAT slabs were done with ATENA finite element software [6]. The finite element models of the structures can be seen in fig. 4.

To ensure that the design model reflected the real structure's behaviour, all the details were modelled including the connection ducts, the injection holes, the rail sleepers and the rails with their exact geometry. One full and one half slab were modelled to be able to investigate the behaviour of the joints. For the connecting surface, an interface material was determined which could only support compression stresses. During the loading process it was found that the slabs 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.

In the model, various material model configurations were used for the different structural elements. For the concrete slab, CEM II concrete material model was used with an added fracture energy material model parameter [7, 8]. For modelling the subbase and the subgrade, linear elastic materials were used with different elastic modulus. The same material model was used for the sleepers as well. For the steel elements, such as the rails and connection cables, a Von Misses material model was used which could 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.

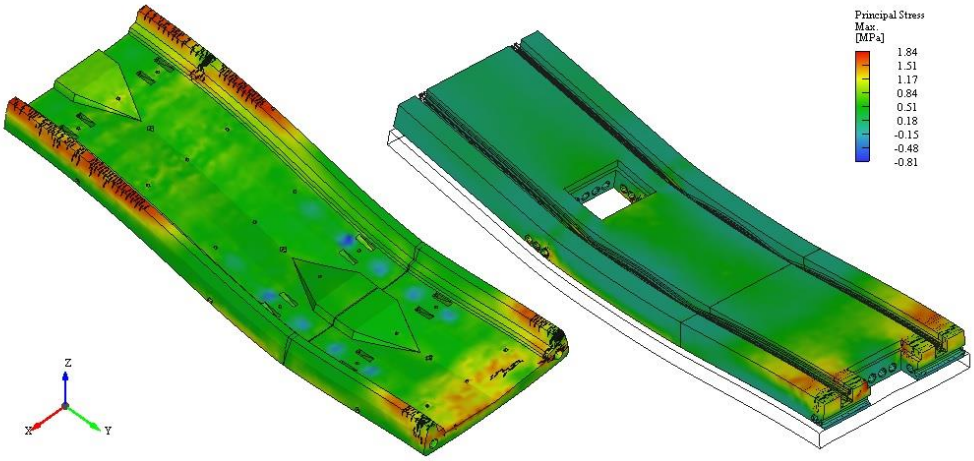

Fig. 4. PCAT numerical model in ATENA (left: off-street slab, right: on-street slab)

To check all the possible effects on the slabs, different loading scenarios were carried out in the finite element software as during its lifecycle, the track slab will be subjected to various conditions. Because the slab is pre-casted, the first loading will come from demoulding of the element. In this case a time dependent material model was used, which means the material parameters changed during the analysis following the hardening of the concrete. With this analysis, the optimum demoulding time can be estimated as well. To the demoulding load, a lifting and tearing force was added to the early age concrete slab. After this, but also in early ages, a rotation effect occurs: the demoulding was made upside down, but the racking of the precast slabs was in the other direction. In these two load cases the lifting and rotating of the elements were also 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 stacking. The highlighted design target was to check the ultimate and serviceability limit states under the train's load and thus 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 the Ultimate Limit State (ULS) the principal stresses were checked and in the Serviceability Limit State (SLS) 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 also done for all the loading positions. The number of the cycles were back-calculated from the estimated lifetime of the structure and the average daily traffic. The finite element software calculated two additional fatigue strains for the maximum fracturing strain [9], one handled 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.

The structure complied with all the design requirements both in ULS and in SLS. In ULS the target was that the structure resists the loads with the appropriate 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) [2]. Both design cases met the requirements in every loading position and design situation.

The slabs deformation was realistic, and 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 cracks appeared in the structure.

2.4 Real scale test

The PCAT slab was installed within their test pit to measure the actual deflection of the slab along the structure using an applied load at various locations. The position of the load was replicated by the arrangement used in the FEM simulation. The PCAT off-street slab was designed for 12 tonne axle loads. For the testing it was proposed, after the first suite of loading at 8 tonne that the load be increased in 4 tonne increments up to 24 tonne, subject to slab performance during the test.

The loading of the slab was carried out using the Rail Trackform Stiffness Tester (RTST) which was 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 RTST apparatus is mounted on a transport frame that can be moved along on rubber-caterpillar tracks whilst off track and then switched to rail wheels. On ballasted tracks, geophones measure the deflection response of the ballast, sub-ballast, formation and subgrade enabling 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.

To ensure the numerical model's accuracy, a finite element analysis was calculated for the RTST test. The model contained the whole test setup including: the concrete pit, the compacted soil, and the two slabs with the previously mentioned detail. The effect of the RTST was added to the slab by using a steel plate which corresponds to the loading beam's foot. The measured value in the finite element model was the vertical deflection. It was measured at 9 different points replicating where the geophones were positioned for the actual test. 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 closely mirrored what happened in reality and the differences between the measured deflections in the model and in the test was less than 0.1 mm. Only one loading scenario occurred where the difference was higher than modelled and this was where the load was positioned over the female joint. This was outlined in the AECOM report which determined a very poor subgrade stiffness in this area. The results of the test and the FEA can be seen in fig. 5.

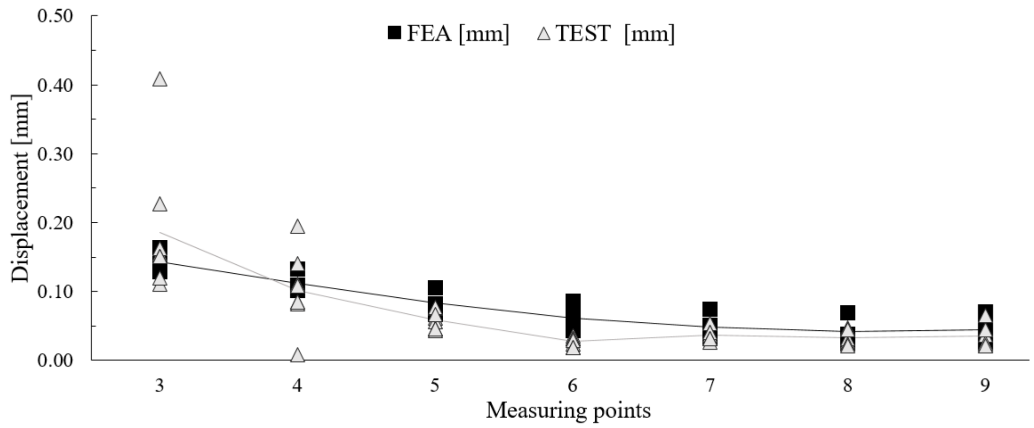

Fig. 5. Results of RTST and FEA

3. Synthetic fibre reinforcement in tunnel structures

Macro synthetic fibre reinforcement's popularity is continuously growing and finds new sectors in tunnel engineering also. The advantage of use of synthetic macro fibres is that they can also be used in precast concrete and in shotcrete structures, where protruding steel fibres can be a ballast hazard.

3.1 Shanghai metro extension

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. 6.

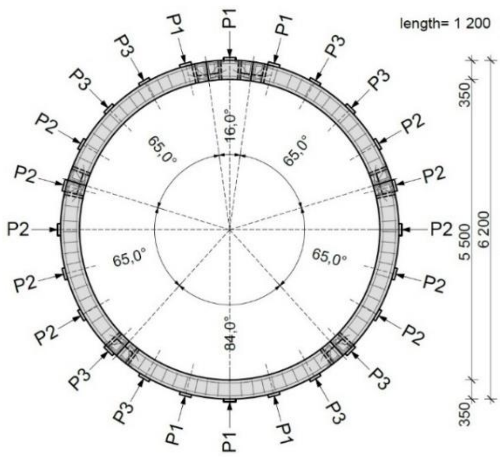

Fig. 6. Geometry, loading configuration and the real scale test

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 [10]. 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.

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 50 MPa cubic, the strain at this stress was 1.8 ‰ (0.0018). The concrete strength class was C40/50 according to the European design standard Eurocode 2 [2]. The grade of the steel bar reinforcement was HRB335 with a yield strength of 335 MPa, using ribbed bars.

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 [11]. 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. 6.

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 displacement was measured at 14 points of the ring. The most important positions herein were the 0, 90, 180 and 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. 7.

3.2 Finite element analysis of the tunnel

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.

The concrete was modelled with an advanced material model, using the combined fracture surface criteria [7]. 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 [8]. 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 [12].

The concrete has a stress-strain diagram according to Eurocode 2 [2]. 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 rebar 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.

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.

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. 7 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. 7.

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.

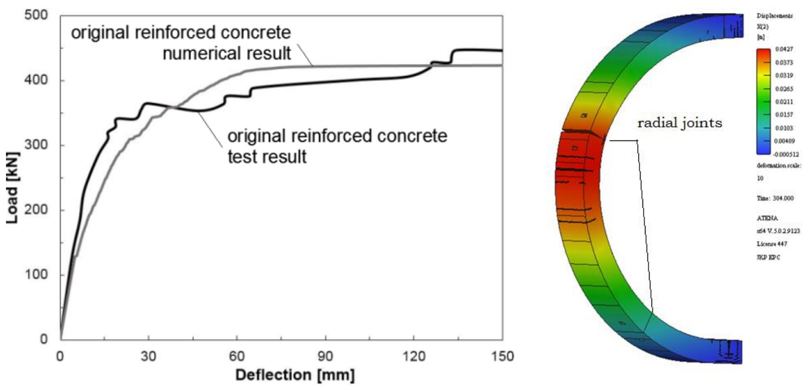

Fig. 7. Results of the laboratory test and FEA

After these calculations were made three viable solutions were proposed, which can be taken from tab. 1.

Tab. 1. Reinforcement optimization with using synthetic macro fibres

	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 [kg]	steel: 559 fibre: 0	steel: 344.3 (-39.8%) fibre: 46.3	steel: 282.4 (-49.5%) fibre: 54.0	steel: 140.4 (-75.0%) fibre: 77.2

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 1 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 improvement in 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 future.

4. Industrial floors

Although fibre reinforced concretes have been used for a long time in the industry, there are only a few design methods available. Among these, the UK Concrete Society's Technical Report 34 [13] is the most popular for industrial floors. While the third edition used the R_{e3} value for characterizing fibre reinforced concretes, the fourth edition tended to use solely the more precise CMOD value (Crack Mouth Opening Displacement) of residual flexural tensile strength. The R_{e3} value can be obtained by a laboratory test defined by the Japanese JSCE [14] standard, while the CMOD value of residual flexural tensile strength can be obtained by the analysis defined in the RILEM TC162 [3] and EN 14651 [15] standard. The values of residual flexural tensile strength characterize fibre reinforcement more accurately than the value of R_{e3}. The guideline clearly states that only the steel- or macro synthetic fibres can be used during designing, micro fibres (mono and fibrillated) cannot be considered from a structural aspect. Micro fibre reinforced concrete as a concrete structure can be designed with a linear calculation, like plain concrete. Based on this “replacing the reinforcement by micro fibres” cannot be valid from a structural aspect.

ACI 360 [16] and TR34 2003 [13] take the data of the fibre reinforced concrete according to the Japanese standard [14], the TR34 2013 [17] does so according to the RILEM TC162 [3] and EN 14651 [15] standards, while the Austrian guideline does so according to the Richtlinie Faserbeton guideline [18]. Material parameters of the steel- or macro synthetic fibre reinforced concrete should be provided by the manufacturer based on their own examinations, but for larger projects it is worth taking the results derived from laboratory analysis of test specimens made from the concrete to be used for the project. As the examination of the concrete should be carried out at 28 days of age, it rarely gets completed before the project.

4.1. Numerical model of the structure

The first step of finite element modelling of a floor is providing the proper geometry for the software, which gives the most realistic results. The soil below the industrial floor, the concrete floor and its reinforcement itself and modelling certain load bearing slabs are equally important. Different parts of the floor (saw-cut joints, dowels, edge) require separate models, this is the only way to be certain that our structure is capable of the necessary load bearing capacity in all of its parts.

Subgrade modelling offers multiple methods. While in one of them the soil is built as a separate material with material models describing proper soils (Drucker-Prager or Mohr-Coulomb material model), the other is a simpler, but similarly precise method with less calculation time, which is modelling the soil by a nonlinear spring. In this case the rigidity of the spring substituting the soil must be set so that it provides the real load bearing capacity of the soil to compression, while it has a close to zero load bearing capacity to tension.

These springs defined this way are under the industrial floor. It is advisable to carry out the design in a three-dimensional model so that the spatial stress state can develop properly. Also, the complex load situations can only be correctly modelled this way.

Finite elements are hexahedra elements with 20 nodes, which can properly follow spatial movement of the structure as well as spreading of the cracks. At least four finite element lines are required to be placed along its depth, as this is the certain way to properly follow flexural stresses. As running time of the calculation depends from the number of finite elements, it is advisable to take advantage of the symmetry of the structure if it is possible, which allows modelling only the half (in case of single symmetry) or the quarter (in case of double symmetry) of the geometry of the structure as sufficient. There is an opportunity to place point-, line and surface supports as well in the software.

A typical FE model of an industrial floor can be seen in fig. 8.

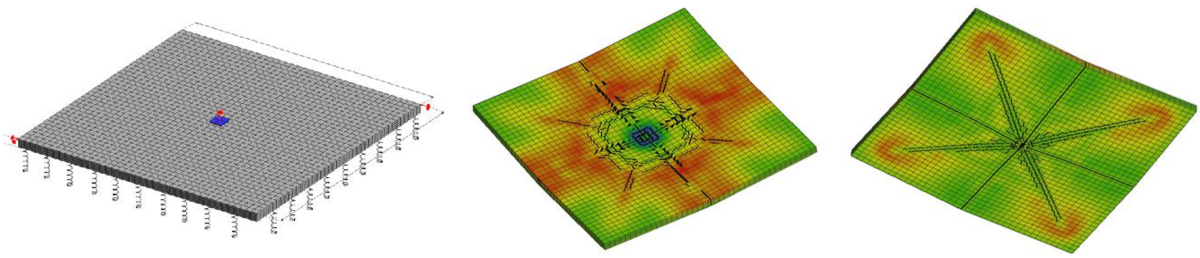

Fig. 8. Crack propagation and FE model of an industrial floor with central point load

4.2. Defining loads and actions

In the finite element software it is possible to define different loads and actions, such as structural loads, displacement or thermal actions. Typically, industrial floors need to be designed for structural loads. Considering their dimensions these loads can be point loads (rack leg load, wheel load), line loads (crane rails) and distributed loads (stored materials, containers).

Special loaded floors can also be modelled by finite element software, for instance the floors of cold storage units or floors that are exposed to sunlight (thermal load). In this case the software allows linear changing of the thermal load, by which it can be considered that the upper layers are getting colder/hotter than layers closer to the subbase. As mentioned before there is also a possibility to model the shrinkage of the concrete, which can be significant in the initial stages of the floor.

When discussing special loads, it is certainly substantial to mention load by fire. Similarly to the shrinkage model it is possible to define a material model dependent on temperature by the finite element software, which can consider the decrease of concrete parameters as an effect of the increase in temperature. Besides the above listed opportunities, it is also possible to consider creep of the concrete, corrosion of reinforcing steel and the deterioration of bond of reinforcing steel.

During finite-element design, dynamic and fatigue loads can also be modelled besides static load. In the case of dynamic load, the speed of load transmission can be modelled. Fatigue design is of key importance for concrete structures if the frequency of the load is high, such as floors of storage halls with regular movement of forklifts, or floors with the rail of an industrial crane. In this case there is an opportunity to decide with finite element simulation whether the floor can withstand the load cycle that can be even several million cycles, as well as defining how many cycles it takes until failure. With these kinds of calculations it is possible to carry out a life cycle design as well.

4.3. Comparison with laboratory experiments

There are a relatively few real size laboratory tests of industrial floors that can be found in literature, which is probably caused by the large laboratory space requirement and the complexity of the testing itself.

An industrial floor was tested by a middle point load and the results of the test were measured until failure [19]. This load bearing capacity was also calculated with the help of guidelines and different types of FEA. The correlation of the results can be seen in fig. 9.

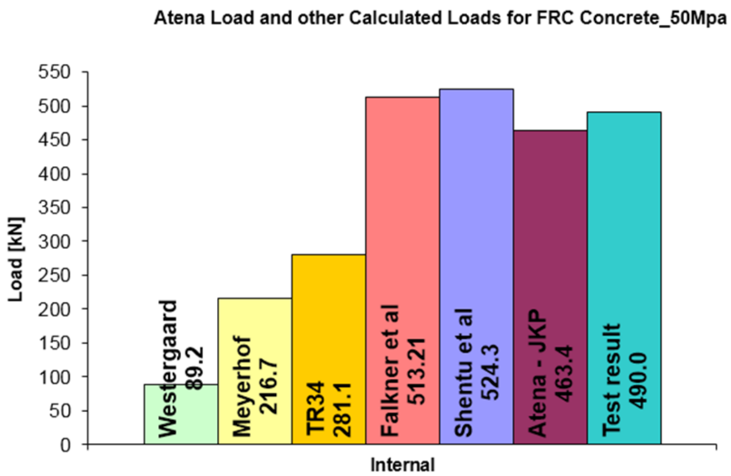

Fig. 9. Comparison of the laboratory test and different analytical and numerical results

It can clearly be seen that the analytical results are much lower than the actual load bearing capacity, as these results include a large factor of safety. Finite element designs of Falkner [20] and Shentu [21] are not far from the real test results, however they defined a higher load bearing value than the actual load bearing capacity, so the approximation is not in favour of safety. The material model developed in ATENA [7] provides a good approximation to the actual load bearing capacity of the floor and is still on the safe side.

On the basis of this data, it can be confirmed that it is possible to provide a good approximation of the load bearing capacity of a floor with the help of a finite element software. The formulae defined by the guidelines are only able to define the peak load of an industrial floor with significant safety.

4.4. International references

The design of several international projects were made by the above-mentioned method. In many cases the complex load arrangement or varying floor thicknesses interfered with the application of the formulae provided by the guidelines, thus in these cases the designs were carried out using a finite element software. It also occurred on several occasions that the load bearing capacity of an already finished industrial floor needed to be defined afterwards, due to the changing functions of the warehouse. These instances required load values quite close to reality, as this was the only way the investment would happen. The use of finite element software became an inevitable necessity as the conservative calculation method of the guidelines had a significant safety factor included.

An industrial floor with a total area of 31,000 m^2 was made in Istanbul, Turkey for EAE Electricity Factory. The floor thickness was 200 mm, the concrete strength class was C30/37, and the synthetic fibre type and dosage was 3.5 kg/m^3 BarChip MQ58. Calculation was made by ATENA [6].

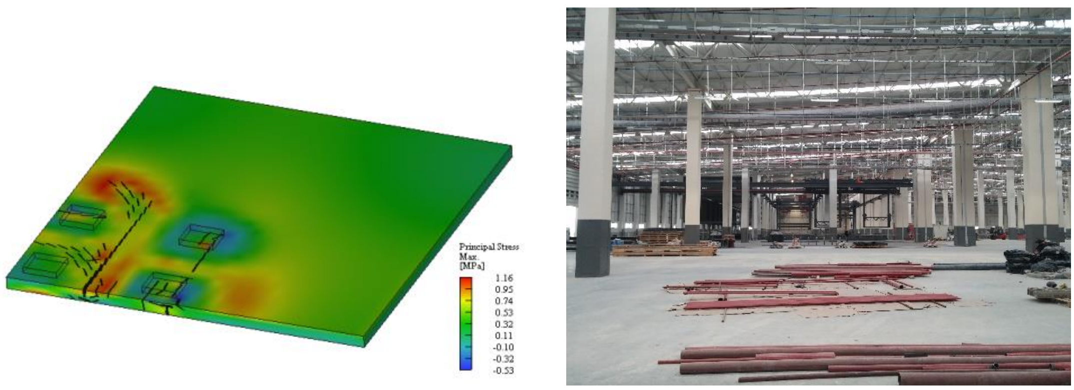

Fig. 9. Industrial floor of EAE Electricity Factory, Turkey

A skate park was made in Gödöllő, Hungary, where due to serviceability, no dilatation (saw cuts) were allowed. Because of the strict conditions on cracks and the complex geometry, it was required to use the finite element method [22]. The floor thickness was 150 mm, the concrete strength was C30/37, and the synthetic fibre type and dosage was 3.0 kg/m^3 BarChip MQ58. Calculation was made by ATENA [6].

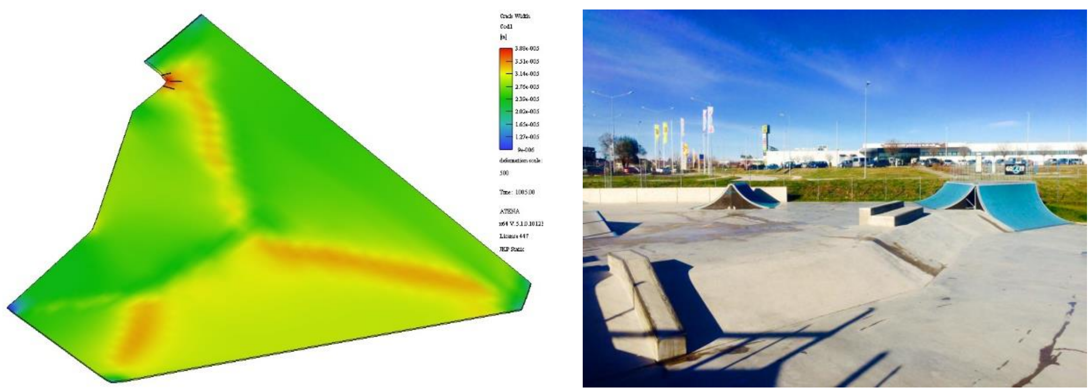

Fig. 10. Skatepark in Gödöllő, Hungary

An industrial floor with a total area of 85,000 m² is being made in Campinas São Paulo for a logistic center called São Loureço Armazéns Gerais. The floor thickness was 160 mm, the concrete strength class was C30/37. The synthetic fibre type and dosage was 5.625 kg/m^3 BarChip MQ58. Calculation was made using TR34 guideline and was also verified with Finite Element Analysis.

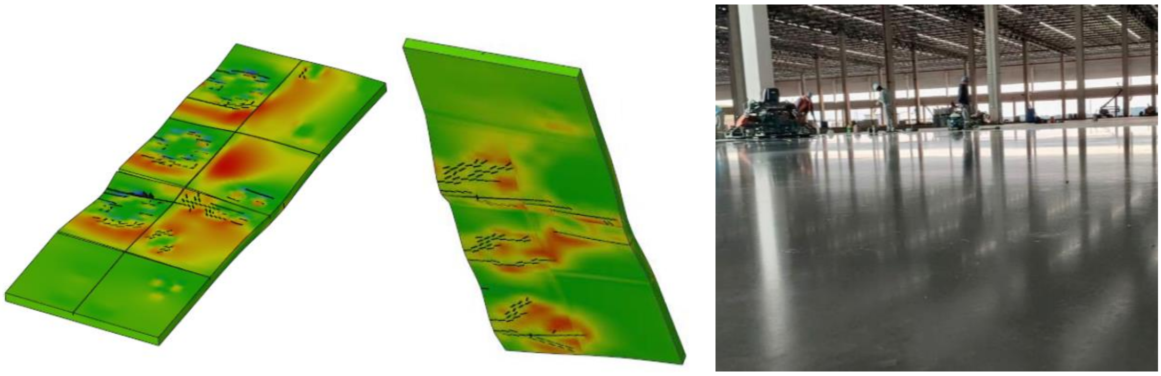

Fig. 11. Logistic center São Paulo

5. Summary

In this paper, a number of applications of synthetic macrofibre reinforced concrete were presented. These segments of the construction industry are just some of the areas where the use of synthetic fibres has great advantages, both economically and environmentally. However, while the use of synthetic macro fibre is fairly easy, the design of this material needs an advanced calculation method, such as the finite element method. In most cases the simple analytical calculations would not yield good results. Both fibre and the use of advanced finite element methods have huge potential for reducing CO_2 emissions, which will be an important task for future engineers.

6. References

[1] RIDOUT A.: Macro-fibre-reinforced concrete slab track. Concrete. September 2009, pp. 16-18.

[2] EUROCODE EN 1992: European Code for design of concrete structures: European Committee for Standardization. 2004, Brussels.

[3] VANDEWALLE L. et al.: RILEM TC 162-TDF : Test and design methods for steel fibre reinforced concrete. Materials and Structures. January-February 2000, Vol. 33, pp 3-5.

[4] https://www.precastadvancedtrack.com

[5] HAMMOND J.: Construction and Reinforcement. Railing Professional, October 2016 Issue, pp. 162-163.

[6] https://www.cervenka.cz/products/atena

[7] CERVENKA J., PAPANIKOLAOU V. K.: Three dimensional combined fracture-plastic material model for concrete, International Journal of Plasticity. 2008, Vol. 24, pp. 2192-2220.

[8] JUHÁSZ K.P.: The effect of synthetic fibre reinforcement on the fracture energy of the concrete. Doctoral thesis, Budapest University of Technology and Economics, Budapest. 2018.

[9] PRYL D., CERVENKA J., PUKL R.: Material model for finite element modelling of fatigue crack growth in concrete. Procedia Engineering 2. 2010, pp. 203–212.

[10] WINTERBERG R.: Segmental Tunnel Linings with Fibre Reinforced Concrete. 2012, SPET Journal No. 35, Society of Professional Engineers Thailand, Bangkok.

[11] BI X, LIU X, WANG X.: Experimental investigation on the ultimate bearing capacity of continuous-jointed segmental tunnel linings. China Civil Engineering Journal. 2016.

[12] ITAtech Activity Group Support: ITAtech Design Guidance For Precast Fibre Reinforced Concrete Segments. ITAtech Report n7, draft, 2015. https://about.ita-aites.org/wg-committees/itatech/publications/1359/itatech-guidancefor-precast-fibre-reinforced-concrete-segments-vol-1-design-aspects

[13] The Concrete Society: TR34 Concrete Industrial Ground Floors. 2003, Crowthorne.

[14] Japan Society of Civil Engineers: Method of Tests for Flexural Strength and Flexural Toughness of SFRC. Standard JSCE SF-4, 1985.
[15] European Committee for Standardization: Test Method for Metallic Fibre Concrete. Measuring the Flexural Tensile Strength (Limit of Proportionality (LOP), Residual), EN 14651+A1:2007. Brussels, Belgium, 2005, https://doi.org/10.3403/30092475
[16] ACI: 360.R-10, Guide to Design of Slab-on-Ground, 2010.
[17] The Concrete Society: TR34 Concrete Industrial Ground Floors. 2013, Crowthorne.
[18] Österreichische Vereinigung für Beton- und Bautechnik: Richtline Faserbeton. Wien, 2008.
[19] ELSAIGH W.A.: A Comparative Evaluation of Plain and Steel Fiber Reinforced Concrete Ground Slabs. University of Pretoria, 2001.
[20] FALKNER H., HUANG Z., TEUTSCH M.: Comparative Study of Plain and Steel Fiber Reinforced Concrete Ground Slabs. Concrete International. 1995, Vol.17 (1), pp. 45-51.
[21] SHENTU L., JIANG D., HSU C.T.T.: Load Carrying Capacity for Concrete Slabs on Grade. Journal of Structural Engineering. 1997, Vol 123, pp. 95-103.
[22] JUHÁSZ K.P., ÓVÁRI V.: Gödöllői gördeszkapálya statikai és betontechnológiai megoldásai. Beton XXIII. 2015, Vol. 3-4.