FIBRE REINFORCED CONCRETE FOR PRECAST TUNNEL SEGMENTS

Jan L. Vítek [1], Matouš Hilar [2], Petr Vítek[3]

Abstract:

Fibre reinforced concrete is a promising material for application in precast concrete tunnel segments. The paper focuses on the material properties of steel fibre reinforced concrete and comparison with those of the classical reinforced concrete. The experimental results on specimens made of steel fibre reinforced concrete are presented. Comments on numerical modelling of steel fibre reinforced concrete indicate that there is a field for future research. If the geotechnical conditions are reasonable the steel fibre reinforced concrete may represent a cost-effective alternative to the classical reinforced concrete segments.

Keywords: Concrete, steel fibres, numerical modelling, tunnel segments, experiment

1. Concrete reinforced with fibres or with bars

Fibres in concrete should improve its mechanical properties. The non metallic fibres, which have a small modulus of elasticity, improve the performance of concrete in early stages (prevention of initial cracking). Polypropylene fibres are used for improvement of the fire resistance. In hardened concrete, the steel fibres are the most efficient due to their high modulus of elasticity and due to their high tensile strength. In the following, the application of only steel fibres is assumed.

Theoretically the fibres are uniformly distributed in the concrete so that the material properties should be similar in all directions. Practically, the differences were observed, if the loading acts in the direction of the casting process or if it acts in the other direction. The amount of fibres may vary. Usually the lowest fibre content is considered about 30 kg/m^3. The maximum fibre content depends on the way of mixing. When the fibres are mixed together with concrete, higher fibre contents (cca 80 kg/m^3 and more) may cause problems during mixing, which often results in cumulation of fibres into balls. If the fibres are not mixed with concrete during its production, the amount of fibres can be substantially higher (e.g. SIFCON or SIMCON, up to 800 kg/m^3). In structures, the economical amount of fibres varies between 30 and 60 kg/m^3.

[1] Jan L. Vítek, Metrostav, a.s., Koželužská 2246, 180 00 Praha 8, and Faculty of Civil Engin. CTU Prague, vitek@metrostav.cz

[2] Matouš Hilar, Faculty of Civ. Engin. CTU Prague, Thákurova 7,166 29 Prague 6, hilar@d2-consult.cz

[3] Petr Vítek, Metrostav a.s., Na Zatlance 5, 150 00 Prague 5, petr.vitek@metrostav.cz

When the fibre concrete is exposed to tension, its initial strength is given by the tensile strength of the concrete matrix. Up to this stage the stress is transferred by both concrete and steel fibres in the ratio of their stiffness. After the crack initiation the fibres are stressed more and carry the tension in the crack. The number of fibres bridging the crack, their strength and their anchorage are the factors which directly influence the force which can be in the crack transferred. From this mechanism, the shape and dimensions of fibres are designed.

If the fibres active in the crack are able to carry the force which was taken by concrete before the crack origin, the condition of minimum reinforcement is satisfied (= critical reinforcement). However, in most of applications, the force carried by fibres in the crack is smaller (lower than critical reinforcement), which means that the load must be reduced after the cracking. If not, the structure would fail immediately.

If an assumption of a uniform distribution of fibres in concrete matrix is accepted it may be clearly defined that only about 1/3 of fibres will lie in one direction. It would mean that theoretically only one third of fibres may be active in the direction of prevailing tension.

In concrete which is reinforced by steel bars, the bars are located in the direction of the principle stress almost completely. Only the auxiliary reinforcement is arranged in other directions, but its amount is much less than 50% of the total reinforcement. The condition of minimum reinforcement had to be satisfied, since it is a code requirement. From this point of view, the fibre reinforced concrete cannot compete in consumption of steel, if the identical requirements to the load carrying capacity and to the crack width would be applied.

2. Tunnel precast segments and their performance

Tunnel precast segments are relatively small precast elements which are used for the assembly of the final tunnel lining with a circular cross-section. Usually 6 to 10 segments form a complete ring of the tunnel lining. The dimensions of the segments are determined according to the geological conditions of the tunnel and according to the applied tunnelling machine. The two groups of loading of the segments must be considered: 1. The temporary loading during manufacturing, transport and construction; and 2. The permanent loading in the final stage, when the tunnel is completed.

The temporary loading includes all the loading stages starting from the time, when the segment is cast up to the time when it is completely embedded in the tunnel lining and the space between the segment and the ground is filled with grout and the grout is hardened.

The loading in the final stage is represented by the long-term interaction of the lining with the ground, by the hydrostatic pressure of underground water, by temperature changes in the tunnel and by other factors which may be specific in individual tunnels. It is important to note, that the segmental lining is usually designed as watertight tunnel lining without any barrier membrane, which means that no cracks going through the lining are allowed. Limit states of serviceability are governing for the segment design.

The evaluation of effects of all loading stages results in the decision on the thickness of the segments and on their reinforcement. The thickness may be sometimes determined according to the final performance of the tunnel lining, because it should be designed in earlier stages of the design documentation, when the details of technology of construction need not be known. It used to be expected, that the designed thickness should be sufficient for the effects of other loading stages. The reinforcement is usually designed later, when more information on the project and on the construction process are available.

The loading stages during the construction cover the loadings, when the loadings are separate elements (moving the segments out from the form, transportation of segments, assembly of the segments into the lining, etc.) and the loadings when the segments interact in the lining ring before its completion (loading by the hydraulic jacks of the TBM, loading by the pressure of the grout, contact stresses between individual segments in the ring or between the rings, edge stresses induced by incorrect assembly or due to the tolerances in dimensions of the segments, etc.). The experience shows that the stresses induced by the thrust forces are extremely important for the reinforcement design. The accuracy of the assembly is essential for elimination or reduction of the edge stresses in individual segments.

3. Design of reinforcement of the tunnel segments

From the previous text, it may be understood that there are some essential loading situations, which are extremely important for the decision on the reinforcement of the segments. The permanent loading stages induce the bending moment and the axial force in the segments. The reinforcement must guarantee that the safety of the structure (ultimate limit states – ULS requirements of the appropriate code) will be satisfied and that the cracking will be in limited extent (no through cracks, limits on the crack width, or possible no cracks allowed). If the tensile stresses are small, it may happen that even only a plain concrete without any reinforcement can satisfy the condition mentioned above, or there is a possibility to use fibre reinforcement with smaller than critical amount of fibres. If the tensile stresses are high, the bar reinforcement must be used so that the safety and serviceability of the lining were guaranteed. In such cases, there is practically no possibility of fibre reinforcement, with exception of combined bar and fibre reinforcement or fibre reinforcement with higher than critical amount of fibres. From this point of view the loading stages of the completed design are usually governing for the decision on the type of reinforcement.

Finally it is necessary to note, that the internal forces in the segmental lining results usually from the general analysis of the ground in interaction with the concrete tunnel lining. The forces and bending moments in the lining are strongly dependent on the geological conditions. They are described by geotechnical parameters like modulus of elasticity or deformation, cohesion, angle of friction, etc., which are not exactly known. They are determined from the geotechnical parameters, evaluated before the beginning of construction. The obtained results of the numerical analysis therefore depend on the scale and quality of the realised site investigation, in case of difficult ground conditions or in case of poor site investigation they can vary from the real behaviour. The geological conditions always bring some level of uncertainty.

During the construction process the thrust forces induce rather high stresses in concrete segments. The number of jacks, their capacity and the thickness of the lining are the parameters which influence the value of tensile stresses under the jacks and the necessary reinforcement. If the quality of concrete is high that its tensile strength may be sufficient carry the induced tension. In such cases no bar reinforcement is necessary and the fibre reinforcement may be recommended.

During the construction the segments may not to fit exactly to their position, geometry of the segments may be shifted in comparison to theoretical position. Consequently the supporting conditions of individual segments are not exactly those following the design. The undefined stresses may occur very close to the surface of the segments. Additionally to that it may happen that the complete loading of the segments vary from the loading stages assumed in the design and then the risk of cracking is higher. The bar reinforcement can carry the tension inside the segment, if it is located in the right place. The bar reinforcement must be covered by a layer of plain concrete (the protection of steel against corrosion, or protection against fire). This concrete cover has no reinforcement and the high stresses induced in this area usually result in cracking, spalling, or local damages. This is a disadvantage of the bar reinforcement. In the case of such loading cases the fibre reinforcement may be very efficient and can substantially reduce local damages of segments. On the other hand it is important to note, that minor cracks may remain invisible, but in the larger cracks the fibre reinforcement is not able to guarantee the watertightness of the lining.

4. Design of fibre reinforced concrete for application in tunnel segments

As mentioned above, the fibre reinforcement (it is assumed fibre reinforcement only, without combination with steel bars) may be used if the final performance without bar reinforcement is possible, i.e. if the tensile stresses are small, or if the effect of the compression force is large enough to eliminate most of the tension induced by bending moments. If the tensile stresses induced under the jacks pushing the TBM are small enough, then the fibre reinforcement will be probably sufficient. These stresses depend on the thrust forces, on their distances and on the thickness of the segment. The two mentioned conditions are usually essential for the decision on the fibre reinforcement. The other loading stages during the production, transport and construction process may be reduced by technological arrangements, so that fibre reinforcement becomes sufficient.

The amount of fibres is usually given by the design procedures developed by producers of fibres. From the experience it is well known than the amounts lower than 40 kg/m^3 have a very limited effect. The higher amounts may result in technological problems during mixing of concrete. The other issue is a uniformity and reliability of the fibre reinforced concrete after hardening. They depend on the type of the concrete mix and on the type of fibres. The actual properties of different mixes differ significantly and are dependent on local conditions.

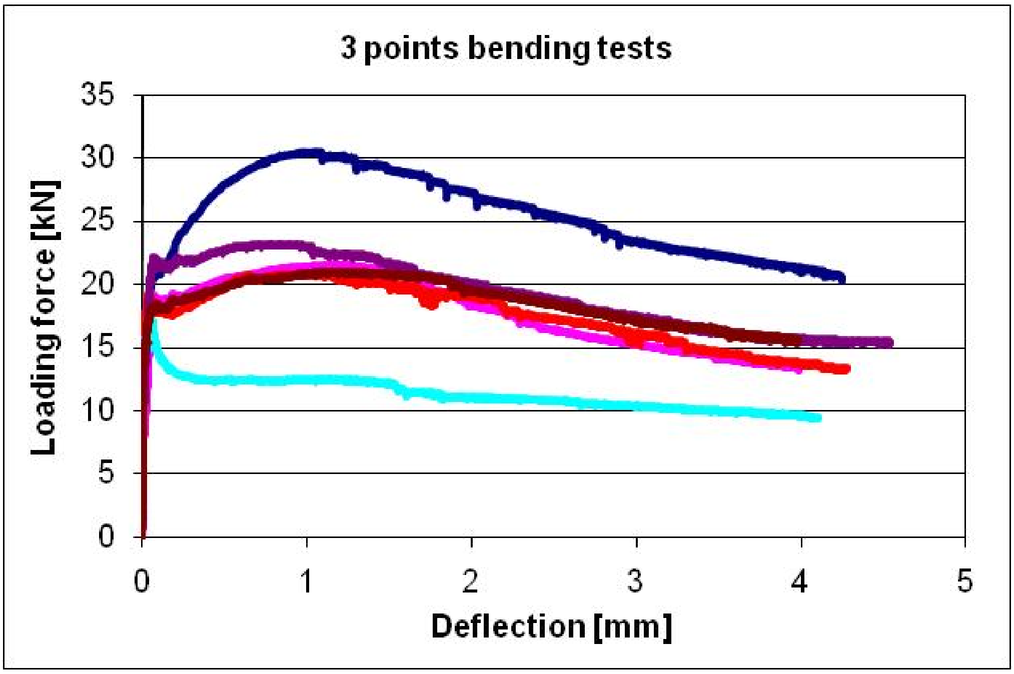

Fig. 1: Experimental results according to the RILEM tests measured on notched beams

5. The tests of fibre reinforced concrete specimens

The fibre reinforced concrete with the matrix class C50/60 was prepared with 50 kg/m^3 of fibres Dramix RC-80/60-BN. Experiments verifying the bending performance were carried out. The two arrangements of tests were applied. The RILEM test assumes notched beams with the cross-section 150 x 150 mm with the span of 500 mm long loaded by 3 points bending. The test according to the German standards which is used also in the Czech Republic assumes a beam of the same dimensions of the cross-section without notch, but of the span 600 mm long. The loading by two forces acting in the thirds of the span represents a 4 points bending test. The beams produced from fibre reinforced concrete were examined using both a 3 points and a 4 points bending tests.

The dependence of deflection at the midspan on the loading force was measured at both tests, and the dependence of crack mouth opening displacement (CMOD) on the loading force was measured at the three points bending test. The results of the tests exhibited a certain statistical scatter, which is at fibre reinforced concrete elements quite usual. The load-displacement diagrams are plotted in Figs. 1, and 2. The diagram CMOD x Loading at three points bending tests is plotted in Fig. 3. The similarity of the diagrams in Fig. 1 and 3 is apparent, due to the mechanism of failure of the specimen under the bending. It is quite

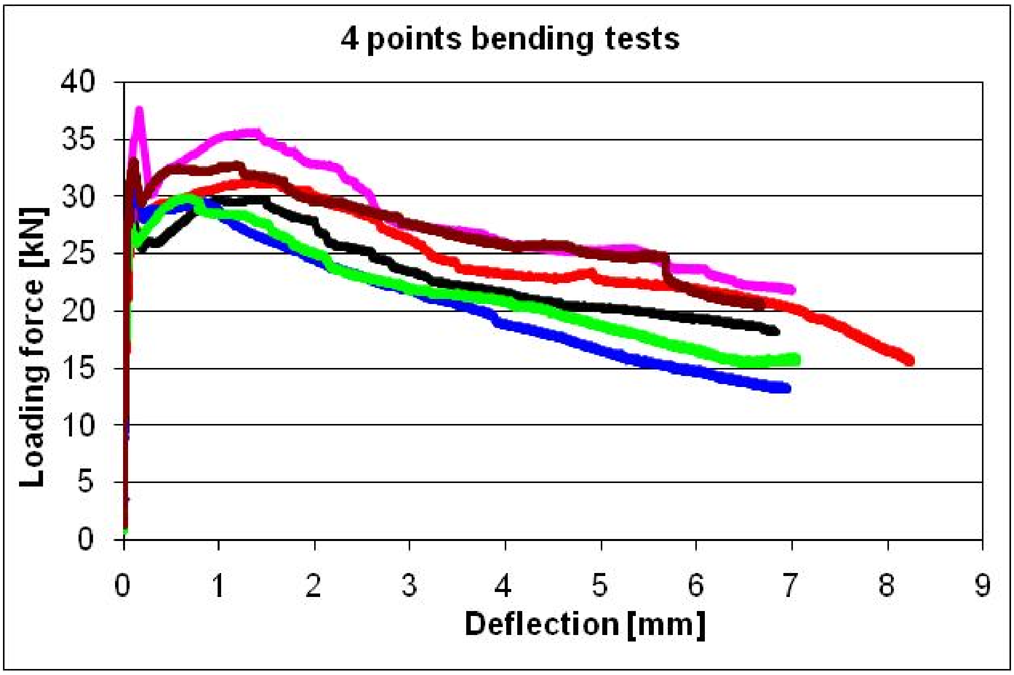

Fig.2: Experimental results according to the German tests measured on beams without notch

clear, that the deflection and CMOD are mutually related. The failure takes place in one section; the remaining parts of the tested beams may be considered without any damage as stiff elements. Under such assumption a geometrical mechanism may be assumed which defines the direct dependence between the deflection of the beam and the CMOD.

The objective of the tests was: i) Comparison of the behaviour of the material with other similar materials (e.g. with FRC reinforced by other fibres) and ii) to get experimental results, which provide a basis for determination of the parameters describing the performance of FRC applicable in numerical models.

It may be seen from the load-deflection diagrams that the results exhibit large statistical scatter. It is unfortunately usual at FRC. The larger scatter was observed at specimens with the notch. It may be explained by the fact, that the section which fails is given in advance, i.e. the response is dependent on one section. On the other hand the specimens without notch fail in the weakest section; there is an entire central area of the beam which potentially fails, and the scatter becomes reduced. The four points bending tests have longer descending branch of the diagram, which provide more precise data for numerical modelling (comp. Sect. 6 and Fig.4).

6. Numerical modelling of FRC

From the bending tests, the load-displacement diagram is usually obtained. The initial part of the diagram (the ascending branch) is dependent mainly on the concrete properties, while the descending branch strongly depends on the fibre reinforcement. If a structural performance is analysed, there are more possibilities of modelling of FRC behaviour. The two basic approaches are mentioned here. i) The section under bending is modelled in a simplified way and the results from the load displacement diagram may be used after some evaluation. The procedure is described e.g. in [1]. ii) The finite elements models are used and then the specification of input parameters requires more detailed analysis.

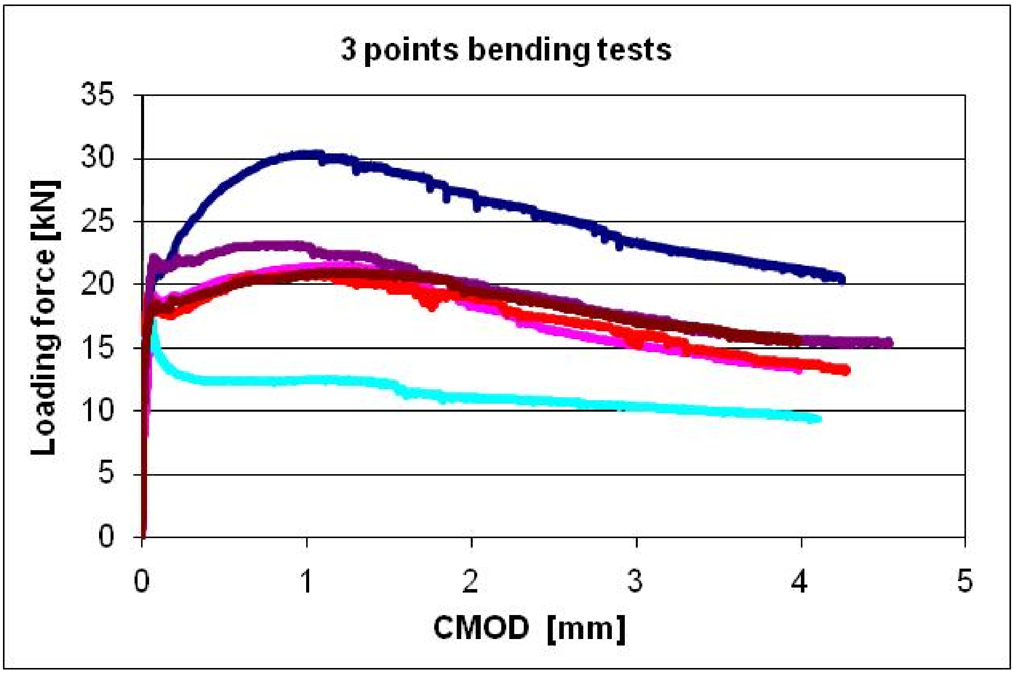

Fig. 3: Crack mouth opening displacement (CMOD) on the notched beams

It is possible to specify a dependence of tensile stress and strain from the load displacement diagram. One might have thought that such diagram could be used as an input for finite element analysis. Such simple approach would result in a problem of the mesh size dependency. It means, that results obtained for different sizes of the mesh, would be different. It is clear that such results would be completely unacceptable. It is necessary to find a procedure which gives the results which are independent on the mesh size. Such procedure is based on the energetic approach which satisfies a condition, that the energy consumed on the crack propagation remains identical for different mesh sizes. If computer programs which are available for concrete structures are used, the parameters describing the performance of the FRC would be the tensile strength, the elastic modulus and fracture energy. Since FRC is a composite material, such approximation is acceptable but has not a correct physical meaning. The fracture energy in the case of FRC becomes only an artificial parameter applicable in the analysis. The fracture energy should be calculated from a complete stress x CMOD or stress – strain diagram. The fracture energy should be derived from the complete area under the stress-strain curve (area A_1+A_2 in Fig. 4). In the case of FRC the complete diagram may be obtained from tests only rarely. Usually the test is finished earlier than the loading force drops to zero (area A_1 in Fig.4). The fracture energy cannot be precisely determined from the incomplete diagram. The problem may be overcome, if the stress-strain diagram is extrapolated until the loading vanishes (area A_2 in Fig.4). Such extrapolation may be rather subjective, but if the extrapolated part of the diagram is not very large, the influence of the estimated area A_2 may be rather limited.

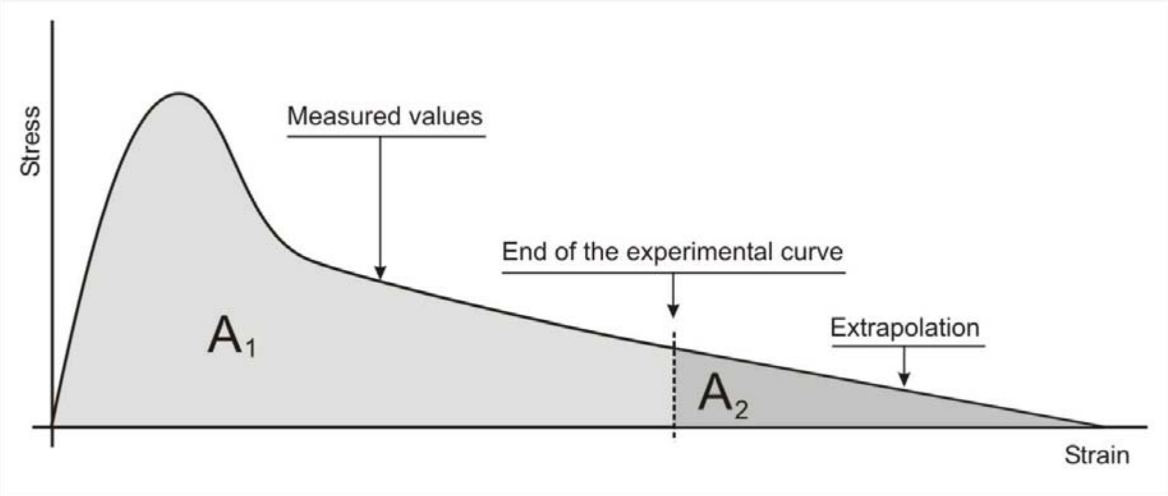

Fig.4: Stress – strain diagram for estimate of fracture energy

FRC is a composite material and its response is dependent on the matrix behaviour and on the fibre reinforcement. The simplified modelling as mentioned before is not completely correct. The matrix is a brittle material for which the models of an isotropic brittle material are completely adequate. The fibres represent a reinforcement which starts to act significantly when the strain increases. It has an effect on the strength in compression, due to the limitation of transverse elongations as well as on the strength in tension. However, main role of fibres is to act after the crack origin. Then the propagation of the crack in concrete matrix (which is described by fracture energy) interacts with subsequent activation of fibres if the crack is small. If the crack becomes large the fibres start to fail or their anchorage fails, which means drop of the force transferred by fibres. Such approach was described e.g. in [2] and [3]. Since the performance of FRC is more complex than that of the simple isotropic material, it would be convenient to use also more complex numerical models, e.g. according to [2].

If a simplified approach assuming FRC as an isotropic continuum is used, then the tensile strength of FRC cannot be taken into the analysis. It should be replaced by the limit of linearity, which roughly corresponds to the tensile strength of the concrete matrix. The fracture energy has to be calculated, as already mentioned from the complete stress-strain diagram, which requires in most of the cases to extrapolate the curve obtained from measured data. Such an approach was verified in evaluation of experimental results carried out on the FRC beams (Sect. 5) in [4].

7. Comparison of RC and FRC in tunnels segments

The comparison of tunnel segments made of RC and of FRC is not fully adequate. According to the authors' opinion, it is only a part of the issue. It is necessary to compare the complete design and technology. The RC segments have a clear advantage, that they can be reinforced relatively strongly in the direction where large stresses appear. Segments made of FRC are not capable to resist the increasing tensile force when it is necessary. The fibre contents would be too large, which would lead to technological problems. On the other hand the fibre reinforcement has technological advantages and may bring savings in production of segments. The advantage of segments made of FRC lies also in lower sensitivity to local damages during assembly of the lining. Therefore it is necessary to take into account the design conditions in the underground space, which provide the geotechnical loading including the underground water pressure. The other loadings given by the technology (production, transport and assembly of segments) may define other unfavourable loadings. If all these factors are taken into account, it is a moment for decision if segments made of FRC may be designed or if the bar reinforcement is necessary. Of course the combination of bar and fibre reinforcement is also possible, but then the main advantage of simplification of the production would be lost.

8. Conclusions

The paper describes the different issues which are to be taken into account if tunnel segments should be designed from FRC. It should provide the answer if FRC is useful to use for tunnel segments and when. The results may be summarised in the following items.

1. The advantage of using FRC for tunnel segments is mainly in easier production and in lower sensitivity to damage during manipulation and assembly of segments at some loading stages.
2. The segments made from FRC are convenient if the geotechnical conditions (permanent loading by ground) do not require the bar reinforcement, i.e. if the shape of the lining, generated load and thickness of the lining provide conditions for low ratio of steel reinforcement (mainly in ultimate limit state).
3. The temporary loading must be taken into account as a secondary effect, if the conditions under the item 2 are satisfied. Mainly the thickness of the segmental lining is important for reduction of the stresses during assembly of the segments.
4. A great attention should be paid to the production technology of segments made of FRC. The distribution of fibres should be uniform as much as possible, which requires a very precise selection of constituents of concrete and fibres, and well developed technology of mixing. Two ways are possible, relatively stiff mix and very efficient compacting using vibration, or self-compacting (or almost self-compacting) concrete with no or very limited compacting. The second alternative is more convenient due to the higher reliability and better environmental conditions in the precasting plant. It is necessary to take into account a significant statistical scatter of the FRC response which is much larger than that of RC.

5. Numerical modelling of FRC is an essential condition for correct design of structural elements. The models for simple technical design are well developed, models for numerical analysis require further research, in order to fit well the progressive material damage until failure.
6. The performance of segments made of FRC and RC cannot be directly compared, since it is only a part of the system. The complete design and technology of the tunnel lining including all the costs during the complete service life may be compared and from such data a conclusion, which segments are more convenient, may be obtained.

Aknowledgement

The support of this research from the Grant Agency of the Czech Republic (project no. P104/10/2023) is gratefully acknowledged

9. References

[1] Betonkalender 2011, Teil 2, Faserbeton, Ernst & Sohn, Berlin 2011
[2] Vítek, J.L., Vítek, P. Fracture of fibre reinforced concrete beams with low fibre content. *Proc. of FRAMCOS-2*, ed. by F.H. Wittmann, Zürich July, 25-28, Aedificatio, Zürich 1995, 793-802
[3] Vítek, J. L.: Steel fibre reinforced concrete beams - Size effect. Fracture Mechanics of concrete structures, *Proc. of FRAMCOS-3*, eds. H. Mihashi, K. Rokugo, Aedificatio, Vol.III, Freiburg 1998, 2103-2112
[4] Šetková, D.: Design parameters of fibre reinforced concrete derived from tests, Bachelor thesis, Czech Technical University in Prague, Faculty of Civ. Engrg. Dept. of Concrete and Masonry Struct. June 2011