Load testing and numerical modelling of SFRC segments

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ABSTRACT: Segmental tunnel lining is usually applied to mechanised tunnelling using tunnelling shields. Precast steel fibre reinforced concrete (SFRC) segments are currently used in praxi without traditional rebars. In the Czech Republic, there is a research underway focused on problems of SFRC segments.

The completed experimental testing of SFRC segments and traditionally reinforced concrete (RC) segments was carried out and it brought interesting information. Naturally, the information on the load-bearing capacity of segments (the magnitude of the maximum load the segments can carry) and on the serviceability of the segments (the origination of first cracks, crack propagation throughout the segment thickness) at various manners of loading is of the most important. This was the first comprehensive set of results of experiments on modern real-size tunnel lining segments in the Czech Republic.

Also back calculations using the Finite Element Method in the ANTENA program were carried out on the basis of the completed tests. Owing to them the deriving of some important parameters of tested materials was possible. A responsible numerical analysis requires the use of sufficiently sophisticated analytical equipment taking into account energetic principles of modelling the development of cracks. The completed comprehensive set of experiments led to the obtaining of data for calculations which could be used for reliable modelling of the response of real elements to the required loading.

The conclusion was made after taking into account the results of the completed research that the produced SFRC segments meet all requirements placed on the lining of Prague metro. For that reason lining rings were produced and assembled (10 rings, i.e. 15 lm of the tunnel) on the alignment of the Line A of Prague metro, using SFRC segments (with dosing of steel fibres of 40 kg/m^3). This lining was installed on a running tunnel in June 2012.

1 PROPOSED EXPERIMENTS

Apart from the testing of small samples, first of all beams, the testing of which has been commonly conducted for a number of years, a comprehensive set of tests on real elements with real sizes was carried out at present. Although segments of tunnel linings are exposed to effects of a range of loading cases (e.g. handling, storing, transport, installation, final loading), measures are being introduced in praxis designed to make only some of them deciding for the dimensioning of the precast elements. Naturally, the load induced by rock mass is the principal design load. With respect to the waterproofing capacity of a segmental lining, even the hydrostatic pressure can play important role, first of all when the water table is above the tunnel level. The above-mentioned loading cases are in action throughout the design life of the structure. Another significant loading factor is the thrust of a tunnelling shield, which is pressed into rock mass by means of hydraulic rams pushing against assembled lining rings. It is true that this is a temporary construction condition and short-term loading, which should not be significant as far as the as economic as possible design is concerned. However, with respect to the anticipated high values of the thrust force of the machine (depending on the predicted geotechnical properties of rock mass), the particular loading case often plays the deciding role in designing segments. It is also with respect to this fact that the full-face TBM technology must be assessed as a whole; the required higher loading capacity is compensated for by numerous advantages.

The following tree types of tests were proposed for the simulation of deciding design conditions (see Figure 1):

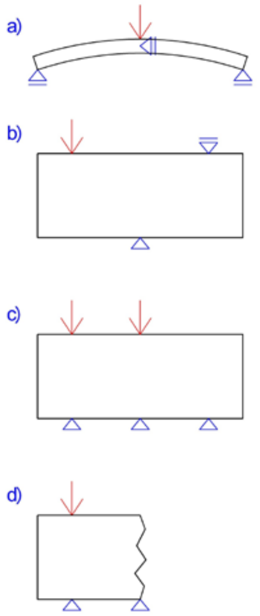


Figure 1. Conducted tests – a) segment bending perpendicularly to the segment plane, b)segment bending in the segment plane, c) unilateral pressure on the segment induced by two loads, d) unilateral pressure induced by a single load acting on remains of segments

A) Simulation of the rock mass induced loading:
A segment is loaded by bending in a plane perpendicular to the segment surface. The segment is placed in the position of a vault (inverted 'U') on movable supports; a linear load acts on the top of the vault. The movable supports mean that only a pure bending load acts, without the influence of a normal force (see Figure 1a). Despite the fact that tunnel linings are in reality loaded by normal forces, a statically simpler model was chosen for the purpose of the testing, so that the results were easier to interpret and provided more suitable grounds for a numerical analysis. A combination containing the normal loading acting on the lining can be subsequently relatively easily modelled in a numerical calculation.

B) Simulation of loading induced by axial rams on the shield – an ideal condition:
As mentioned above, the loading induced by rams on the shield providing the required thrust of the machine against the excavation face is one of the loading cases deciding for the segment design. It is necessary to have clear information about the load under which cracks start to develop and the moment at which they start to propagate throughout the lining thickness. Despite the fact that the loading capacity of a segment can be sufficient, a crack running throughout the segment thickness means that the lining is permeable for water, which naturally is unacceptable. The test is arranged in a way where the segment is loaded by a pressure inside the central plane. With respect to the capability of the loading equipment (maximum force of 10 MN – 1000 t), the test was composed in two variants, namely with the loading by a single load (see Figure 1b) with the possibility of reaching the total load-bearing capacity of the element, and the loading by two loads (see Figure 1c) without the possibility of reaching the loading capacity of the element.

C) Simulation of loading induced by axial rams on the shield – non-uniform bearing of the segment:
Segments in lining rings are bonded in a way similar to brickwork. This system brings many advantages, including the increase in the rigidity of the lining. When the loading by the tunnelling shield is being applied, the loading force is transmitted to two segments of the previous ring. If the state occurs where the segmental lining is not assembled geometrically accurately, the segment being loaded by rams is supported non-uniformly. In the case being assessed, one segment is exposed to loading in 3 points (the simulation of 3 rams) and is placed on 3 supports. With respect to the fact that a statically indeterminate structure is in substance in question, the element is loaded by bending when a support drops. The test is adjusted to this fact. The segment is fixed on two supports and the side support is omitted; it is loaded by a single load acting in the central plane in the end point of application (see Figure 1d). The element is therefore loaded as a high cantilever.

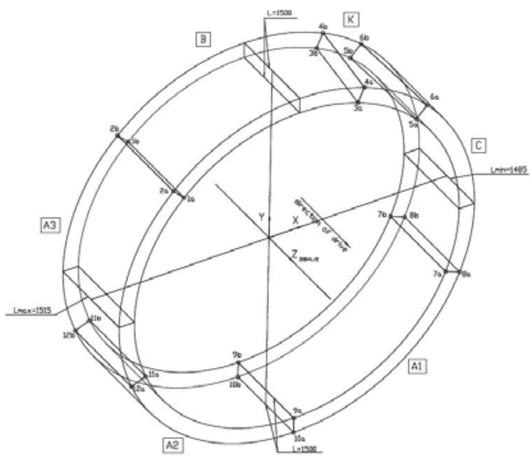


Figure 2. Geometry of segments in a lining ring

2 PARAMETERS OF TESTED SEGMENTS

The pre-cast segments for the loading tests were produced using moulds for the production of segments for mechanised excavation of running tunnels of the Prague metro Line A extension. The geometry of the segments is presented in Figure 2. The lining ring has the inner diameter of 5.3 m and outer diameter of 5.8 m and thickness (of segments) of 0.25 m. One lining ring is 1.5 m long (the width of one segment). The shape of all segments is identical. Vertical views of completed rings are trapezoidal. The straight alignment of the tunnel as well as changes in its direction (horizontal and vertical curves) can be secured by rotating the rings against each other around the axis. Three largest segments (A1, A2 and A3) have parallel edges of radial joints, whilst other two segments of a similar size (B and C) are angled on the key side and the closing segment (the key) has angled radial edges on both sides and its size is about one third of the other segments. The segments are interconnected with bolts (both longitudinally and transversally). For that reason each segment has holes and boxes for the installation of bolts. The waterproofing of the lining is secured by means of rubber gaskets installed in peripheral grooves in each segment. The annular gap between the outer side of the ring and the excavated tunnel wall is concurrently backfilled with grout.

During the course of the construction, each lining ring is loaded by 16 pairs of hydraulic rams located in the rear section of the tunnelling shield. The rams are uniformly distributed around the circumference (the angle of rotation of 22.5°). Each of the five large segments is loaded by 3 pairs of rams, whilst only one pair of rams acts against the key. Two rings were produced for the testing purposes using steel fibre reinforced concrete (SFRC) without traditional reinforcement, with the doses of steel fibres of 40 kg/m^3 and 50 kg/m^3. Common steel bar reinforced concrete segments with 105 kg/m^3 of the reinforcement were also tested to allow comparison. The values of the acting forces, the magnitude of deformations measured by installed potentiometric path transducers and signals from the strain gauges glued to the surface of segments were recorded during the testing.

A hydraulic testing press Amsler 10000 kN 1523 (metrology number KÚ S 07 010 M) was used for the testing. The values of acting forces, the magnitude of deformations measured by installed potentiometric path NOVOTECHNIK TR10 a TR25 were recorded during all tests. In addition, signals from X350-type Mikrotechna strain gauges with the grid length of 100 mm, which were glued to the surface of segments, were recorded. A PEEKEL Autolog 2100 data logger was used for data collection.

3 LOADING BY BENDING PERPENDICULAR TO SEGMENT PLANE

Při During the course of the particular test, segments were subjected to bending perpendicular to the segment plane. The test simulated the loading by bending moments during handling, transport, storing and loading by the pressure induced by ground mass. Segments were placed with the curved surface upward (see Figure 3); bottom edges were supported by sliding supports allowing horizontal movement and preventing vertical movement. The uniformly distributed load, acting on segments throughout the length of the top of the vault, induced controlled vertical deformation. This means that the loading force introduced by the hydraulic cylinder was adjusted with the aim of regular, evenly increasing of the deformation on the loading ram cylinder. This means that the loading force initially grew and subsequently, after the origination of cracks, was reduced until the capacity was exhausted (i.e. until the moment of breaking). The entire sophisticated system was controlled by a computer with a special software. Undisputable advantage of the loading through “controlled deformation” was the fact that a complete diagram, including the descending branch, was obtained. The decision to terminate the test was made only when the element no more supported its own weight. The above procedure was applied to 4 steel fibre reinforced segments A3. The test results are presented in Table 1.

Table 1. Results of segments loading by bending perpendicular to the segment plane

Segment	Amount of fibres (kg/m^3)	Max. reached force (kN)
A3 - S1	40	115
A3 - S2	50	106
A3 - S3	40	124
A3 - S4	50	154

Figure 3. A segment loaded by bending perpendicular to the segment plane

Petty cracks started to appear in a strip with variable width on the bottom face of the segment before the maximum loading force was reached. They gradually developed and subsequently localised themselves in a single crack (see Figures 4 and 5). This crack gradually opened, with a corresponding decrease in the loading force. It was possible during the course of the process of the crack opening to directly observe steel fibres being gradually pulled out. Typical spreading of cracks in the SFRC was registered, characterised by a number of thin cracks developing in the close vicinity of the most stressed cross section and one of them later propagating itself further.

Figure 4. A segment loaded by bending perpendicular to the segment plane (underside view)

Figure 5. A segment loaded by bending perpendicular to the segment plane after becoming disturbed (side view)

Another interesting thing is that the highest and lowest values of the loading capacity were reached on samples reinforced with 50 kg/m3 of fibres, whilst samples reinforced with 40 kg/m3 exhibit similar loading capacity. The values were always obtained only on two samples, it is therefore impossible to consider them to be statistically significant. In spite of that, an explanation offers itself that concrete with the amount of steel fibres of 50 kg/m3 is already more difficult to mix and it is therefore more difficult to secure even dispersing of steel fibres and large scattering of the loading capacity values therefore occurs. It is likely that, in the case of the conducted tests, one segment with very favourably dispersed fibres was tested, whilst the dispersion in the other segment was very unfavourable. The term ‘favourable’ is used instead of ‘even’ on purpose. The high loading capacity can be caused by the concentration of steel fibres at the bottom surface of the element, i.e. in the tensioned area. This may be caused, for example, by intense vibration. It is therefore not an entirely favourable phenomenon because of the fact that it is possible to presume on the contrary that the loading capacity in the case of the opposite direction of loading (tensioning in the upper part of the element) will be proportionally reduced. In reality, segments are loaded in both directions.

4 LOADING BY UNIAXIAL COMPRESSION APPLIED TO REMAINS OF SEGMENTS

The particular testing was conducted on the remains of segments which originated during the segment loading by bending perpendicular to the segment plane. The remains of the segments were loaded by uniaxial compression in the vertical direction. The acting force was being increased with 600 kN increments and the remaining segment was unloaded between individual loading stages down to the value of 200 kN. The remainder of the segments was loaded until the loading capacity was exhausted. This particular method was applied to the testing of 6 remainders of segments and one segment K. The testing results are presented in Table 2.

Table 2. Results of uniaxial compression of the remainders of segments (L – left-hand part, R – right-hand part)

Segment	Amount of fibres (kg/m³)	Force – the first crack (kN)	Force – crack through segment (kN)	Max. reached force (kN)
K	50	4200	4200	7247
S1 – L	40	6000	6000	6600
S2 – L	50	4800	4800	7500
S3 – L	40	6000	6000	6600
S3 – R	40	6000	6000	7480
S4 – L	50	5400	6000	8300
S4 – R	50	6000	6600	7900

In contrast to the previous test, the segment was loaded in a vertical position; the origination of cracks on both the inner and outer surface of the segment was therefore well observable. First cracks are localised on the inner surface, above the bolt box. Subsequently the cracks propagate themselves through the box, along one edge. It is evident that the weakening by the box acts in an unfavourable way and leads to the localisation of stress to edges. It is therefore possible to state that the angular shape of the boxes is improper; a rounded shape would have been more proper. During the course of further loading the cracks developed downward, in one or more strips under the box or slightly aside. All cracks were gradually opening and only then did one of them significantly localise itself. The element subsequently got split by transverse tensions in that particular location (see Figure 6).

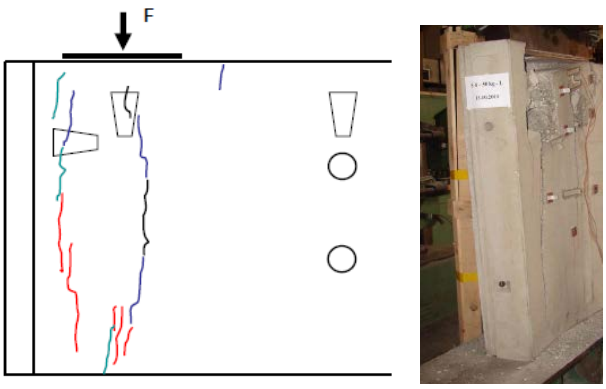


Figure 6. A segment remains split by transverse tensions

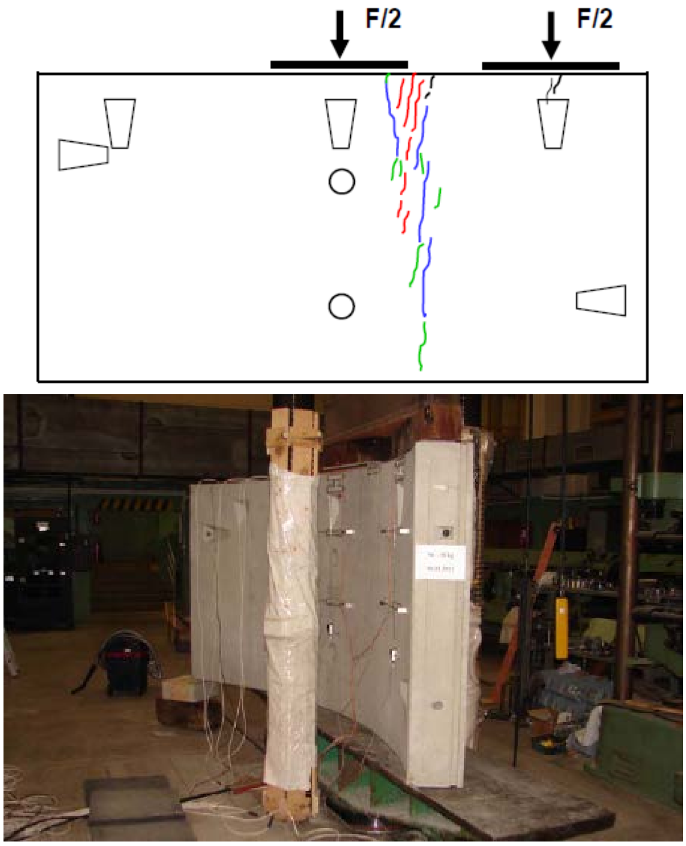


Figure 7. A segment compressed by two loads

5 LOADING BY UNIAXIAL COMPRESSION INDUCED BY TWO LOADS

During this particular test, segments were tested in compression; the test simulated the loading induced on the lining by rams of the tunnelling shield, where the direction of the acting force is parallel with the longitudinal axis of the tunnel tube. The tests were carried out with two forces acting (the simulation of two rams by means of a solid distribution beam – see Figure 7). Taking into consideration the system of the placement of the segment in the testing machine, the forces acted vertically. The segments were placed on the carriage of the testing machine including sololit boards without sealing gaskets. One 9 mm thick hardened PVC plate and one steel sheet P20 plate matching the area of contact of the shield rams were fitted to the upper compressed surface. The acting forces were increased in equal increments; after each increasing of loading forces, the segments were unloaded. The forces were increased until the loading capacity of the segment was exhausted. The cracks which originated during the test were recorded. In total, two SFRC segments A3 were tested. The testing results are presented

Table 3. Results of uniaxial compression of SFRC segments

Segment	Arrangement	Amount of fibres (kg/m^3)	Force – the first crack (kN)	Force – crack through segment (kN)	Max. reached force (kN)
A3–S5	2x F/2	40	3600	6000	9000
A3–S6	2x F/2	50	3600	6000	9300

The test arrangement was similar to that used in the previous case, the character of the disturbance was therefore also similar. The principal advantage of this test was that it was possible to observe the segment stressing in the space between the points being subjected to loading. This space was characterised by the origination of tensile stresses. Cracks (most frequently one small crack) appeared in this part during the early phases of the loading process. The crack no more opened with the increasing load; it restricted itself solely to the edge of the segment. In addition, it was not significant for the reduction of the element load-bearing capacity. The origination of the crack between the points of lading was only a local matter, despite the fact that this crack originated as one of the first cracks. The subsequent development of cracks was virtually identical with the case where only a single point was loaded, with the only difference that it ran nearly in parallel under both loading points. The development of cracks in the surroundings of one loading point was usually delayed for one loading step. As opposed to theory, it corresponded to the accidental nature of material characteristics and the accidental eccentricity of the loads. The test ended when the capacity of the loading machine (the total load force of 9 MN) was exhausted. At that moment the maximum force attributed to one loading point reached 4.5 MN, which value is lower than the loading capacity of the segment.

6 COMPARATIVE UNIAXIAL COMPRESSION LOADING TESTS OF RC SEGMENTS

These compression tests were conducted on traditionally reinforced concrete segments. The test simulated the lining loading by rams of the tunnelling shield, where the direction of the acting force is parallel with the longitudinal tunnel tube axis. Some tests were carried out with the action of a single force (the simulation of a single ram), some tests were conducted with two forces acting (the simulation of two rams). Taking into consideration the system of the placement of the segment in the testing machine, the forces acted vertically. The segments were placed on the carriage of the testing machine including sololit boards without sealing gaskets (with the exception of segment K, which was tested with gaskets on it). One 9 mm thick hardened PVC plate and one steel sheet P20 plate matching the area of contact of the shield rams were fitted to the upper compressed surface. The acting forces were increased in equal increments; after each loading forces increasing, the segments were unloaded. The forces were increased until the loading capacity of the segment was exhausted. The cracks which originated during the test were recorded. In total, 7 traditionally reinforced concrete segments (2xA1, A2, A3, K, B, C) were tested. All of the tested segments were reinforced with 105 kg/m3 of steel bars. The arrangement of tests and testing results are presented in Table 4.

Table 4. Results of uniaxial compression of traditionally reinforced concrete segments

	Arrangement	Amount of fibres (kg/m^3)	Force increment (kN)	Force reduction to (kN)	Force – the first crack (kN)	Force – crack through segment (kN)	Max. reached force (kN)
K	1x F	105	300	90	3300	3300	5868
B	1x F	105	600	200	5400	5400	8448
C	2xF/2	105	1000	300	6000	6000	8608
A1	1xF	105	600	200	4800	4800	7235
A2	2xF/2	105	1200	400	4800	5800	-
A1	1x F	105	600	200	5400	5400	7260
A3	2xF/2	105	1200	400	6000	7200	8960

Even though this paper is first of all focused on steel fibre reinforced concrete segments, it is certainly in order to present the comparison with the tests of steel bar reinforced concrete elements. These tests were carried out identically with the tests of the SFRC segments. The values of the loading applied at the moment of the origination of cracks running throughout the thickness of the element are nearly identical for both the steel bar reinforced concrete segments and steel fibre reinforced concrete segments. Even the load-carrying capacity of the traditionally reinforced concrete segment is comparable with that of a SFRC segment; nevertheless, the failure mode is totally different. The traditionally reinforced concrete segment was in all tested cases disturbed in the plane parallel with the central plane. It means that the material became delaminated, with a cover layer separated after the load-carrying capacity was exhausted and a core of concrete clamped between reinforcing bars originated inside the element (Figure 8). At the concrete cover to the reinforcement of 5 cm and the thickness of the segment of 25 cm, the core was a mere 15 cm thick.

Figure 8. Delamination of traditionally reinforced concrete segments loaded by unilateral pressure

7 LOADING BY BENDING IN THE SEGMENT PLANE

During this particular test, segments were subjected to bending in the segment plane. The test simulated the tunnel lining loading by rams of the tunnelling shield at a uniform support of segments (i.e. the simulation of the shifted geometry of the previous ring – see Figure 9). The segments were loaded by a single load acting on the segment edge. The opposite edge of the segment was clamped so that vertical shifting was prevented. In addition, the segment was supported non-symmetrically on the side of the clamping so that the segment half exposed to loading was not supported. The acting force was increased with 100 kN increments, without unloading, until the load-bearing capacity was exhausted. This procedure was used for the testing of 6 segments A (4 steel fibre reinforced concrete segments with 40 and 50 kg/m^3 of fibres, 2 traditionally reinforced concrete ones with 105 kg/m^3 of reinforcement). The results are presented in Table 5.

Table 5. Results of segment loading by bending in the segment plane

Segment	Reinforcement kg/m^3	Force – the first crack (kN)	Force – crack through segment (kN)	Max. reached force (kN)
A3-S11	50	200	400	500
A3-S12	50	300	560	753
A3-S13	40	300	530	629
A3-S14	40	300	500	610
A1-S15	105	300	370	610
A2-S16	105	200	350	991

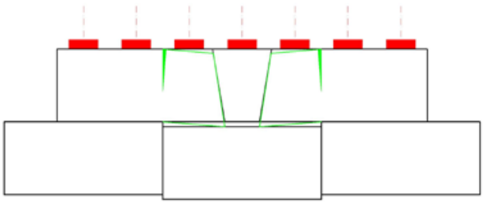
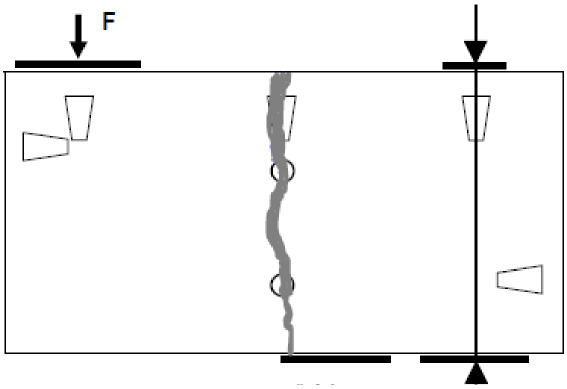


Figure 9. Graphical depiction of non-uniform support of segments

The above-mentioned tests were characterised by low values of forces at which cracks started to originate. The cracks localised themselves in the area above the box for a bolt and continued to extend downwards. It was possible at the segments produced from steel fibre reinforced concrete to observe the origination of numerous minute cracks; one of them gradually opened and, subsequently, the load-carrying capacity got exhausted (Figure 10). The traditionally reinforced concrete segments were disturbed in a different way. One crack originated and started to open; it started to branch out only when a high load value was reached. Failure limits were not reached, but the element loaded in this way was completely unsatisfactory (with respect to the extension of cracks in the lining).



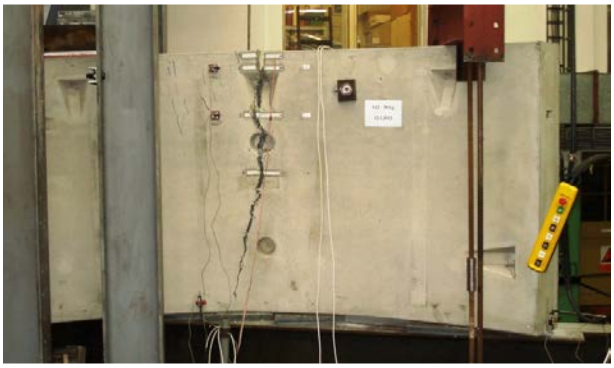


Figure 10. SFRC segment disturbed by loading by bending in the segment plane

The character of the response of the tested materials to the loading was totally different, but the materials can be considered to be comparable as far as the serviceability is concerned. In general, it is possible to state in the case of both materials that the segments are brittle and susceptible to fracturing even when loaded by small forces. The origination of cracks at 300 kN and the propagation of cracks to throughout thickness of the segment at 500 kN, if compared with the design load of 2400 kN, means significant problems with the serviceability of segments. The deformation (the deflection of the element subjected to bending) of about 1 mm on the origination of cracks and about 2 mm on the origination of cracks running throughout the element thickness, which values are very low, corresponds to this information. The deflection at the failure load of the SFRC elements varied around 6 mm. The rigidity of the lining providing support for the machine thrust forces is relatively low because the rubber gaskets sealing the joints can be subject to creeping. It follows from the results of the experiment that the difference in the position (pushing in) of two neighbouring segments of 1-2 mm means significant risk of the origination of a crack in the segment, which may affect the waterproofing capacity of the lining in the case it propagates throughout the segment thickness. It is therefore necessary during the course of the excavation to secure uniform support of the segments being subjected to loading, which means that the lining has to be installed as accurately as possible so that the origination of cracks is prevented. In addition, the above-mentioned factor should be taken into consideration when the arrangement of segments is being designed – which can be more advantageous if compared with the arrangement being assessed.

8 BACK NUMERICAL ANALYSIS

The testing of segments was paralelly analysed by numerical modelling using the finite element method. Non-linear models were used for modelling of RC a SFRC. Modelling of response and failure of the segments exhibited to various types of loads was realised using the commercial software ADINA. Non-linear numerical analysis of the segments allows detailed investigation of a loaded segment, namely generation and propagation of tension cracks, determination of the capacity, ductility and further phenomenons during process of the loading. Also post-critical behaviour of a segment after exceeding of the limit load can be evaluated. Many characteristics of the model can be continually evaluated as distribution of stresses and deformations, width of cracks, plastic extension of reinforcement, etc. Similar detailed monitoring of various features is in the real test almost impossible.

Both RC segments and SFRC segments with various dosage of fibres were evaluated via numerical modelling. Mechanical properties of RC and SFRC were obtained from accompanying material tests, in case of SFRC results of 4-point beam tests were used.

Results of realised numerical modelling were used for the following purposes:

1. Verification that material parameters of SFRC obtained from beam testing are useful for modelling of segment testing (models matched well with realised tests).
2. Numerical models allowed more detailed evaluation of segment and its material response on an acting load, namely during phase of failure.
3. Modelling allowed comparison of behaviour and character of failure of both RC and SFRC segments, moreover impact of fibre dosage could be evaluated.
4. More complicated experiments (loading by bending in the segment plane) were originally simulated via numerical modelling to deter-

mine in advance required parameters (eg. stiffness or loading capacity) of loading machine and support of a segment.

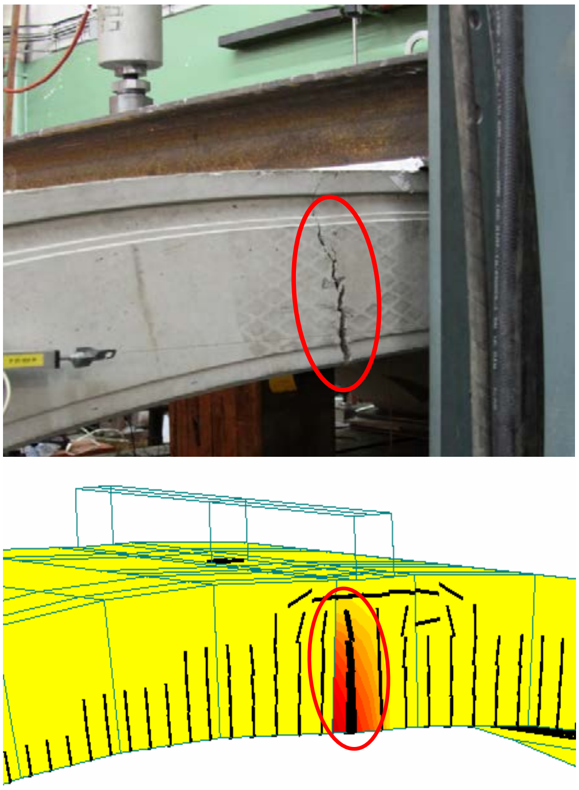
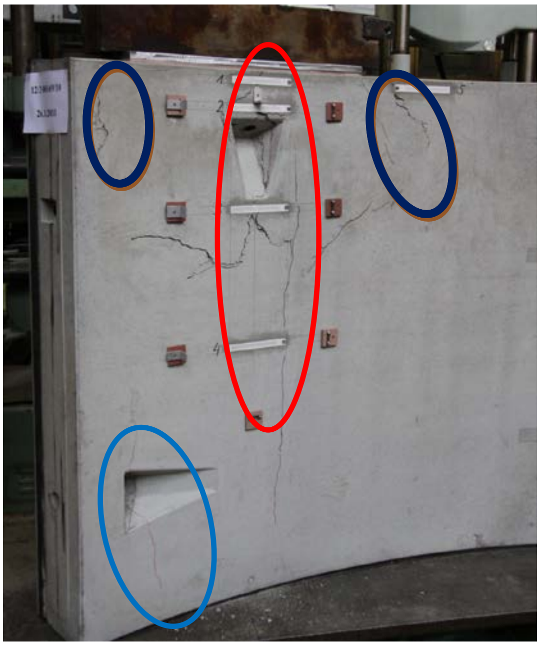


Figure 11. Comparison of crack locations from test and numerical modelling, SFRC segment loaded by bending perpendicular to segment plane



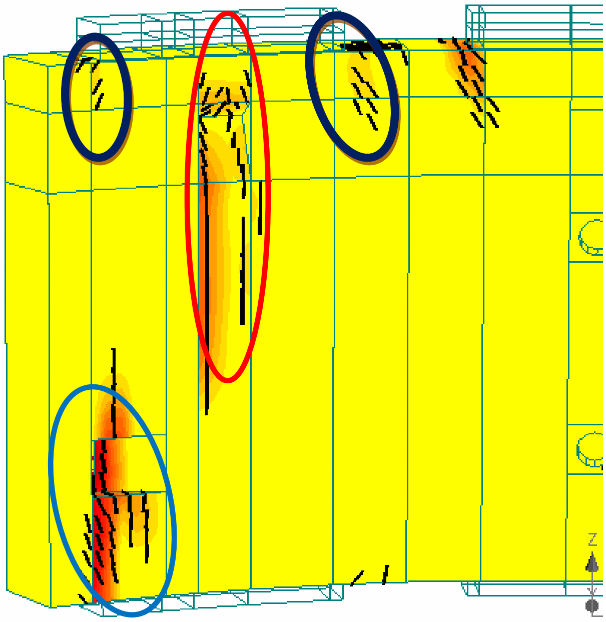


Figure 12. Comparison of crack locations from test and numerical modelling, RC segment loaded by axial compression

Figs. 11 and 12 show results of numerical modelling together with results of experimental testing. The presented comparison shows a very good agreement of modelling and tests.

9 CONCLUSION

The completed experimental testing of SFRC segments and traditionally reinforced concrete segments brought a big amount of very precious information. Naturally, the information on the load-bearing capacity of segments (the magnitude of the maximum load the segments can carry) and on the serviceability of the segments (the origination of first cracks, crack propagation throughout the segment thickness) at various manners of loading is of the highest importance. The results of the tests proved that a lining produced from steel fibre reinforced concrete in specified conditions can replace traditionally reinforced concrete segments. As far as the limit state of serviceability is concerned, it is possible to consider the greater scattering of cracks, leading to the smaller risk of influencing the waterproofing capacity, to be certain advantage.

Similarly significant contribution lied in the experience with the technology of the production of SFRC segments, which, in comparison with traditionally reinforced concrete segments, brings numerous problems which had to be solved. In general, it is possible to state that the amount of steel fibres of 50 kg/m3 and 40 kg/m3 leads to mechanical properties which are comparable. Because of the small number of tests it is not possible to credibly statistically assess and compare the results. However, it is possible to conclude that bigger problems with the dispersion of steel fibres in concrete occur when a greater amount of fibres is used. This technological problem has to be solved during common large-volume production of concrete using professional steel fibre dosing and dispersion equipment. During the course of the production of concrete samples for experiments, steel fibres were dosed manually; at this process it was therefore difficult to secure reproducibility of the product with an identical result.

In the field of segmental linings this was the first comprehensive set of results of experiments on modern real-size tunnel lining segments in the Czech Republic. It has turned out that the character of the response to segment loading completely differs from the character determined in the cases of small samples (i.e. testing beams 70 cm long). It is therefore impossible to apply results of experiments on small samples to complete structures using simple calculation procedures (the theory of elasticity).

Even backward calculations using the Finite Element Method in the ANTENA program (Havlásek et al. 2011) were carried out on the basis of the completed tests. Owing to them the deriving of some important parameters of tested materials was possible. A responsible numerical analysis requires the use of sufficiently sophisticated analytical equipment taking into account energetic principles of modelling the development of cracks. The completed comprehensive set of experiments led to the obtaining of data for calculations which could be used for reliable modelling of the response of real elements to the required loading. The experiment results supported the fact that a segment design must be viewed in a very comprehensive manner and a range of design factors must be taken into consideration. A narrow and one-sided view of the problems leads to neglecting of some influences, which may subsequently complicate the process of the execution of pre-cast tunnel lining and reaching required end-use properties of the lining.

The conclusion was made after taking into account the results of the completed research that the produced SFRC segments meet all requirements placed on the lining of Prague metro. For that reason lining rings were produced and assembled (10 rings, i.e. 15 lm of the tunnel) on a trial section on the alignment of the Line A of Prague metro, using steel fibre reinforced concrete segments (with dosing of steel fibres of 40 kg/m^3). This lining was installed on a running tunnel of the above-mentioned construction in June 2012 (see Figure 13). It was verified after the inspection of the completed trial section that no cracks originated on the particular segments.

Figure 13. Segmental lining of a running tunnel on the Line A of Prague metro

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