Synthetic Fibre Reinforcement in Concrete Structures – Applications and Design

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Abstract. Macro synthetic fibre reinforcement has become widely used in concrete structures, such as tramlines, tunnels, industrial floors and precast elements. With using synthetic fibres as a reinforcement in concrete structures the casting time and the labour work will decrease, while the ductility will increase. In most cases the steel reinforcement can be omitted entirely from the structures using macro synthetic fibres, which can lead to more green structures. Nowadays, the environmental consciousness, minimizing the environmental footprint and the CO_2 emissions have taken a significant role in every part in the industries. Using synthetic fibre reinforcement in concrete structures, the CO_2 emissions are much lower than with traditional steel reinforcement, because of their production, shipping and labour work have less environmental loads. The uniformly distributed fibres in concrete can also increase the residual flexural strength of the concrete independently from the location which 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. The typical use of precast FRC elements are tunnel segments, pre-cast wall and roof elements and also tramline elements. The calculation process of these structures always has to comprise the static load, the dynamic load and if exist the effect of cyclic loading, i.e. fatigue. The precast elements also needed to be designed for temporary situations, such as demoulding, lifting, transporting and placing on site. These effects can be handled with 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.

Keywords: FRC · synthetic fibres · finite element analysis · concrete · design

1 Introduction

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

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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 an environmental point of view, the choice of synthetic macro fibres is obvious, and the development and standardization 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.

2.1 Cast in Place Tramlines

One of the most common structures for tramlines is the cast in place track slab. 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].

In 2010 and 2011, during the extension and reconstruction process of the A and C sections of tramline Nr. 1 in Szeged, Hungary 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. 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.

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.

One of the most successful design references is the PCAT system. PreCast Advanced Track's (PCAT) 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 [4]. 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 slabs connect to each other with a dry male-female joint for initial alignment and then with curved bolt connections. 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.

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). 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 [5]. 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.

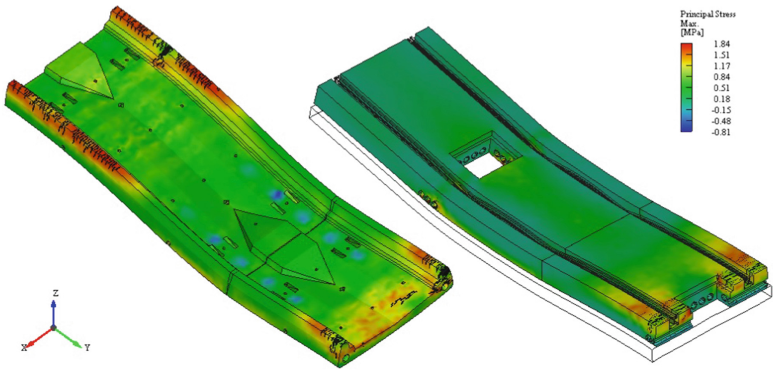

Fig. 1. PCAT numerical model in ATENA (left: off-street slab, right: on-street slab).

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 [6, 7, 11]. 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.

The structure complied with all the design requirements both in ULS, in SLS and Fatigue [8] (Fig. 1). 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]. All design cases met with the requirements in every loading position and design situation.

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 loading of the slab was carried out using the Rail Trackform Stiffness Tester (RTST) which was developed by. 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. 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.

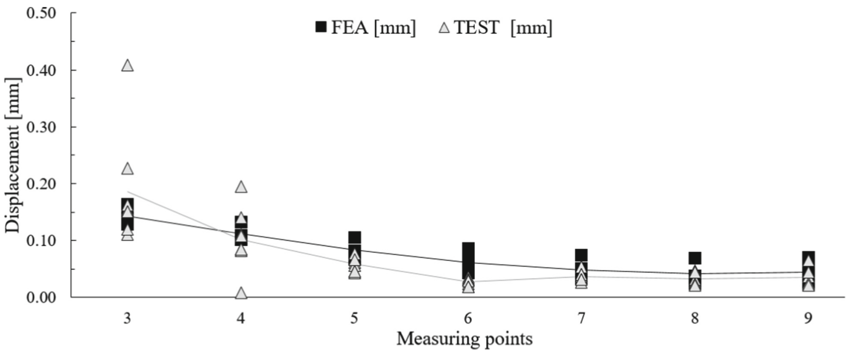

Fig. 2. Results of RTST and FEA.

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. 2.

3 Synthetic Fibre Reinforcement in Tunnel Structures

Macro synthetic fibre reinforcement's popularity is continuously growing and finds new sectors in tunnel engineering also [9]. 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

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 [10]. 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°, the key 16 degrees, and the four sides 65°.

Fig. 3. Geometry and loading configuration of the real scale test.

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. 3.

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. 3.

The displacement was measured at 14 points of the ring, from these results a load-displacement diagram was generated.

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. From these results the material parameter for FRC was defined with invers analysis.

The concrete and the fibre reinforced concrete was modelled with the above presented material models.

Steel rebars and bolts were modelled as discrete link elements with a uniaxial ideal elastic-plastic stress-strain material model.

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. 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. 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. 4 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 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.

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.

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 hybrid solution 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.

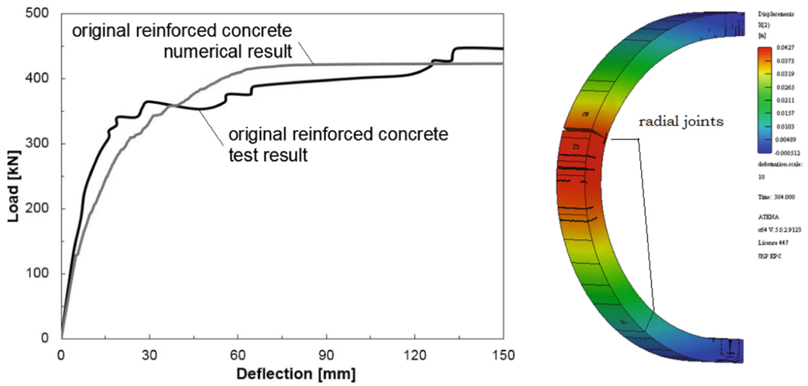

Fig. 4. Results of the laboratory test and FEA.

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 [12] is the most popular for industrial floors. This 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.

ACI 360 [15] take the data of the fibre reinforced concrete according to the Japanese standard [13], the TR34 2013 [12] does so according to the RILEM TC162 [3] and EN 14651 [14] standards, while the Austrian guideline does so according to the Richtlinie Faserbeton guideline [16].

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 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.

As running time of the calculation depends on 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.

4.2 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 [17]. This load bearing capacity was also calculated with the help of guidelines and different types of FEA (Fig. 5).

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 [18] and Shentu [19] are not far from the real test results, however they defined a higher load bearing value than the actual load bearing capacity. 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.

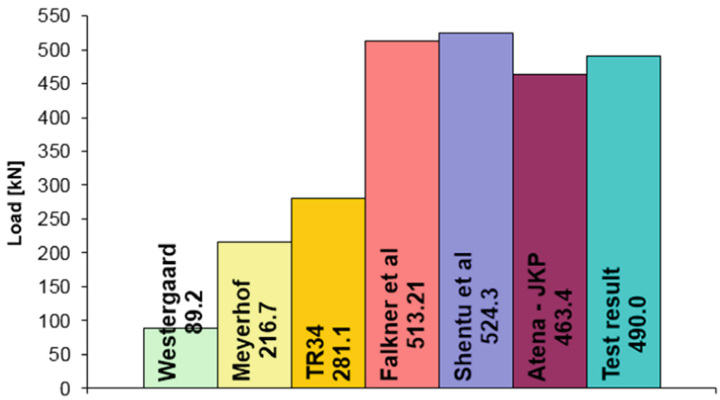

Fig. 5. Comparison of the laboratory test and different analytical/numerical results.

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.

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.

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