Steel Fiber Reinforced Concrete in Tunneluing Applications.

A. <u>Sprayed concrete with steel fibers</u>

Introduction

Steel fibre reinforced concrete is used for many years in spray concrete for tunnel as temporary lining and even final lining.Multiple research studies and tests on the behaviour of steel fibre reinforced concrete have been carried out in recent years in various countries. They have greatly contributed to a better characterisation of Steel Fibre Reinforced Concrete (SFRC), and have thus allowed to gain a better understanding of the behaviour of this material and to specify minimum performance requirements for each project. The state of the art is well known and lot of international standards provides clear guidance and performance criteria to used safely steel fibre reinforced concrete.

1. MATERIAL PROPERTIES OF STEEL AND POLYMER FIBRES

1.1 *Tensile strength of the fibres*

The tensile strength of steel wire is typically 1.000-2.000 MPa, versus 300-600 MPa for macro synthetic fibre.

1.2 *Specific density of the fibres*

The specific density of steel fibres is typically 7.850 kg/m³, versus 910 kg/m³ for polymer fibres, and 1.000 kg/m³ for water. Polymer fibres are light, which is favourable for health and safety, but they are lighter than water: the polymer fibres actually float on water, with potential risks for fibres at the surface.

1.3 *Modulus of Young of the fibres*

The reinforcing ability of a fibre depends on the anchorage of the fibre into the concrete, the tensile strength and modulus of Young.
The Young's modulus of concrete is typically 30.000 MPa, of steel fibre typically 210.000 MPa, and of polyolefin fibre typically 3.000 to 10 000 MPa.
For well anchored fibres, and equal solicitation of the fibre, the elongation of the polymer fibre, and the corresponding crack width in concrete, might be considerably higher compared to steel fibres. This might have an impact on the durability of the concrete, especially in combination with traditional reinforcement.

1.4 *Fire resistance of the fibres*

Metallic fibres have a neutral to positive impact on the fire resistance of structures. Due to a decreased spalling effect, a structure in metal fibrous concrete behaves rather better in the presence of fire than a mesh reinforced structure according to tunnelling specialists (segmental lining). Steel keeps its mechanical performance up to a temperature of 350-400° C.
The macro synthetic fibres though start to loose their mechanical properties as soon as the temperature reaches 50°C and even disappear at 160°C. In a fire, a structure with macro synthetic becomes rather soon unreinforced – with no load bearing capacity left at all – and may result in an unsafe situation from the first hours onwards.

Micro Polypropylene fibres typically melt at temperatures around 160°C. Therefore micro polypropylene fibres (monofilament, length 6mm, diameter nominally <20 micro mm) are proven to be suitable to improve the fire resistance. The exact reason is now fully understood, as it is generally accepted that the fine micro fibres start to melt in extreme fire conditions, thereby leaving small channels through which the pressurized vapour can escape. Consequently less damage, less spalling of the concrete is to be expected.
Macro synthetic fibres do melt at equal temperature, but are not fine enough to provide the concrete under fire with the necessary network of channels. Moreover since the fibres melt, they are not suitable in those building constructions, where the reinforcing effect of the fibres is important.

1.5 *Resistance against oxidation*

Polymer fibres don't rust, even if the fibres are sticking out at the surface.
Regarding metallic fibres: experience and research conclude:
Steel fibres need only a concrete cover of 1-2 mm compared to 30-40 mm for normal rebar and mesh.
Corrosion of the fibres at the surface may cause discolorations but does not affect the mechanical properties of the steel fibre concrete reinforced structures.
Fibres in crack openings smaller than 0.25 mm do not corrode (Brite Euram project).
When no stains required, galvanized fibres can be applied

1.6 *Fibre content in the fresh and hardened concrete*

This European Standard 14721 specifies two methods of measuring the fibre content of metallic fibre concrete.
Method A measures the fibre content of a hardened concrete specimen. Method B measures the fibre content of a fresh concrete specimen.
This point should be solved with polymer, no method available, for the moment in order to meet the quality control requirement for many projects.

1.7 *Water proof membrane*

There was a concern about the danger of steel fibres protruding from the sprayed concrete surface to punch through the waterproof membrane.
The CETU in 1993 (French tunnel administration) had already financed puncture tests (under hydraulic pressure) on the geo membrane (600gr/m2) placed on fiber-reinforced shotcrete supports. These revealed the importance of the lower protection geo textile, without however revealing puncturing risks when it was placed between the PVC geo membrane and the fiber-reinforced shotcrete.

1.PROPERTIES OF STEEL FIBRE CONCRETE

Fibre concrete is well known for its ductility. The effect of fibres is a combination of reinforcement and networking. Steel fibres in particular mainly change the behaviour of the concrete: steel fibres transform a brittle concrete into a ductile material which is able to withstand fairly large deformations without loosing its bearing capacity. Ductility means load redistribution and a higher bearing capacity of the structure with the mechanical properties of the basic concrete material unchanged.

2.1 *Usual Performance criteria for spray concrete*

The test plate usually used (600 x 600 x 100 mm panels) (see EN 14.488-5) is designed to determine the energy absorbed from the load/deflection curve. Slabs intended for the punch-flexure test shall be made in receptacles of 600 x 600 x 100 mm. In this case, care will be taken to obtain an even surface and a thickness of 100 mm.

Spraying shall be carried out rigorously under the same conditions as recommended for the works: constituents, machine, lance holder and spraying methods in particular.

This approach tries to simulate the real lining behaviour. It gives a good idea of the load bearing capacity and the energy absorption of a shotcrete lining.

Instead of determining a material characteristic, which requires a proper design model in order to calculate the allowable solicitation of the structure, the EN plate test approach allows skipping that step and immediately checks the energy absorption and the load bearing capacity of the lining.

It has to be stated very clearly that the statically indeterminate slab test is a structural test to check the behaviour of a construction. It is not a test to determine material properties to be used as design values.

Based on this plate test, three SFRS classes (E500, E700, and E1000) are defined for a C30/37:

500 Joules for sound ground/rock conditions

700 Joules for medium ground/rock conditions

1000 Joules for difficult ground/rock conditions

These values are proposed for a concrete class C30/37, usually specified for a temporary support. Compressive strengths with a too low and too high strength class may have undesired side effects.

In case o higher compressive strength, the performance criteria proposed by the EN standard should be increase in order to keep the same level ductility required for the safety.

The plate test is also appropriate for a comparison of different fibre types and dosages. It allows for a comparison between mesh reinforcement and fibre reinforcement concrete, provided that the failure mode is the same according to EN 14 487-1 Sprayed concrete, definition, specification and conformity. That is why the performance criteria based on this test and currently proposed test should only be used to compare steel mesh and steel fibres (material with same E modulus of young).

The relative importance of load carrying capacity at small crack widths, and hence small deflections and rotations, is of recent times, assuming much greater importance to the designers of civil engineering tunnels

NB: Due to the very low E-module of macro-synthetic fibres and the mode of failure observed with this type of fibres, the plate test is not sufficient to compare steel fibres and macro-synthetic fibres. In case of using polymer fibre another criteria should be added in order to have complete information, as residual strength.

2.2 *Residual strength: Reinforcing effect measured in wide beam tests*

To determine the residual strength, the European EN 14651 is mainly used: Test method for metallic fibered concrete - Measuring the flexural tensile strength (limit of proportionality (LOP), residual).

This test procedure is mentioned in the final recommendation Rilem TC162TDF “test and design method for steel fibre reinforced concrete”

This European Standard specifies a method of measuring the flexural tensile strength of metallic fibered concrete on moulded test specimen. The method provides for the determination of the limit of proportionality (LOP) and of a set of residual flexural tensile strength values.

This testing method is intended for metallic fibres no longer than 60 mm. The method can also be used for a combination of metallic fibres and, a combination of metallic fibres with other fibres.
The characterization test enables the contractor who proposes an FRC to check that this FRC satisfies the “mechanical” specification resulting from dimensioning.
In order to improve this approach, we could propose to follow the following requirements:

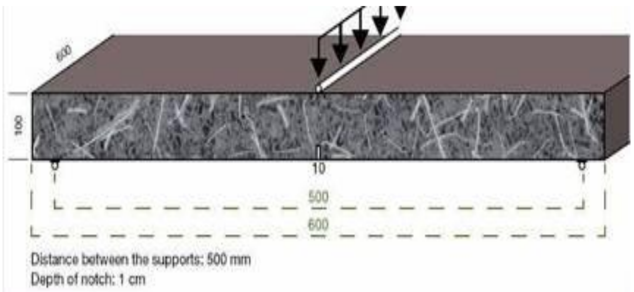

Figure 1: 3 point bending test

The geometry and dimensions of the specimens, as well as the casting method adopted, should ensure distribution of the fibres in the matrix, which is as close as possible to that encountered in the actual structure as spray concrete or flooring
The dimension of the test specimen is acceptable for handling within a laboratory (no excessive weights or dimensions).
The test is compatible, as far as the experimental means permit, with use in a large number of normally equipped laboratories (no unnecessary sophistication).
The geometry should be the same as in the EN 14 488-5 plate test for Energy absorption
One geometry for isostatic and hyperstatic test. Easy to manage a test program could also be sprayed on the job site with the same procedure as the plates test lower scatter than the beam test.

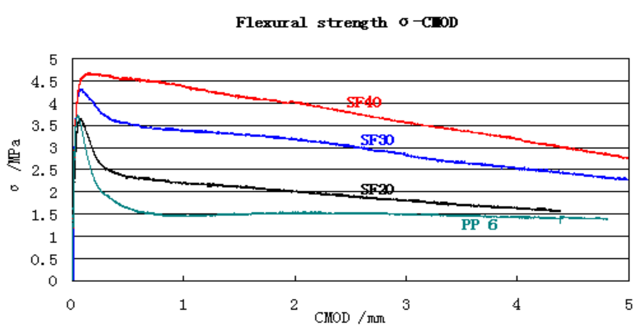

Figure 2: Flexural strength σ-CMOD

Result for different CMOD (crack mouth opening displacement according to EN 14 651)
PP= Macro polymer fibre 6kg/m3
SF20/30/40 = Steel fibre (Dramix RC65/35BN) at 20, 30,40kg/m3
After the first cracking, the load bearing capacity of Macro fibre drops down about 60% rapidly. This means that the 6kg/m3 fibers have lower influence on the residual strength than steel fibers.

Higher dosage of macro synthetic will have big influence on the concrete mix workability and pumpability

2.3 *Creep of steel fibre fibre concrete*

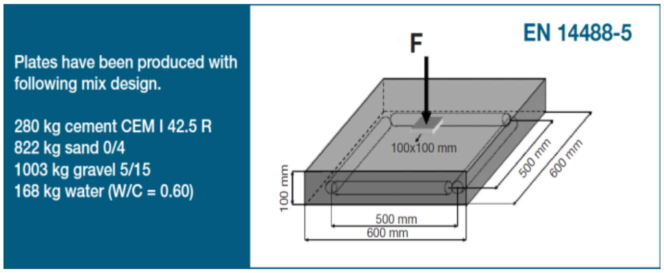

Figure 3: creep test – square panel according to EN 14488-5

The plates have been tested in a displacement controlled manner as described in EN 14488-5. At a deflection of 3 mm the load has been removed.
The plates are now ready to be subjected to the creep test and have been reloaded with 60 % of the applied load at a deflection of 3 mm. The deflection is measured and shown on the Y-axis in 1/100 mm as on the graph.

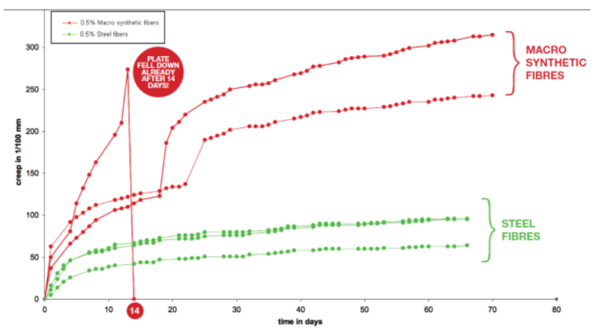

Figure 4: Creep result on square panel

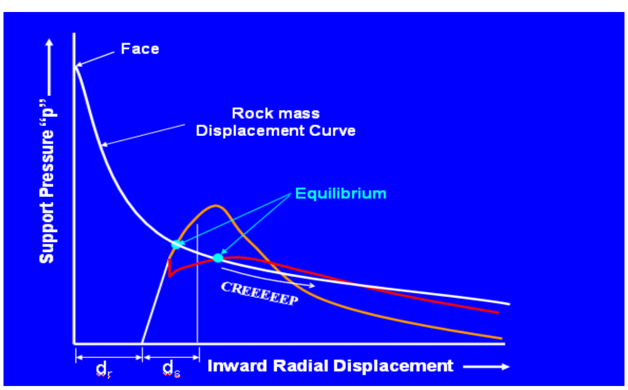

Figure 5: Curve support pressure- inward radial deformation

Consequence due to creep: this type of material will not provide significant reinforcement with the aim of stabilising the ground and minimising any future movement it may well be necessary

2.4 *Design rules for steel and macro synthetic fibres*

Since October, 2003, Rilem TC 162-TDF design guidelines are available for steel fibre concrete. No such guideline is available yet for macro synthetic fibre concrete.

2.5 *Quality control of steel versus macro synthetic fibre concrete*

As part of the quality production control, wash-out tests are quite common in order to check the dosage of fibres in fresh concrete. This is possible when the fibres can be removed by a magnet, as is the case for steel fibres.

CONCLUSION

Steel fibre used for spray concrete spray concrete has proven over the years to be a reliable construction material for tunnelling application. After 30 years of experience, the return of experience is very positive. Official international standard are now available.
Macro synthetic may be used, in sprayed concrete support for some mining applications (could be in combination with mesh) or specific technical need.
However only steel fibres, no macro polymer fibres can act as structural reinforcement of concrete for the following reasons:
-Polymer fibres melt at 165°C; in a fire any “reinforcing” effect of the macro fibres fades away as the temperature rises.
-The Young’s Modulus is 3 - 10 MPa, which is largely insufficient to reinforce concrete material with a modulus of 30 MPa.
-Macro polymer fibres creep (see further more elaborated).
Clear test procedure and performance criteria should be specified for each project in order to meet the technical requirement and ensure the safety.

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The European standards *EN 14.488-5* Testing sprayed concrete - Part 5: Determination of energy absorption capacity of fibre reinforced slab specimens

Brite Euram Project (Durability final report)

B. Steel fiber reinforced concrete in tunneling precast segments

This paper discusses the use of steel fibre reinforced concrete in tunnelling applications with special regard to segmental linings. The steel fibre performance, the way to test the same and its specification play a decisive role and are introduced here. Especially for high concentrated and for dynamic loads steel fibre reinforced concrete is supposed to be an appropriate material. Concentrated loads at high value are acting on segmental lining elements and these loads are pretty often the governing load requirement. Lots of research work has currently been done to reveal the effect of steel fibres at these critical zones. This paper will also give detailed overview about the achieved results of these tests.

In the early nineties, recommendations for design rules for steel fibre reinforced concrete started to be developed. Since October 2003, Rilem TC 162-TDF Recommendations for design rules are available for steel fibre reinforced concrete.

Contrary of the views of many in underground community, steel fibre reinforcement is by no means new technology. Steel fibres have been used in segmental linings as structural reinforcement and for durability reasons for over 25 years. From the first steel fibre reinforced pre-cast tunnel lining in Italy, in 1982, projects have been constructed using steel fibre segments around the world – in the UK, Germany, Singapore, Ecuador, Brazil, Canada, New Zealand and in the United states.

1 DESIGN REQUIREMENTS

As for every structural member of a building a sound analysis needs to be provided. Segmental tunnel linings are unique structures to design, because of the many different loads they must resist. Segments are exposed to bending within a few hours of casting when they are removed form moulds and stacked in curing chambers. Within 24 hours of curing, segments are stacked in matched rings for storage. The segments are then transported to the jobsite, lowered into the Tunnel and placed into position with the TBM. Once in place, TBM shove forces create high, concentrated bursting and splitting forces. Once this is done, the segments are left to support the bored tunnel, imposing high compressive stresses and moderate bending stresses in the lining.

Figure 1: Stacking of segments

Figure 2: TBM shove forces on a segment

The segment design must meet the demands of different customers, each with own expectations. The precast manufacturer wants to produce quick and efficiently and requires high early flexural strength. The contractor wants to install segments that are robust and will not spall during handling and installation. So he requires high splitting tensile strength.

The engineer wants segments that will carry ground and hydrostatic loads, and fulfil the service requirements. So he demands for compressive and flexural properties. Finally, there is also the owner, who requests for a long lasting and durable solution with as less maintenance work as feasible.
Steel fibre reinforced concrete can be designed to meet all the before mentioned requirements. Certainly there are some rules to be considered to match these demands. In the following chapter the steel fibre performance which is a crucial point to be considered, will be issued.
Detailing the methods of design with steel fibre reinforced concrete is beyond the scope of this article. Any tunnel designer can develop load cases and compute the occurring stresses in the segments.

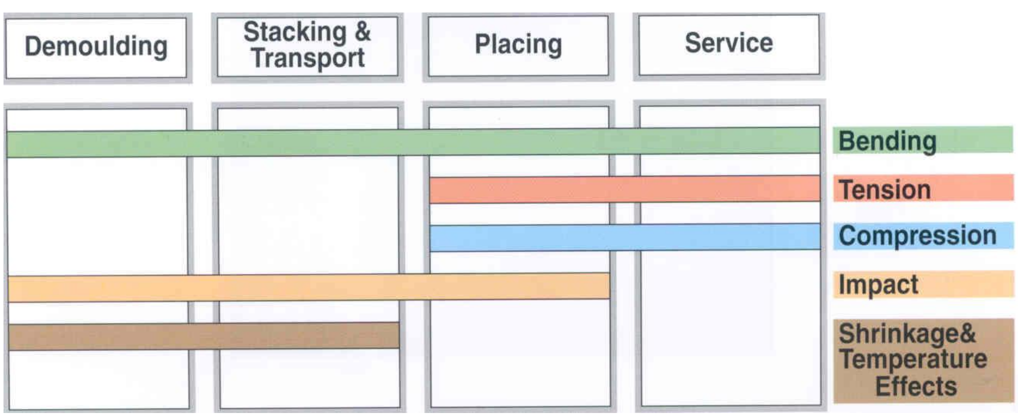

Figure 3: Illustration of the acting loads on segments

2 PERFORMANCE OF THE STEEL FIBRE REINFORCEment

Like with any kind of reinforcement, it is important to provide as much reinforcement in a section as needed. But comparing a fibre dosage with another fibre dosage would not lead to the right conclusions. The reason is that different factors are influencing the fibre performance in a very significant way. The main influencing factors are:

- the material
- the shape (straight, hooked, undulated, crimped, twisted, coned)
- the length (30 to 60mm)
- the diameter (0,4 to 1,3mm)
- the tensile strength (1000 – 2500 N/mm²)

In case of the same type of anchorage, especially the length and the diameter are having the biggest influence on the final steel fibre performance. It can be stated that fibre performance increases by increasing the fibre length and decreasing the diameter. Glued fibres are specially developed to enable a homogenous fibre distribution in concrete especially for high performing fibres where a huge amount of fibres for each kg is given. The risk of fibre balling will be avoided effectively by using glued fibre types.

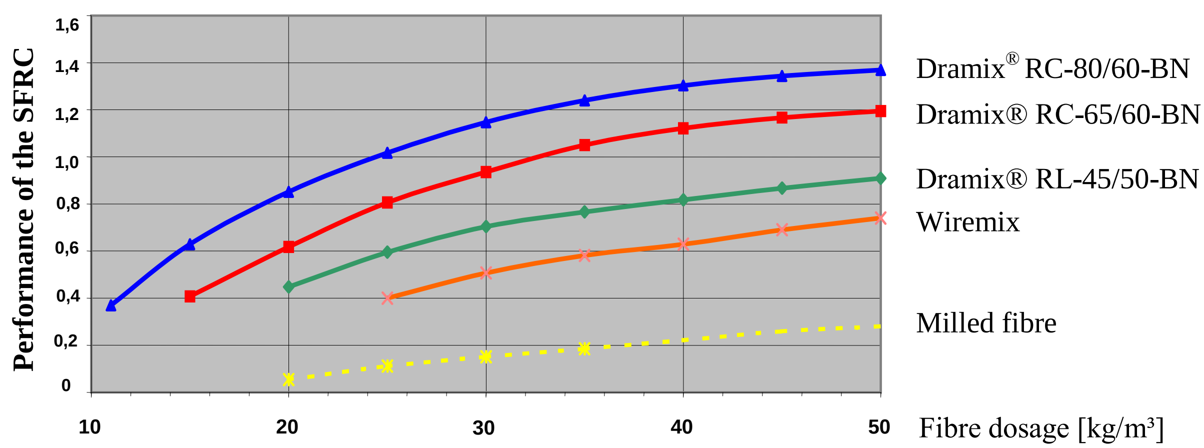

Figure 4: Performance classes in dependency of the fibre type

As soon as concrete cracks fibres are bridging these cracks and provide the so called post crack strength. The value of the post crack strength is in dependency of the fibre type. The following criterions are the decisive points to finally reach high post crack strength.

- Steel fibres
- hooked ends
- as thin as possible
- as long as possible

- high slenderness
- adapted tensile strength to the concrete strength
- optimized concrete recipe

Following three examples of different steel fibre types are illustrating both the entire length of wire and the amount of single fibres for 1kg/m³ of each of these fibre types. The ratio l/d means length/diameter.

RL-45/50-BN l/d = 45	L = 147 m / kg	2800 fibres/ kg
RC-65/60-BN l/d = 65	L = 200 m / kg	3200 fibres/ kg
RC-80/60-BN l/d = 80	L = 288 m / kg	4600 fibres/ kg

The higher the amount of fibres and the longer the fibre is, the bigger the possibility that a fibre meets a crack.

3 Performance testing of steel fibre reinforced concrete

3.1 Statically determined beam tests

Testing of the material property is done by means of beam tests (figure 5/5.1). These tests are statically determined ones and thus they are suitable to derive design stresses (e.g. for M-N interaction and shear). The results of these tests are taken for the design of segmental linings. Below illustrated a typical four point and three point bending test is illustrated. As well established test method the EN 14651 [8] and the JSCE SF-4 [10] beam test, shall be mentioned in this context.

Figure 5: Four point bending test beam

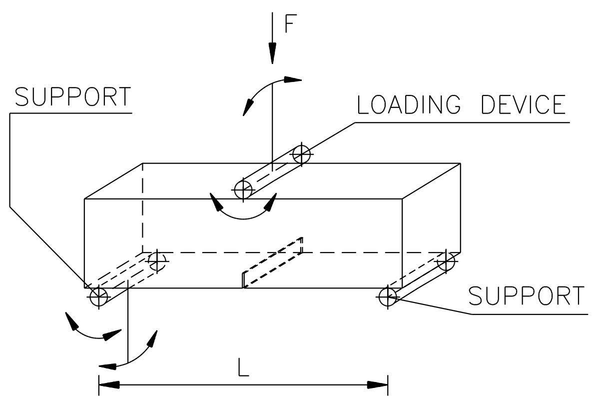

Figure 5.1: Three point ebnding test with notched

The result of a beam test is a load deflection curve out of which the flexural bending strength of the SFRC can be revealed. Residual values are values which are picked up at a certain deflection whereas equivalent values are the performance under a certain area of the load deflection curve. The beams are deflected in common up to 3,0 mm.

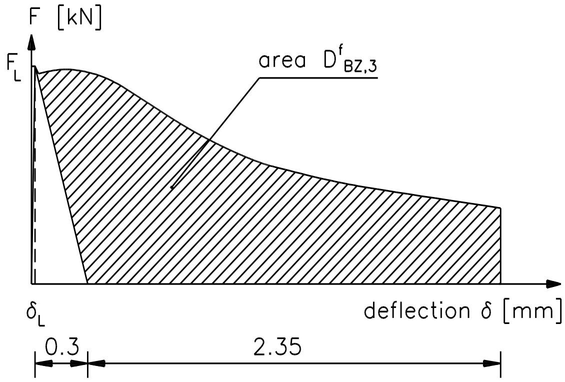

Figure 6: Load-defelction curve, Evaluation by the area under the curve (JSCE SF-4)

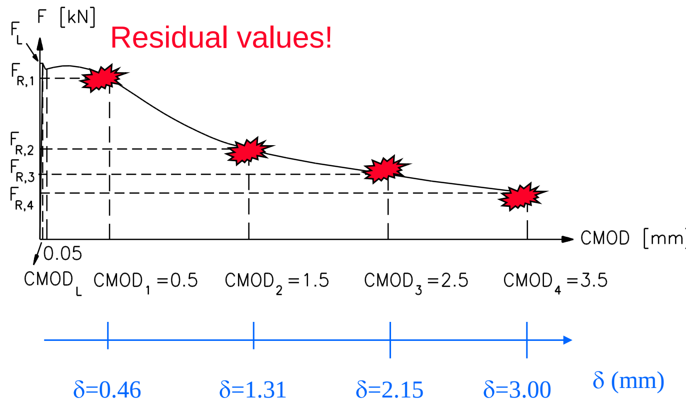

Figure 7: Load- deflection curve, Evaluation by residual values (EN 14651)

3.2 Verification by testing

For the design of fibre reinforced concrete structures theoretical models are available, which proved to be reliable. These design models and the simplifications however get less optimised, where structural elements and load conditions are more complex. Even the most detailed design approach will not be capable to reach the limit of the system resistance of a material. Especially for design models which are formulated to general or for which the available design equations are to far on the safe side (not considering the plastic material reserves at all), full scale tests are an appropriate method to find out the real material resistance. It is therefore sometimes necessary to study the behaviour of full-scale precast segments under a combination of imposed loads (see chapter 5).

Figure 8: Full scale load tests on precast tunnel segment

4 Experimental program on joints between tunnel LINING SEGMENTS

4.1 Introduction

For the construction of tunnels using precast tunnel lining segments, detailed attention must be given to the design of the joints. These joints are indeed strongly stressed, and the failure of the concrete at a joint can significantly compromise the stability of the whole tunnel structure. Concentrated loads, as imposed by TBM or at the conjunction between joints, cause most damages of single lining elements. There are some design equations described how to derive to the occurring spalling and bursting forces. However SFRC is supposed to be a very helpful material for such cases, as all parts of the concrete is reinforced and thus the tendency to spalling is decreased significantly. Especially under severe geological conditions additional loads, are imposed particular on the joints.
The Oenzberg Tunnel, located on the main line between Berne and Zurich, was built by the Swiss Federal Railway (CFF) within the scope of the development of railway infrastructure. At a distance of approximately 80 m from its east end, this tunnel crosses another railway tunnel. The unfavourable geological conditions caused additional loads to be imposed on the precast tunnel lining segments and, in particular, on the joints between the precast segments. It was thus necessary to reinforce these segments in the zone where the two tunnels crossed.

Various reinforcement solutions were studied and, after numerous discussions, the use of steel fibre reinforced concrete (SFRC) was considered. Added in sufficient proportions, steel fibres increase the tensile splitting strength of concrete and improve the ductility of concrete structures. Moreover, the need for complicated reinforcement cages near the joints was eliminated. To study the behaviour and the effectiveness of the SFRC for tunnel lining segments, the CFF commissioned the University of Applied Sciences (UAS) Fribourg, with a comparative experimental study.

4.2 Test program (experimental studies)

To analyze their resistance to concentrated loads, compression tests were carried out on the transverse and longitudinal joints [3,4]. These tests were conducted on full-scale structural elements, cut out from precast tunnel lining segments produced on the Oenzberg Tunnel construction site (fig. 9).

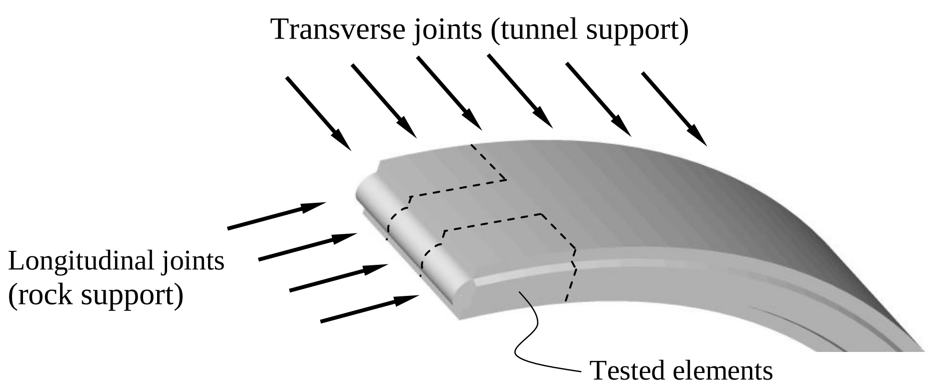

Figure 9: Cut out of tested elements

For the transverse joints, the acting loads includes forces introduced by the tunnelling machine, which has to be supported, and thus imposes loads on the lining segments already in place. For the longitudinal joints, the loading comes essentially from the surrounding rock and, in the particular case of the Oenzberg Tunnel, from the nearby tunnel with a weaker lining.

Three alternative reinforcement solutions were selected for this comparison:

- concrete reinforced with steel bars (standard cages),
- steel fibre reinforced concrete, 60 kg/m^3,
- mixed solution SFRC, 30 kg/m^3, and reduced bar reinforcement.

These three solutions were subjected to an experimental program. The study on the joints between the tunnel lining segments (fig.10) will be introduced as follows. For the transverse joint tests, the line load between two adjacent lining elements acts on a flat contact surface with a width of 200 mm. For the longitudinal joints the load is applied through a circular area. In order to stabilize the two curved lining elements, metal supports were placed on either side. The curvatures of the two elements were reversed to limit the load eccentricity. In addition, load-bearing tests were carried out on the transverse joints, using a linear load applied over the entire length by means of a steel plate, 60 mm or 100 mm in width. The purpose of these tests was to study the initiation of concentrated forces into the lining segments. Thus a series of tests under very high compression loads were performed. These bearing tests do not represent a real case, but were considered to be useful to judge the concentration effects of the loads.

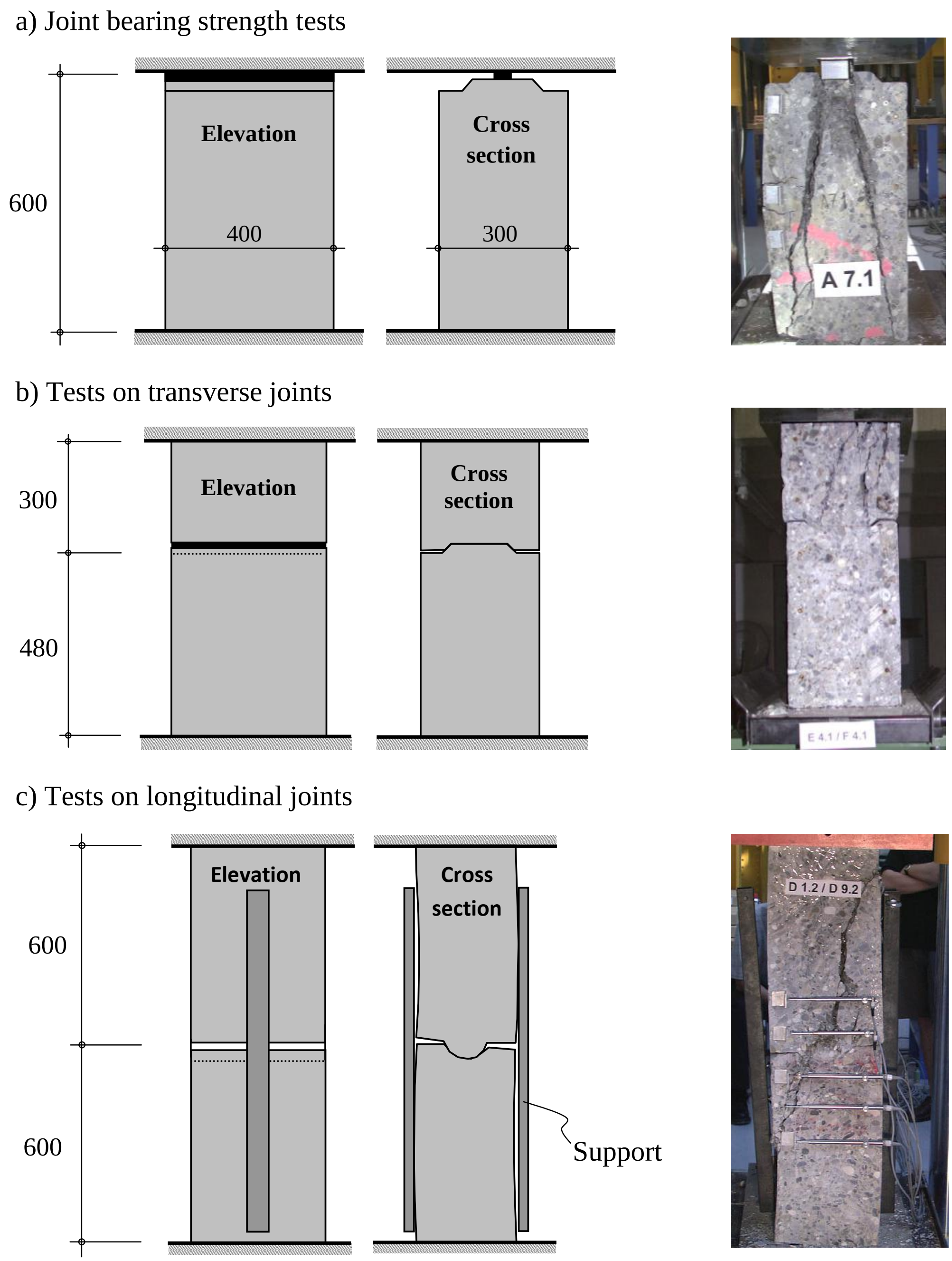

Figure 10: Tests set-up on joint connections between segments

4.3 Test results

The use of SFRC, either alone or in combination with traditional reinforcement, shows an almost identical maximum load (fig. 11). At the longitudinal joints, due to its round shape, an installation of an effective traditional reinforcement cage is hardly possible. This results in a large zone of unreinforced concrete. Steel fibres, though, are capable to reinforce these parts of joints, giving them a higher resistance, combined with a more ductile material behaviour. Indeed, movements of the surrounding rock can impose displacements on the arch structure. Thus the capacity to withstand these displacements is favourable. It is nicely illustrated in figure 11c) that the solution with steel fibres only reached the highest peak of load resistance.

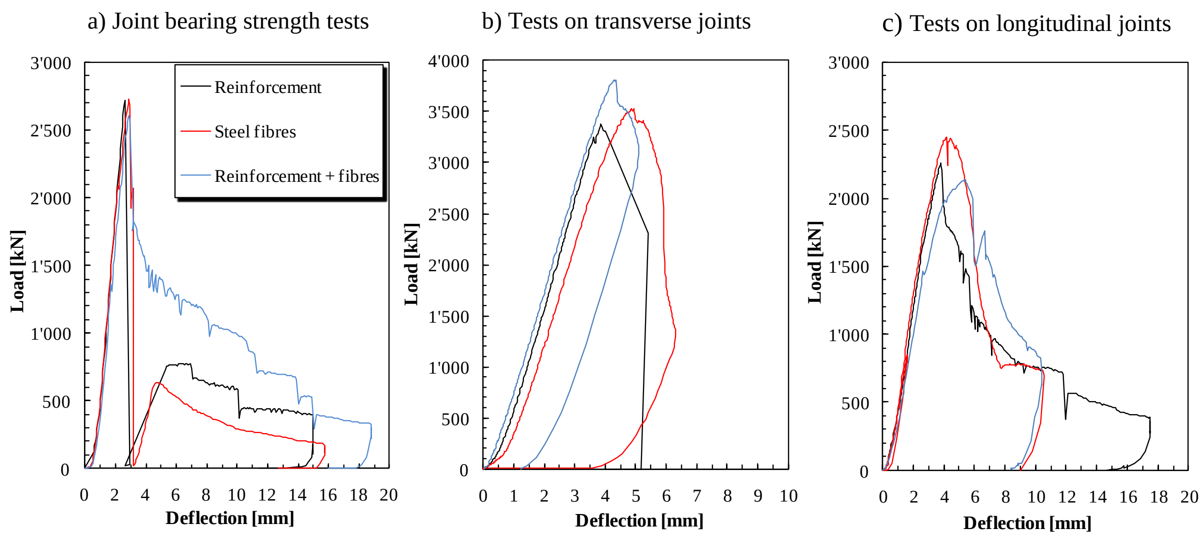

Figure 11: Load – deflection curves of different joint tests

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