THE USE OF STEEL FIBRE REINFORCED CONCRETE IN TUNNELLING APPLICATIONS

Dipl.-Ing. Philipp Guirguis (1)

(1) Bekaert GmbH, Technical Manager Building Products, 61381 Friedrichsdorf, Germany

Abstract

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.

Keywords: Steel fibres, Steel fibre reinforced concrete (SFRC), Segmental lining, Shotcrete, Performance Testing of SFRC, Joints, concentrated loads

1. INTRODUCTION

Steel fibre reinforced concrete has been introduced in the market in the second half of the 1970's. Neither standards nor recommendations were available at that time which was a major obstacle for the acceptance of this new technology. In the meantime, SFRC has been applied ever since in many different construction applications, such as in tunnel linings, mining, floors on grade, floors on piles, prefabricated elements.

In the beginning, steel fibres were used to substitute a secondary reinforcement or for crack control in less critical constructions parts. Nowadays, steel fibres are widely used as the main and unique reinforcement for tunnelling applications, industrial floor slabs and prefabricated concrete products. Steel fibres are considered for structural purposes helping to guarantee the construction's ability and durability in:

- full replacement of the standard reinforcing cage for tunnel segments
- reinforcement of concrete walls and load bearing slab foundations
- steel fibres as shear reinforcement in pre-stressed construction elements
- combination with steel fibres and traditional reinforcement for crack control

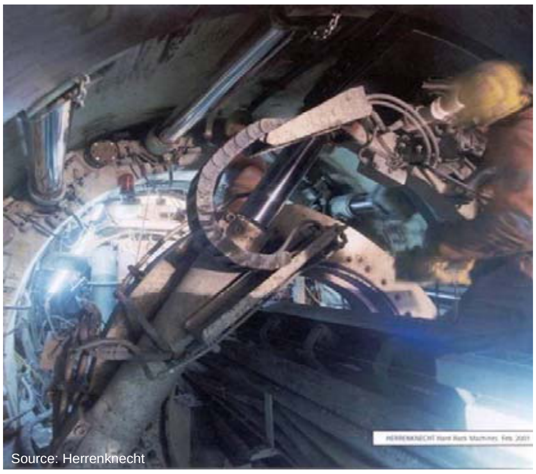
This evolution into structural applications was mainly the result of the progress in the SFRC technology, as well as the research done at different universities and technical institutes in order to understand and quantify the material properties. In the early nineties, recommendations for design rules 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.

As the use of steel fibres in shotcrete has already established well and can be seen as state of the art in so many different countries, the following paper will mainly focus to the use of steel fibres in segmental linings for tunnelling projects. 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.

2. 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



Source: Herrenknecht

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.

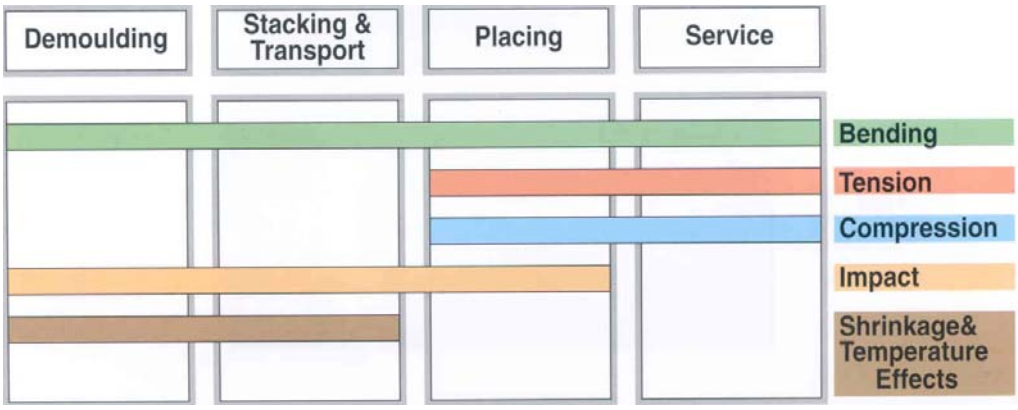


Figure 3: Illustration of the acting loads on segments

3. 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.

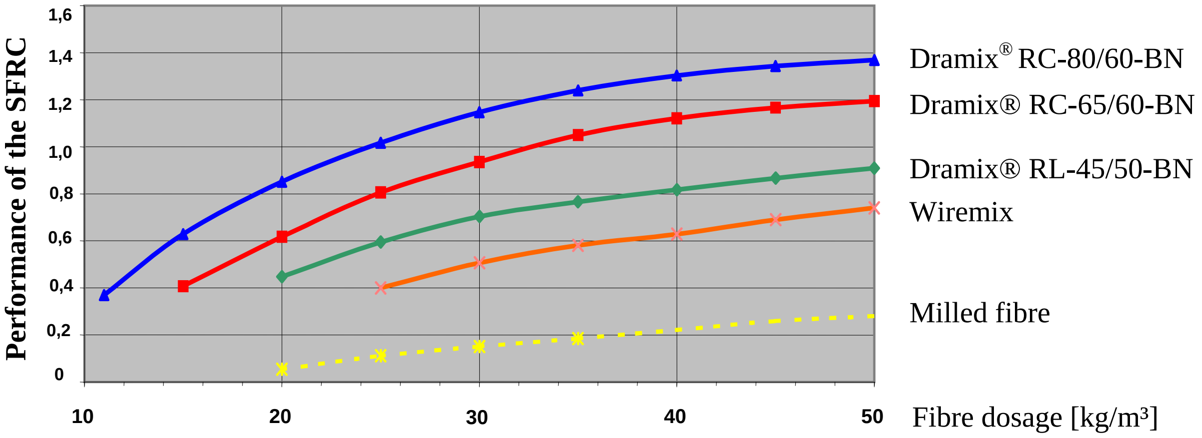


Figure 4: Performance classes in dependency of the fibre type

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.

4. PERFORMANCE TESTING OF STEEL FIBRE REINFORCED CONCRETE

4.1 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

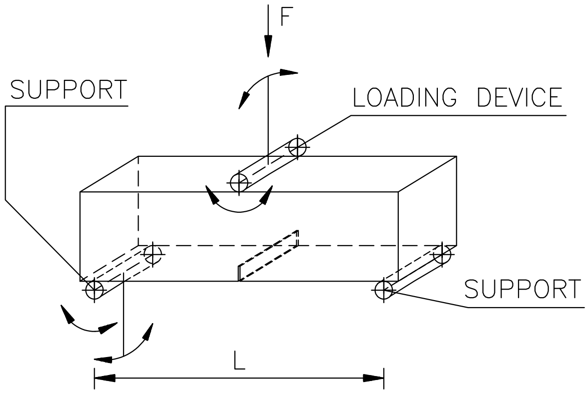


Figure 5.1: Three point ebnding test with notched beam

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.

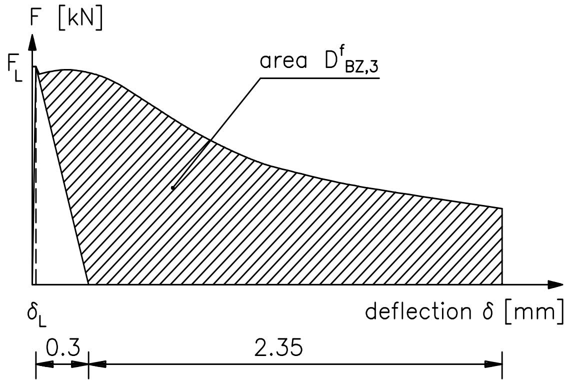


Figure 6: Load-defelction curve, Evaluation by the area under the curve (JSCE SF-4)

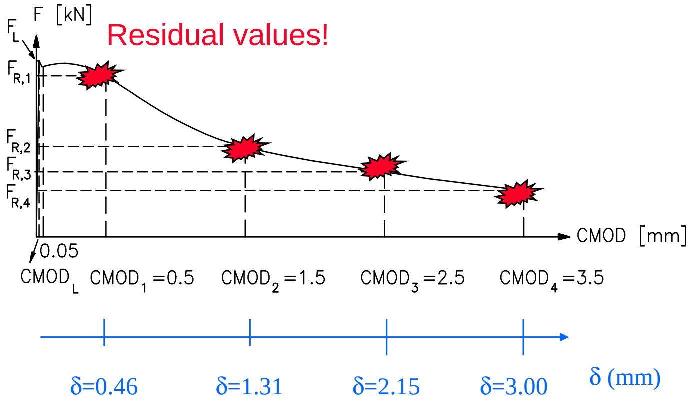


Figure 7: Load- deflection curve, Evaluation by residual values (EN 14651)

4.2 The EFNARC Panel test

Plate tests are considered to figure out the system behaviour. The EFNARC panel is used for shotcrete applications. This test approach is a hyperstatic one and suitable to derive energy absorption. As the system property is determined by this test and not a material property, the resulting values can not be used for a design of section forces.

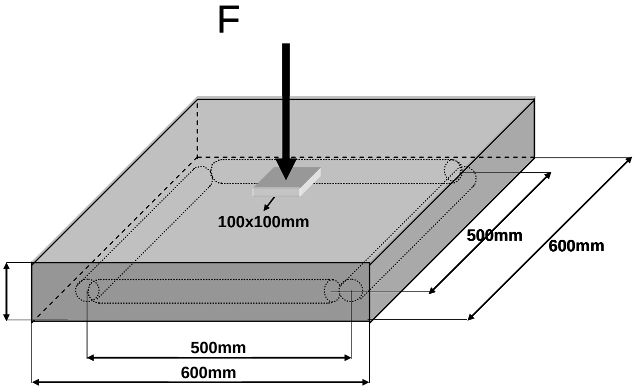
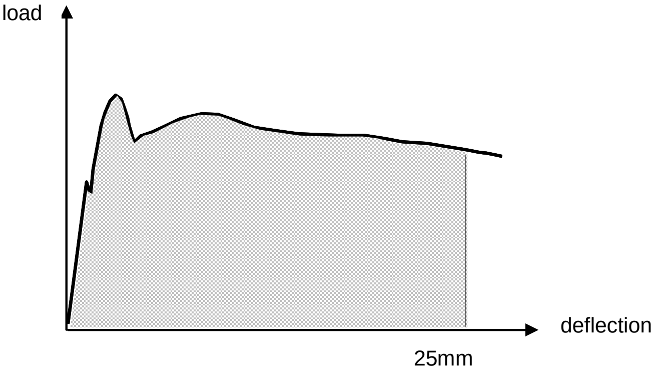


Figure 8: Testing of an EFNARC Panel *Figure 9: measurement of the EFNARC panel*

The reason why this test is so suitable for shotcrete applications is that a shotcrete tunnel lining behaves like such a slab. The hyperstatic conditions allow for load redistribution which is also considered in this test method. The usual requirement of a shotcrete layer is expressed as a Joule classification. As minimum 500 J should be available which is considered for small diameter tunnel; 700 J are most often required and suitable for less good rock conditions. A value of 1000 J (high ductility) is mainly demanded for bad soil condition. The panel is deflected up to 25mm and the results are express in the load deflection curve and in an energy curve (figure 10 and 11).



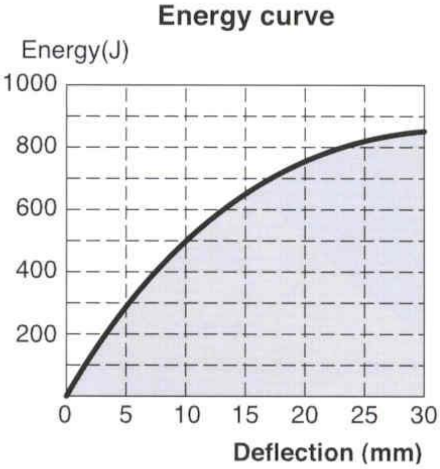


Figure 10: Load deflection curve of an EFNARC Panel *Figure 11: Energy curve*

4.3 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 12: Full scale load tests on precast tunnel segment

5. EXPERIMENTAL PROGRAM ON JOINTS BETWEEN TUNNEL LINING SEGMENTS

5.1 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 but there is slightly available for the resistance part, particularly for the material SFRC. 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.

5.2 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. 13).

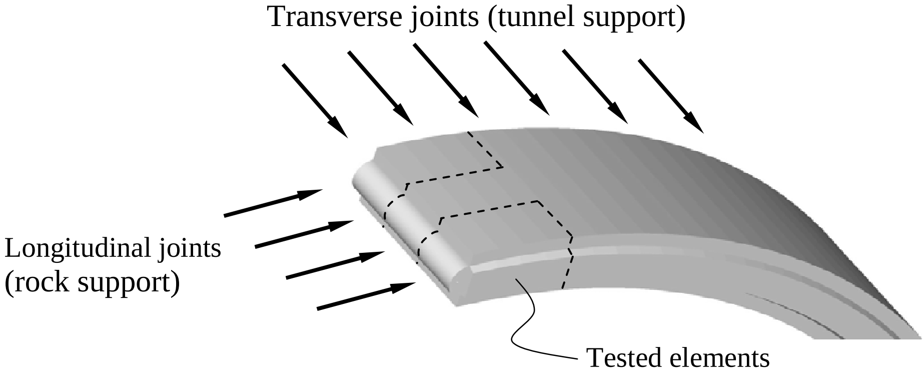


Figure 13: Cut out of tested elements

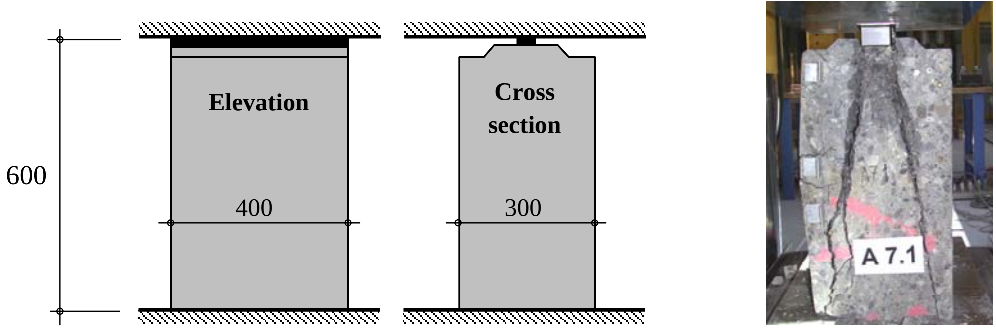
For the transverse joints, the acting loads includes forces introduced by the tunnelling machine, which has to be supported, and thus imposes loads on the lining segments already in place. For the longitudinal joints, the loading comes essentially from the surrounding rock and, in the particular case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

Three alternative reinforcement solutions were selected for this comparison:

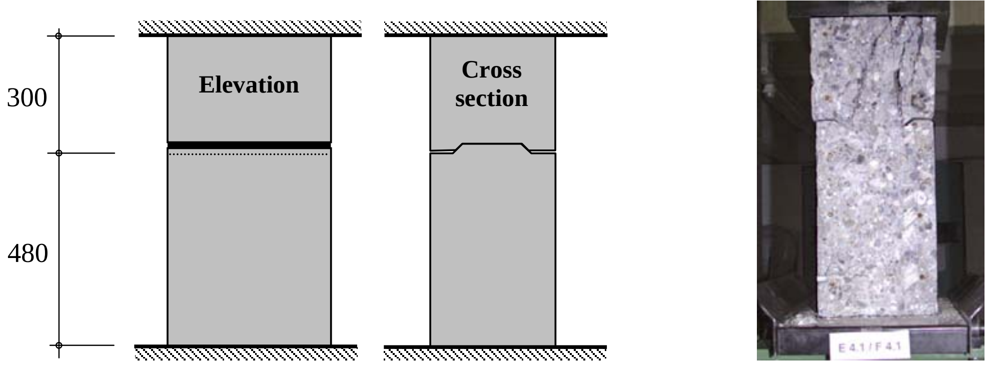
- concrete reinforced with steel bars (standard cages),
- steel fibre reinforced concrete, 60 kg/m^3,
- mixed solution SFRC, 30 kg/m^3, and reduced bar reinforcement.

These three solutions were subjected to an experimental program. The study on the joints between the tunnel lining segments (fig.14) 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.

a) Joint bearing strength tests



b) Tests on transverse joints



c) Tests on longitudinal joints

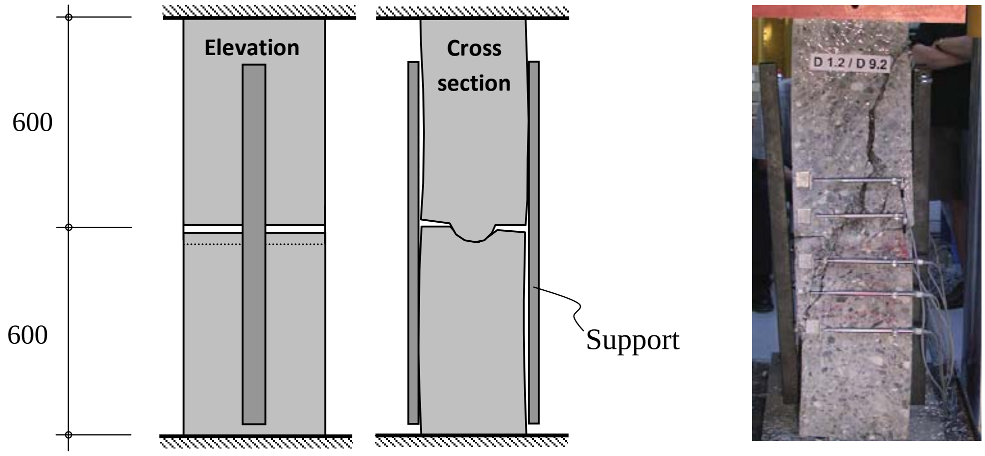


Figure 14: Tests set-up on joint connections between segments

5.3 Test results

The use of SFRC, either alone or in combination with traditional reinforcement, shows an almost identical maximum load (fig. 15). 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 15c) that the solution with steel fibres only reached the highest peak of load resistance.

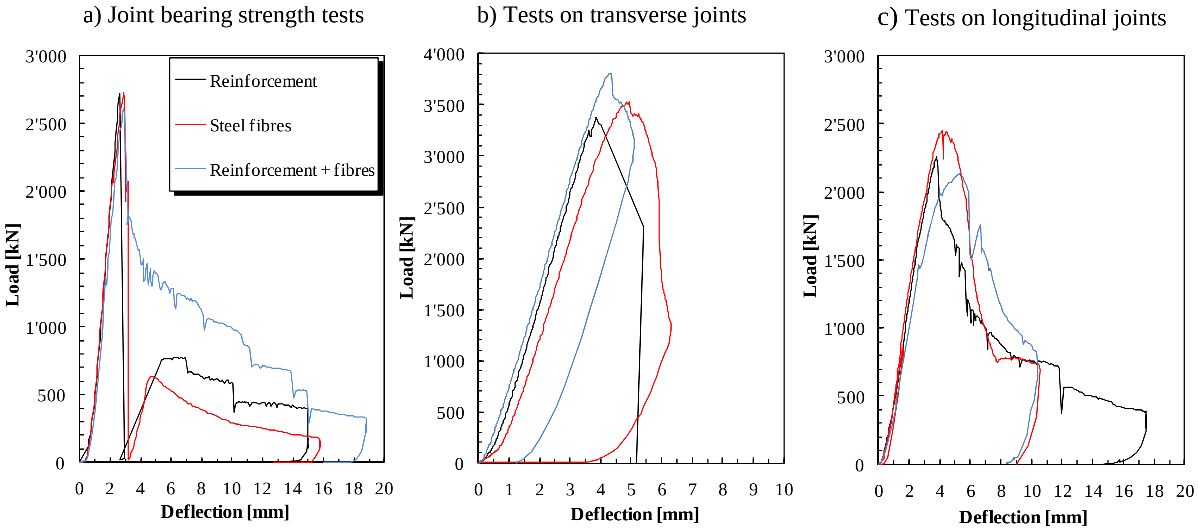


Figure 15: Load – deflection curves of different joint tests

6. REFERENCES

[1] M. Vandewalle, Tunnelling is an Art, NV Bekaert SA, 8550 Zwevegem, Belgium, 2005.

[2] P. Marti, T. Pfyl, V. Sigrist, T. Ulaga, Harmonized Test Procedures for Steel Fibre Reinforced Concrete, ACI Materials Journal, Vol 96 No 6/1999.

[3] R. Suter, K. Bergmeister, Tübbinge aus Stahlfaserbeton, Beton- und Stahlbetonbau 11/2004, pp. 858-864.

[4] R. Suter, P. Buchs, Precast fibre reinforced tunnel lining segments, Experimental Study, Final Report, University of Applied Sciences, Fribourg, 2008.

[5] H. Falkner, Stahlfaserbeton - ein unberechenbares Material ?, Bauseminar, IBMB Heft 164, Braunschweig, 2002.

[6] Th. Pfyl, Tragverhalten von Stahlfaserbeton, PhD Thesis, Swiss Federal Institute of Technology, Zürich, 2003.

[7] R. Suter, L. Moreillon, High performance fibre reinforced concrete, Experimental Study, Final Report, University of Applied Sciences, Fribourg, 2009.

[8] EN 14651, Test method for metallic fibered concrete – Measuring the flexural tensile strength (Limit of proportionality (LOP), residual)

[9] EN 14889-1, Fibres for concrete – part 1, Steel fibres – Definitions, specifications and conformity

[10] JCI, Test for flexural strength and toughness for fibre reinforced concrete, JSCE SF-4 Japan Concrete Institute, 1984