Opportunities for synthetic fibre reinforcement in concrete tramlines

Karoly Peter Juhasz[1], Peter Schaul[2],

[1] : Budapest University of Technology and Economics, Department of Mechanics, Materials & Structures, Műegyetem rakpart 1-3, Budapest, Hungary

[2] : Budapest University of Technology and Economics, Department of Construction Materials and Technologies, Műegyetem rakpart 1-3, Budapest, Hungary

Abstract

In the past decade macro synthetic fibre reinforcement has become widely used for concrete track slabs including tramlines. By using macro synthetic fibres as a reinforcement in concrete slabs both the casting time and manual work will decrease, while the concrete's ductility will increase. In addition the durability will be higher with using synthetic fibres, and the carbon footprint will be lower compared to steel mesh or fibre reinforcement. In most cases the steel reinforcement can be omitted entirely from the structures using macro synthetic fibres. The uniformly distributed fibres in the concrete can increase the residual flexural strength of the concrete independently from the location. This makes it possible to use the fibres in both cast in situ and precast elements used for tramlines. The calculation process for these structures always has to comprise of both the static load, the dynamic load and the effect of cyclic loading, i.e. fatigue. These load calculations can be handled using advanced finite element analysis software, which is specialized for concrete and fibre reinforced concrete structures. The paper will present the opportunities for using macro synthetic fibres together with the process of designing fibre reinforced concrete tramlines.

Keywords

macro synthetic fibre reinforced concrete, finite element analysis, tramline design, concrete track slab

1 Introduction

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 or precast structures.

Corrosion resistance is the greatest benefit of macro synthetic fibre where durability can be assured but also synthetic fibres behave better with 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 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 (Ridout, 2009). 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 track slab was made using a traditional slab structure with a pre-stressed concrete sleepers on it supporting the rails (Figure 1). The reinforcement was a hybrid of traditional steel bar reinforcement together with macro synthetic.

Figure 1: Elasto Ballast track railway (Ridout, 2009)

The first synthetic fibre reinforced track slab in Europe was the Docklands Light Railway near London in 2004. The slab was reinforced with 6 kg/m^3 macro synthetic fibre reinforcement (BarChip48 high quality macro syntethic fibre) which made the construction process considerably faster (Ridout, 2009).

The first only macro synthetic fibre concrete cast in place tramline in Europe was built in Szeged, Hungary. Macro synthetic fibre was considered over steel reinforcement as at a certain point in the track it was not possible to use any steel reinforcement due to the operation of a special switch that collected stray current and so this part of the track was reinforced with macro synthetic fibre reinforced concrete. Because of the positive experiences and cost saving in this part of the track the contractor changed to this solution for the entire track and thus replaced all the steel reinforcement with macro synthetic fibres (Nagy et.al. 2014; Nagy et.al. 2015a; Nagy et.al. 2015b).

Beside the cast in place solution the use of precast concrete tramline 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 first and only macro synthetic fibre reinforced precast concrete track to date is the PreCast Advanced Truck (PCAT) system (Hammond, 2016). This precast element is highly optimised both by the dosage of the fibre and its geometrical shape.

In this paper both the cast in place and precast macro synthetic fibre reinforced concrete tramline structures and their design processes will be presented.

2 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 form worked track slab or the track slab extruded 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 pours the macro synthetic fibre reinforced concrete between the moving formwork. In this case the joints are made by saw cutting the slab, which reduces the likelihood of any crack formation.

2.1 Szeged tramline

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

Figure 2: Tram line in Szeged, Hungary

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 (EUROCODE, 2004). Finite element analysis was made on the basis of the recorded material model recommended by RILEM TC 162-TDF (Vandewalle, et.al., 2002). According to the calculations the tramway met the standard loads and load combinations.

2.2 Tramlines around the world

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.

2.3 Finite element analysis of the tramlines

Initially the finite element analysis of the tramlines was made by using Ansys finite element software. This software can handle the Rankine and Von-Misses combined failure criteria, which is a good approach for a fibre reinforced concrete material as the effect of the fibres is taken into consideration as a plastic model after the cracking (after yield point). Although because of the plastic material model both the crack propagation and the crack width of the concrete cannot be properly determined.

Due to this only a concrete specific finite element software should be use for the design and optimisation of fibre reinforced concrete tramlines. The two most well-known software are the ATENA and the DiANA. In our design ATENA software was used. ATENA uses Menétrey-William and Rankine combined fracture-plastic failure surface (Rankine cube is at the tension side) (Cervenka and Papanikolaou, 2008). Tension is handled by a fracture model, based on the classic orthotropic smeared crack formulation and the crack band approach. It uses 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 (Kolmar, 1986). The model showed that the concrete met the stress-strain diagram criteria 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 method that could realistically represent the cracks in a quasi-brittle material which is the main advantage of this advanced material model.

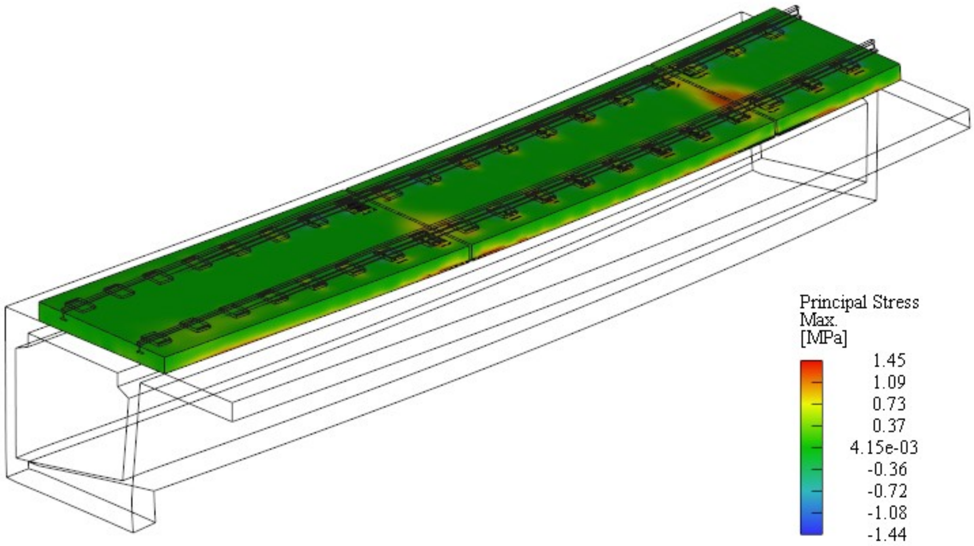

Figure 3: Tramline on a viaduct calculation with ATENA

However, it is important to note that these models only define the peak strength of the material and not the post-cracking response. Numerous other models can be used to approximate the post-cracking capacity of FRC such as the Modified Fracture Energy Method (Juhász, 2013) presented in the ITAtech guideline (ITAtech Activity Group Support, 2015) which was used here.

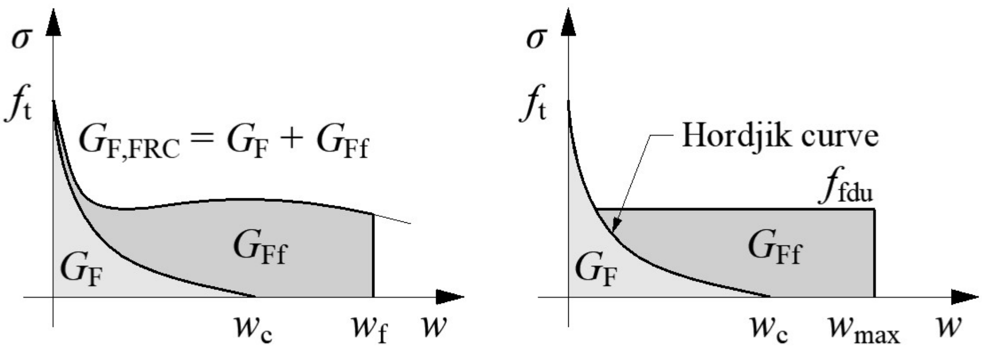

Figure 4: a) Fracture energy of FRC b) Tensile function used in the calculations

When stresses exceed the tensile strength of the concrete it will crack. There will be residual stress at the crack surface that is dependent on the crack width opening distance. This stress is associated with an energy, called fracture energy (G_F). Fibres increase this fracture energy (G_{Ff}), thereby making the concrete a more ductile material. The most important criterion for the selection of the FRC material model is to be able to model this increased fracture energy ($G_{F,FRC}$) and select a value that is appropriate to the FRC used for a design (see Figure 4).

3 Precast concrete tramlines

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 other loads beside above their final load cases such as early age demoulding, rotation, lifting, stacking, transporting and installation on site. Usually these elements are made from concrete with higher strengths i.e. from C40/50 than the cast in place slabs i.e. from C25/30. Generally the precast elements have a higher dosage of macro synthetic fibre to the track slabs that are cast in place.

3.1 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 (Hammond, 2016). 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 maximising the slab's strength and minimises the stiffness needed for the track foundation. 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. 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.

Two types of slabs were developed to serve all potential installation requirements. One is 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). This type of the slab can be used in streets and thanks to the sunk 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 120 year lifetime.

3.2 Finite element model of the structure

The numerical modelling of the PCAT slabs were done with ATENA finite element software. The finite element models of the structures can be seen in Figure 5.

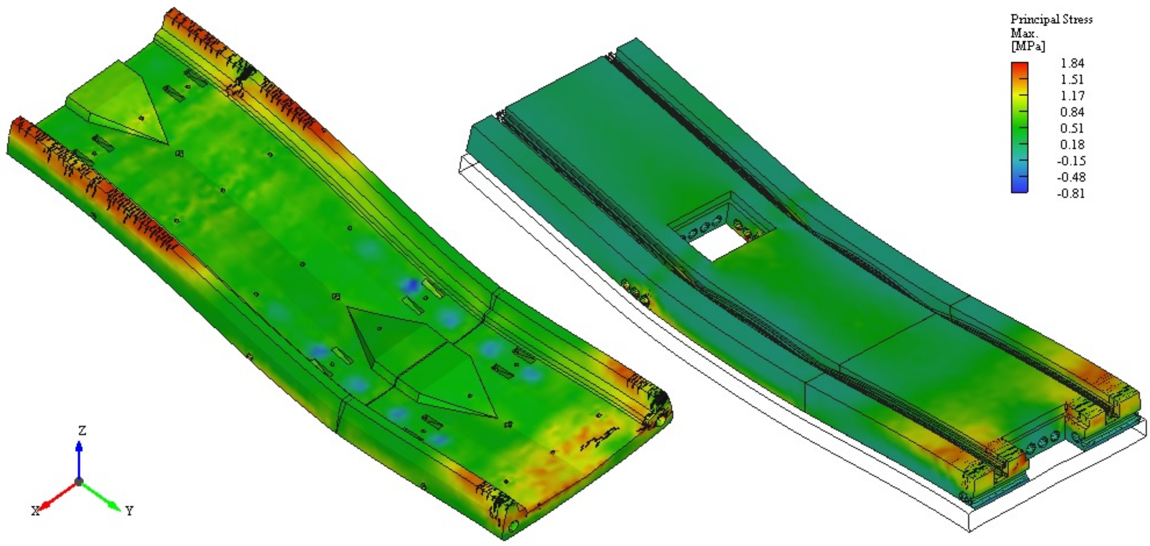

Figure 5: Principal stresses and cracks in deformed ATENA model

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. A one and a one 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 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 the previously presented concrete material was used. For modelling the subbase and the subgrade linear elastic materials were used with different elastic moduli. 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 case to be as close to the real behaviour as possible.

To check all the possible effects on the slabs, different loading scenarios were carried out in the finite element software as 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 were in the other direction. In this two load case 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 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 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 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 calculated two additional fatigue strains for the maximum fracturing strain (Pryl et al. 2010), 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). 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.

3.3 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 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) (Figure 6) which was 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 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 track 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 property, 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 with 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.

Figure 6: The RTST testing (AECOM PCAT Test report)

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 was 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 Figure 7.

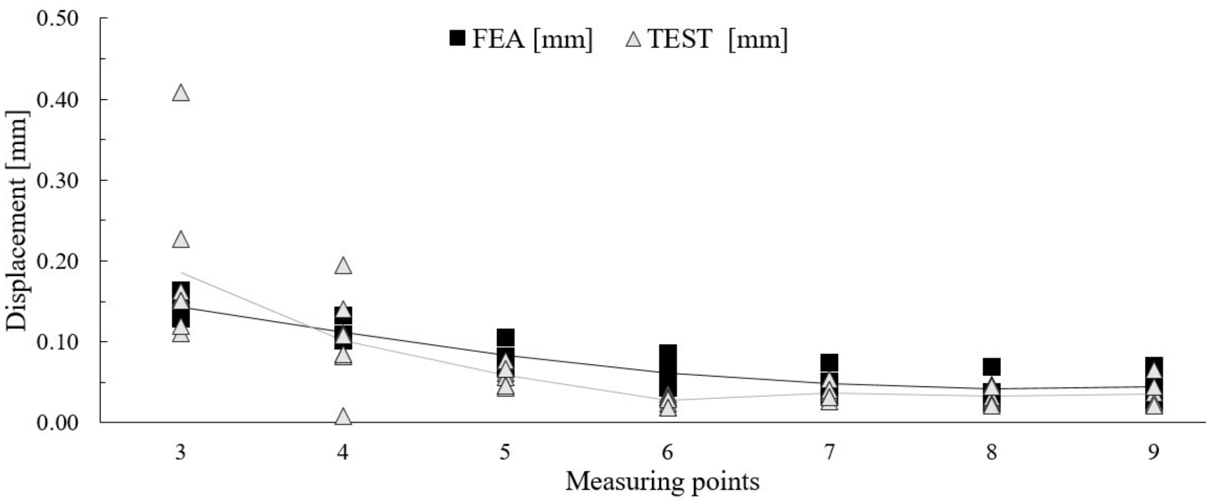

Figure 7: Results of RTST and FEA

4 Conclusion

The use of macro synthetic fibre reinforced concrete has become more and more popular in the building industry and thus also in the concrete track slab constructions. Track slab structures are typically heavily exposed to weather and mechanical loads, and because of this must have sufficient ductility and durability. At the same time the repair or replacement of these elements is difficult as generally the traffic must be stopped for a long periods during this process. Based on these criteria the use of macro synthetic fibre is a good alternative reinforcement to mesh and steel bars. The concrete reinforced with the already mixed in corrosion-free fibres is easy to handle and the track slab can be constructed faster, thus by using FRC, labour can be decreased and the ductility increased. Further macro synthetic fibres are better for dynamic loads also, which is a significant advantage of this type of construction.

Design and optimizing of the track slab means the determining of the required thickness of the track slab and the macro synthetic fibre dosage for the varying load cases, such as ultimate and serviceability limit state, and fatigue. For these special tasks advanced finite element software is needed. The influence of the fibres could be taken into account by the modification of the fracture energy of the plain concrete. These design models have been validated by full scale laboratory tests.

5 References

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

EUROCODE EN 1992 (2004), *European Code for design of concrete structures: European Committee for Standardization*, Brussels.

Hammond, J. (2016), *Construction and Reinforcement*, Railing Professional October 2016 Issue, pp. 162-163.

ITAtech Activity Group Support 2015, (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*, Fibre Concrete 2013: Technology, Design, Application, pp. 89-90.

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

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

Nagy J., Juhász K. P., Mészáros A. (2014), *The beginning: the tramway in Szeged*, Innoteka, 2014 September, pp. 24-25.

Nagy J., Juhász K. P., Herman S., Herman K. (2015a), *Az első magyar, műanyag szállal erősített és füvesített villamospálya 1. rész (The first Hungarian synthetic fibre reinforced and grassed tramline 1st part)*, Sínek világa, 2015/2, pp. 18-21.

Nagy J., Juhász K. P., Herman S., Herman K. (2015b), *Az első magyar, műanyag szállal erősített és füvesített villamospálya 2. rész (The first Hungarian synthetic fibre reinforced and grassed tramline 2nd part)*, Sínek világa, 2015/3, pp. 10-14.

Ridout, A. (2009), *Macro-fibre-reinforced concrete slab track*, Concrete, September 2009, pp. 16-18.

Vandewalle, L., et al. (2002), *RILEM TC 162-TDF : Test and design methods for steel fibre reinforced concrete,* Materials and Structures, Vol. 33, January-February 2000, pp 3-5.