Design, dimensioning and execution of precast steel fibre reinforced concrete arch segments

Text presented by Pascal Guedon (Arcadis) Working Group leader

With the collaboration of:

Philippe Autuori (Bouygues) - Rémi Billangeon (Spie Batignolles) - Bruno Dardard (SNCF Ingénierie) - Benoît de Riva (Bekaert)
Gabriel Durand (Argotech) - Lionel Linger (Vinci) - Patrick Peltier (Stradal) - François Petit (Vinci) - Pierre Rossi (IFSTTAR) - Bernard Ruby (RATP)
Jean-François Tessier (SIAAP) - François Toutemonde (IFSTTAR) - Marc Vandewalle (Université Polytechnique de Catalogne)

Thanks for re-reading to:

Daniel Brunet (Expert) - Michel Deffayet (CETU) - Sylvie Giuliani-Leonardi (Vinci) - Catherine Larive (CETU) - Jean Launay (Vinci)
Michel Pré (Setec) - François Renault (Vinci) - Loïc Thevenot (Elfage) - Hubert Tournerie (Egis Tunnels) - Jacques Triclot (Egis Tunnels)

AFTES welcomes all suggestions relating to this text.
Steel fibres have been used for a number of years to reinforce tunnel linings in precast arch segments the world over (Europe, the United States, and so on). However, their application and their use in this field have been limited by the relatively small amount (or indeed complete lack) of regulatory frameworks to deal with this type of product. With the appearance of specific EU standards for the use of steel fibres and the coming into existence of national recommendations in France, Italy, Japan and elsewhere, the use of fibre-reinforced concrete in structures is now possible.

A large amount of research and testing of the behaviour of steel fibre-reinforced concrete has been conducted in recent years in the United States, Canada, France, Belgium, Great Britain, Italy, Switzerland, Japan and other countries. This has contributed considerably to a better characterisation of SFRC and thus made it possible to have a better understanding of the behaviour of this material and specify the minimum performance values for each project.

The purpose of this document is to supply recommendations for the design, dimensioning and construction of precast arch segments installed to the rear of a TBM, and follows on from the recommendation published for reinforced concrete arch segments.

Consequently, subsequent reference should be made to this previous recommendation, particularly for the general chapters dealing with lining functions and the description of the arch segment ring concept.

## 1 - Overview

Steel fibres have been used for a number of years to reinforce tunnel linings in precast arch segments the world over (Europe, the United States, and so on). However, their application and their use in this field have been limited by the relatively small amount (or indeed complete lack) of regulatory frameworks to deal with this type of product. With the appearance of specific EU standards for the use of steel fibres and the coming into existence of national recommendations in France, Italy, Japan and elsewhere, the use of fibre-reinforced concrete in structures is now possible.

A large amount of research and testing of the behaviour of steel fibre-reinforced concrete has been conducted in recent years in the United States, Canada, France, Belgium, Great Britain, Italy, Switzerland, Japan and other countries. This has contributed considerably to a better characterisation of SFRC and thus made it possible to have a better understanding of the behaviour of this material and specify the minimum performance values for each project.

The purpose of this document is to supply recommendations for the design, dimensioning and construction of precast arch segments installed to the rear of a TBM, and follows on from the recommendation published for reinforced concrete arch segments.

Consequently, subsequent reference should be made to this previous recommendation, particularly for the general chapters dealing with lining functions and the description of the arch segment ring concept.

## 2 - Design of SFRC tunnel linings

### 2.1 - Introduction

As specified above, the reference document relates to the AFTES recommendation entitled "Design, dimensioning and execution of reinforced precast concrete arch segment linings installed to the rear of a TBM" (La conception, le dimensionnement et l’exécution des revêtements en voussoirs préfabriqués en béton armé installés à l’arrière d’un tunnelier), Version 1, 1997.

The wide variety of design elements of arch segments and the ring, as set forth in this recommendation, are still applicable today.

In this recommendation, the design and dimensioning of SFRC linings also draws on Model Code 2010 (MC 2010)[5] for structures made of concrete developed and perfected by fib (formerly CEB-FIP). This is a pre-normative document used as an international reference for subsequent regulations: Eurocodes, in particular, have been based on it. MC 2010 also examines new developments in concrete structures and concrete as a material, as well as other innovative ideas such as SFRC. The 2010 version of the Model Code (September 2011) was the most advanced version at the time of publication of this recommendation.

### 2.2 - General design of SFRC linings

Current experience of fibre-reinforced ring segments rests mainly on a concept involving solid arch segments, combined with an arch segment geometry consisting of rectangles plus trapezoid shapes, parallelograms plus trapezoids, or trapezoids alone.

---

AFT: Fédération Internationale du Béton (International Federation for Structural Concrete)
Screwed assemblies must also be assessed, taking into account the additional stress to be borne during assembly as well as in service. It is usually possible to know in-service levels of stress and indeed these will have been used to dimension the connectors. Consequently, the strength of the assembly areas that constitute singularities (such as the concrete section between the bolt or anchor bolt path and the inner surface) should be verified.

Here, too, tests may be carried out to assess the robustness of the assembly. In general, if such sections are thin (small diameter arch segments) and even if they have traditional steel reinforcements, steel tubing coupled with “tie rebars” should be installed to distribute the stress throughout the body of the arch segment. This system is also feasible for fibre-reinforced arch segments: the “ties” are of one piece with the tubing, enabling them to be properly positioned.

Screw assemblies for arch segments that are only fibre-reinforced may be more difficult and specific tests must be carried out to verify the resistance of the assembly areas. Other solutions should therefore be preferred, and are in fact increasingly widespread for safety aspects (less intervention by operators to install elements) as well as due to issues of productivity when installing rings.

2.4 - Durability

Just as with traditional rebars, steel fibres may be subject to corrosion. Two different scenarios need to be taken into account when analysing the corrosion of steel fibres and its consequences.

- Firstly, if the fibres do not cross a surface crack
- Secondly, if the fibres do cross a surface crack.

2.4.1 - Fibres do not cross a surface crack

As in the case of reinforced concrete rebars, the protection of steel fibres from corrosion depends on how compact the matrix is. The more compact the matrix, the more difficult it is for aggressive agents to spread, and the more effective the protection of the fibres from chemical attack will be. However, for identical components, matrices containing fibres are always less compact than in their absence.
This problem, which relates to the physics of granular stacking, may easily be minimised by optimising the matrix formulation. This optimisation involves increasing the quantity of paste (cement plus mineral additives) and fines (sand) as the percentage of fibre increases. In conventional SFRC, fibres are not in contact given doses of less than 100 kg/m³, thus limiting the spread of corrosion, including corrosion relating to stray currents. For this reason, and for the purposes of an initial approach, coating concrete serving as a “barrier” to aggressive agents may be the same thickness for both concrete and fibre reinforced concrete, provided that the appropriate strength for the exposure class is ensured.

In summary, corrosion of non-cracked SFRC leads to the following being observed:

- fibre corrosion at the surface of the structure, without this corrosion penetrating inwards (no contact between fibres); no concrete bursts; small quantities of corrosive products; matrix porosity is “sealed” at the surface of the structure by the corrosive products.
- no deterioration in the mechanical properties of the SFRC.

These observations are thoroughly supported by research. One of many such examples that may be cited is the relatively complete experimental study carried out by the French National Agency for the Handling of Radioactive Waste (ANDRA, Agence Nationale pour les Déchets Radioactifs), (Dubois et Nouguier (1989)) [21].

2.4.2 - Fibres cross a surface crack

This is a significant scenario with regard to the potential mechanical consequences of fibre corrosion. Indeed, the question is whether fibres crossing cracks corrode to an extent that they lose their reinforcement potential (since cracks considerably accelerate the chloride ion diffusion process).

An examination of the literature on this subject indicates that it may reasonably be assumed that for cracks with a crack mouth opening displacement of less than 150 µm, steel fibres do not undergo corrosion leading to any decrease in the mechanical characteristics of SFRC. (No evidence exists as to whether larger cracks lead to any harmful mechanical corrosion occurring). This conclusion may be explained by the fact that the products that corrode fibres passing through cracks located close to the structure’s surface tend to seal the cracks in question: when the cracks are not very wide, they may in fact be seen to heal over.

In the event of a wide crack appearing, the relevant section of the structure must be monitored and maintenance performed if necessary, depending on the degree of structural risk involved.

2.4.3 - Specific instance of mixed structures in which reinforcements consist of reinforced concrete rebars and steel fibres

The main point to be borne in mind is that in service, cracks are much narrower and less straight in mixed structures than in structures made solely of reinforced concrete. The consequence of this fact is that it is much more difficult for aggressive agents to reach the rebars in mixed structures.

It is easier for the mechanisms through which cracks are sealed and heal over to occur in a mixed structure than in one made solely of reinforced concrete.

2.4.4 - Conclusion

- SFRC structures do not present any mechanically damaging corrosion issues.
- Mixed structures containing both rebars and fibres are less subject to corrosion than structures made solely of reinforced concrete.

In the light of these observations, the following design recommendations may be made with reference to exposure classes defined in NF EN 1992-1-1:

- in more aggressive environments, corresponding to exposure classes XS3, XD3 and XA3, check that the Serviceability Limit State (SLS) frequent combination tensile stress remains lower than the characteristic tensile strength (f_{cub,cs} as defined in EC2) which corresponds to situation 2.4.1 and to a condition deemed to be that of non-cracking in service.
- in other cases, corresponding to situations 2.4.2 and 2.4.3, limit the SLS frequent combination design width of cracks wₕ to 0.15 mm (exposure classes XS1, XD1, XS2, XD2, XA1 and XA2) or 0.2 mm (exposure classes XC1, XC2, XC3 and XC4). Crack mouth opening displacement calculations to be performed pursuant to §7.7.4.2 in document MC2010.
- in all cases, in the presence of rebars, except in specific, substantiated cases, ensure coating of a value greater or equal to c_{min,dur} as per standard NF EN 1992-1-1 section 4 (minimum coating to ensure durability).
- For aggressive environments, or where surface fibre corrosion is to be avoided for aesthetic reasons, it should be noted that galvanised steel and even stainless steel fibres are available on the market; these offer very high protection against corrosion. Their specific physical and mechanical properties should be taken into consideration when designing and dimensioning the arch segment. In standard cases, their use is not necessary.

2.5 - Fire performance

Fire performance tests have recently been carried out on SFRC arch segments in Europe (CTRL, etc). These have shown that steel fibre represents an improvement on reinforced concrete which, due to the thermal conductivity of rebars, rapidly leads to the bursting of exposed concrete.

While spalling is still present, resulting not only from local vapour overpressure, but also due to biaxial compression of the exposed wall [14], this phenomenon is less pronounced than in the case of reinforced concrete.

As in the case of conventional concrete arch segments, the use of a sufficient proportion of polypropylene fibres in the SFRC composition brings down the risk of spalling considerably, by means of a mechanism of which details can be found, for instance, in [15].

Consequently, combining steel fibres with polypropylene micro-fibres is an adequate solution for better fire performance, although it involves special attention being paid to the tradeoff between the rheology of the fresh material and the prevention of risks relating to thermal instability (spalling).

In the absence of a reference document providing support for the cross-section of SFRC subject to high temperatures (ISO or HCM “modified hydrocarbon” curves), specific tests must be carried out to support the design in terms of expected stability.
3 - Dimensioning of SFRC arch segments

3.1 - Foreword

Reference will be made subsequently to the previously quoted recommendation for dimensioning reinforced concrete arch segments in order to identify, as exhaustively as possible, all load conditions that may influence the dimensioning of SFRC arch segments.

Indeed, mechanical reinforcement of arch segment concrete by rebars or fibre may address the need to balance tensile stress in six principal scenarios:
1. Combined bending and axial stress on arch segments, with ovalisation of the ring due to thrust from the soil and soil-structure interaction.
2. Burst stress in localised areas of compression: assembly points between arch segments, areas supporting TBM footplates, hard contact points, etc.
3. Bending while the concrete is fresh, during removal from moulds and/or storage.
4. Tensile stress as a result of impacts during transport and handling.
5. The risk of a lack of support, in the absence of specific precautions, during thrust exerted by the TBM jacks to install an arch segment, resulting in tensile stress on part of the arch segment between the points at which the support reaction is concentrated.
6. Tensile stress as a result of differential shrinkage of the concrete, in the event of very thick sections.

The effectiveness of fibre reinforcements compared to reinforced concrete rebars to deal with situations 4 and 6 is proven, and in most cases does not require supporting design calculations since minimising cracks and spalling is a benefit that is directly visible at the worksite stage. Demonstrating the effectiveness of fibres for situation 2 should be conducted on the basis of representative tests, taking into account the design arrangements adopted and the procedures for installing the SFRC, which will determine how the fibres are aligned.

The effectiveness of SFRC in situation 5 in particular has been studied as part of the national BEFIM project [4, 7, 8]. If the characteristics of the soil and the design of the arch segments and the way the rings are installed means that it is impossible to avoid significant gaps between the points at which the support reactions arising from the thrust exerted by the TBM are concentrated, the load-bearing capacity of SFRC in terms of tensile stress may not be enough to ensure the desired level of safety: the presence of reinforced rebars at the edges of the arch segments will be necessary. In this case, elements of design support for a method using connecting rods are available, for instance in [4]. Full-scale tests may also be carried out to ensure appropriate behaviour under this type of stress.

The following guidelines are therefore intended principally to provide design calculation support for mixed or fibre reinforcements for situations 1 and 3.

3.2 - Procedures for dimensioning SFRC arch segments

If SFRC is being considered for an arch segment, a specific approach must be stringently followed in order to achieve a reliable technical solution. This approach consists of a number of stages:

1. Defining the design stress for the tunnel and arch segments under consideration.
3. Carrying out suitability testing in order to verify whether the proposed SFRC complies with the mechanical characteristics used for dimensioning.
4. Carrying out in-factory tests in order to monitor the quality of the SFRC used during manufacture of the arch segments.

This is in fact a conventional approach in which only steps 2, 3 and 4 are specific to SFRC. A number of clarifications are supplied for these stages below.

Clarifications for step 2 - Dimensioning

The Model Code 2010 includes supporting design calculations for the following:
- resistance to normal stress
- resistance to tangential stress
- distribution of concentrated loads

and provides for the possibility of experimental substantiation.

In the case of verification by calculation, the principal mechanical data for SFRC relate to its post-cracking tensile behaviour (in other words, after localisation of the crack or, in other words, after its elastic limit has been reached). Regarding SFRCs to be used in tunnel arch segments, this post-cracking tensile behaviour generally results in softening (or negative hardening): stress decreases (once the crack is localised) as it opens. However, in some cases, post-cracking behaviour may feature strain hardening.

Pragmatically speaking, on the basis of current knowledge, it is necessary to make assumptions about the post-cracking behaviour to be taken into account in calculations and simplify the post-cracking design law with regard to experimental reality (in order to simplify dimensioning calculations).

Transitioning from an experimentally-derived law to a design law

The post-cracking behaviour of “traditional” SFRC may generally be represented as shown in figure 1.

This combines a crack mouth opening displacement $w_c$ with the serviceability limit state; the ultimate limit state corresponds to a crack mouth opening displacement $w_u$. 
To transition from the experimental behaviour shown in figure 1 to a simplified
design behaviour, let it be assumed that the design behaviour is elasto-plastic
with linear softening (stress varies linearly subsequent to the elastic limit).

To transition from the experimental behaviour shown in figure 1 to a simplified
design behaviour, let it be assumed that the design behaviour is elasto-plastic
with linear softening (stress varies linearly subsequent to the elastic limit).

The design curve is obtained on the basis of a characteristic experimental curve,
determined on the basis of at least 6 tests, such that the probability of the load-
bearing capacity being in excess of the characteristic curve is 95%. The relation-
ship between the experimental and the design curves is one of energy. In
other words, for a serviceability limit state design, the non-linear energy beneath
the design curve is the same as that beneath the experimental curve, for a
 crack mouth opening displacement equal to w_s. The same applies to the ultimate
limit state where the crack mouth opening displacement is w_u (figure 2).

The design curve incorporates the effect of using SFRC in the arch segment
by using a K-factor, as specified in the Model Code (cf §5.6.7 MC 2010), called
“orientation factor”.

For an isotropic distribution of fibres in the structural element identical to that
in the characterization prism, this factor is equal to 1.0.

In the event of an unfavourable effect, a K value > 1.0 must be applied and
verified experimentally.

In the event of a favourable effect, a K value < 1.0 may be applied if verified
experimentally and if it remains safe for all possible stresses on the arch seg-

The design curve is obtained on the basis of a characteristic experimental curve,
determined on the basis of at least 6 tests, such that the probability of the load-
bearing capacity being in excess of the characteristic curve is 95%. The relation-
ship between the experimental and the design curves is one of energy. In
other words, for a serviceability limit state design, the non-linear energy beneath
the design curve is the same as that beneath the experimental curve, for a
 crack mouth opening displacement equal to w_s. The same applies to the ultimate
limit state where the crack mouth opening displacement is w_u (figure 2).

The design curve incorporates the effect of using SFRC in the arch segment
by using a K-factor, as specified in the Model Code (cf §5.6.7 MC 2010), called
“orientation factor”.

For an isotropic distribution of fibres in the structural element identical to that
in the characterization prism, this factor is equal to 1.0.

In the event of an unfavourable effect, a K value > 1.0 must be applied and
verified experimentally.

In the event of a favourable effect, a K value < 1.0 may be applied if verified
experimentally and if it remains safe for all possible stresses on the arch seg-

The crack mouth opening displacement values w_s and w_u must now be defined
in order to determine the tensile stress values $\sigma_s$ and $\sigma_u$ to be used in design
calculations. For w_s, the limit values and verifications for crack mouth opening
displacement have been set forth at 2.4.4.

For w_u, the problem is more complex and delicate.

For issues of bending, the crack mouth opening displacement that corresponds
to the maximum bending moment will depend on the height of the section.
It is known that SFRC currently used in tunnel arch segments (which typically
have between 30 and 60 kg/m$^3$ of fibre in concrete with characteristic strength
of the order of 50 MPa) behaves well in terms of post-cracking tensile stress
for crack mouth opening displacement of up to approximately 3.5 mm.

Pending further experience, design calculations should be performed with w_u
equal to 2.5 mm, as specified in Model Code 2010.

The crack mouth opening displacement values w_s and w_u must now be defined
in order to determine the tensile stress values $\sigma_s$ and $\sigma_u$ to be used in design
calculations. For w_s, the limit values and verifications for crack mouth opening
displacement have been set forth at 2.4.4.

For w_u, the problem is more complex and delicate.

For issues of bending, the crack mouth opening displacement that corresponds
to the maximum bending moment will depend on the height of the section.
It is known that SFRC currently used in tunnel arch segments (which typically
have between 30 and 60 kg/m$^3$ of fibre in concrete with characteristic strength
of the order of 50 MPa) behaves well in terms of post-cracking tensile stress
for crack mouth opening displacement of up to approximately 3.5 mm.

Pending further experience, design calculations should be performed with w_u
equal to 2.5 mm, as specified in Model Code 2010.

The crack mouth opening displacement values w_s and w_u must now be defined
in order to determine the tensile stress values $\sigma_s$ and $\sigma_u$ to be used in design
calculations. For w_s, the limit values and verifications for crack mouth opening
displacement have been set forth at 2.4.4.

For w_u, the problem is more complex and delicate.

For issues of bending, the crack mouth opening displacement that corresponds
to the maximum bending moment will depend on the height of the section.
It is known that SFRC currently used in tunnel arch segments (which typically
have between 30 and 60 kg/m$^3$ of fibre in concrete with characteristic strength
of the order of 50 MPa) behaves well in terms of post-cracking tensile stress
for crack mouth opening displacement of up to approximately 3.5 mm.

Pending further experience, design calculations should be performed with w_u
equal to 2.5 mm, as specified in Model Code 2010.
Clarifications for step 3 – Suitability tests

This step consists in checking that the SFRC proposed has mechanical characteristics that are at least equal to those adopted for dimensioning, especially as regards behaviour under tensile stress (in a similar manner to what is conventionally carried out for compressive strength behaviour). To do so, suitability tests are performed.

The post-cracking tensile behaviour of SFRC depends on the preferential orientation of the fibres within the structure. This orientation is linked to the type of structure and the mode of use.

Suitability testing therefore involves executing a prototype arch segment in representative conditions of fabrication and curing, and then taking prism specimens from this element to be subjected to tensile stress testing by bending in directions that are representative of the tensile stress expected in the arch segment. These tests will make it possible to check that the behavioural law of which they form the basis is compatible with the design law used for the project. These are conducted pursuant to standard EN 14651 (cf. 3.3.2.2.).

Since both mean and characteristic curves must be determined, testing of 6 samples as well as moulded test specimens is necessary.

By comparing them with prisms made during fabrication of the control element, the specimen prisms also make it possible to determine the K factor pursuant to Model Code 2010 § 5.6.7. This factor may be used to determine the target values to be attained during control tests on poured test specimens (see stage 4).

Notes:

1. The K factor is largely dependent on the pouring mode used for the arch segments. If this is altered, even if the SFRC formula remains unchanged, the suitability test must be repeated.

2. With the benefit of increased experience in the manufacture of SFRC arch segments and the development of digital tools that make it possible to predict the effects of how the material is deployed on the way the fibres are distributed, it is likely that suitability testing will be simpler and less extensive in the future. For the time being however, this testing remains a crucial stage in ensuring the overall safety of the elements where this depends on the ability of the SFRC to bear post-cracking tensile stress.

3. In theory, the post-cracking tensile behavioural law could be determined by direct tensile stress testing on prism specimens taken from the element, rather than on the basis of the inverse analysis of tensile bending tests. However, the difficulties involved in this type of test and the dispersion that is generally observed mean this alternative is unfavourable.

4. With regard to “design assisted by testing” as detailed in Model Code 2010 § 7.12, suitability tests using prism specimens could be replaced by full-scale tests performed on prototype arch segments that are representative of the design stress intensity of the project. The margins to be adopted in this approach are set forth in Model Code 2010 § 7.12. In the light of the required resources and the additional time required, typically several weeks, when arch segment production commences, this approach should only be considered for major projects.

Clarifications for step 4 - In-factory control tests

The in-factory control tests that form part of the factory’s quality plan may be highly simplified. Indeed, for a given arch segment geometry and installation procedure, the mechanical performance of SFRC infrastructures are fully dependent on the following:
the compactness of the matrix (the concrete), characterised by the compressive strength of the SFRC,
- the percentage, shape, dimensions and mechanical characteristics of the reinforcements (the fibres).

Consequently, the control process should consist, during the project, of verifying that the following:
- the compressive strength of the SFRC
- its characteristics when fresh
- the nature and quantity of fibres and the mixing procedure
- the protocol for using the SFRC in forms
- and the curing and maturing process are identical to those defined following the suitability tests.

To do so involves all relevant data being recorded during the suitability tests.

3.3 - Performance criteria for SFRC specifications

3.3.1 - Overview

Steel fibre reinforced concrete performance increases in line with a number of factors:
- the performance of the concrete matrix
- the dose of fibres (up to some limit)
- the intrinsic performance of the fibres in the matrix (geometry, l/D, anchoring method, etc.)
- the orientation of the fibres with respect to the potential cracking process

Steel fibres must comply with European Standard NF EN 14889-1.

It is particularly important to observe the following tolerances with regard to geometry:

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Symbol</th>
<th>Deviation of the value from the declared value</th>
<th>Deviation of the mean value from the declared value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length and extended length</td>
<td>L, Ld</td>
<td>± 10 %</td>
<td>± 5 % ± 1,5 mm</td>
</tr>
<tr>
<td>&gt; 30 mm ≤ 30 mm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&lt; 30 mm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diameter (equivalent)</td>
<td>d</td>
<td>± 10 %</td>
<td>± 5 % ± 0,015 mm</td>
</tr>
<tr>
<td>&gt; 0,30 mm ≤ 0,30 mm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&lt; 0,30 mm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Length/diameter ratio</td>
<td>λ</td>
<td>± 15 %</td>
<td>± 7,5 %</td>
</tr>
</tbody>
</table>

Table 1 - Tolerances for fibre length and diameter as per EN 14889-1

Minimum proposed recommendation:
- Drawn steel wire:
  - tensile strength of steel wire: \( f_y > 800 \text{ MPa} \) minimum. (tensile strength of the wire must be consistent with that of the matrix, \( f_y \geq 1.5 \text{ GPa} \) for HPC)
  - dimensional tolerances as per Table 1
- a maximum network effect \((\text{m/m}^3)\) should be sought, ensuring that the selected mode of use includes checking the proper orientation of fibres with regard to mechanical behaviour
- optimising the anchor system (hooks at the end to ensure the fibre is anchored in the concrete matrix, or other systems)

Fibre conditioning must take account of the following:
- introduction of the fibres using an automatic dosing system
- arraying the fibres in the concrete to obtain perfectly uniform distribution
- complete elimination of the appearance of fibre balls for fibres with \( \text{I/D} >65 \) (detrimental during installation phase)

The use of bonded fibres or other systems (untangling, etc) are therefore recommended to fulfil the above requirements.

Surface aspect:
- For some types of structure, the use of galvanised fibres may avoid the risk of fibres at the surface corroding.

Galvanised steel fibres should be produced using hot-galvanised steel wire. The specifications for the zinc coating must comply with French standard A 91-131 and be of type B classification, for which the minimum zinc coating is 30 g/m².

The galvanised steel fibres must be protected by a gas inhibitor. This controls the zinc/cement reaction, helps prevent this phenomenon, and ensures both resistance of the galvanisation and the adherence of the fibres within the concrete matrix. The results of saline fog durability tests pursuant to standard ASTM B117 or NF X41-002 in an approved laboratory must be supplied in order to guarantee that no trace of corrosion has appeared after 1000 hours of storage immersed in a saline solution.

Any specification of stainless steel fibres must be supported by precise knowledge of the aggressive environment to which the concrete and fibres will be exposed. Special care should be taken when choosing the grade of stainless steel and in taking into account the specific physical and mechanical properties of the fibres.

3.3.2 - Mechanical characterisation of SFRC

3.3.2.1 - Purpose

When dimensioning a steel fibre concrete arch segment, a reference test method should be used to define performance values. In addition to mechanical performance, other properties of the SFRC may be specified.

These properties could include the following:
- Properties and performance of the base matrix
- cement dose and quality
3.3.2.3 - Summary table of characterisation, suitability and control tests

Tests to be performed have been grouped together and summarised in Table 1. It should be noted that these tests relate to the materials making up the concrete, fresh concrete, and hardened concrete.

<table>
<thead>
<tr>
<th>Tests to be performed</th>
<th>Characterisation</th>
<th>Suitability</th>
<th>Control</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Materials</strong></td>
<td>Y</td>
<td>Y</td>
<td>N</td>
</tr>
<tr>
<td>Aggregates</td>
<td></td>
<td>Y</td>
<td></td>
</tr>
<tr>
<td>Additives</td>
<td></td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Cement</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Fibres</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td><strong>Fresh concrete</strong></td>
<td></td>
<td>Y</td>
<td></td>
</tr>
<tr>
<td>Fibre dose</td>
<td>Y</td>
<td>Y</td>
<td></td>
</tr>
<tr>
<td>Water dose</td>
<td>N</td>
<td>N</td>
<td>N</td>
</tr>
<tr>
<td>Workability (*)</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Density</td>
<td>Y</td>
<td>Y</td>
<td></td>
</tr>
<tr>
<td><strong>Hardened concrete</strong></td>
<td></td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Compressive strength</td>
<td></td>
<td>Y</td>
<td></td>
</tr>
<tr>
<td>EN 14651 bending test</td>
<td></td>
<td>Y</td>
<td></td>
</tr>
</tbody>
</table>

Y = Yes, N = No
(*) to be adjusted depending on the consistency of the SFRC used.

Table 2 - Characterisation, suitability and control tests to be performed on SFRC.

4 - Control and installation

4.1 - Acceptance and storage of fibres

4.1.1 - Acceptance

Acceptance of fibres should include checking that they correspond to the type and requirements specified on order.

The arch segment manufacturer’s control plan must detail acceptance operations, including the following (for fibres whose origin is known to the user, from a supplier offering suitable internal quality monitoring guarantees):
• an inspection prior to acceptance of the delivery slip and/or label on the packaging, indicating compliance with the order (the purpose is to ensure compliance of the delivery to the order and the proper origins thereof); this should be carried out for every delivery,
• simplified visual and dimensional control of a sample from the delivery in order to confirm the type of fibre (form, length and diameter or shape of the cross-section and any anti-corrosion treatment applied),
• for conditioning including pre-dosing of fibre, sample control of the conformity of this pre-dosing.
In the event of fibres whose conformity has not been evaluated or determined prior to delivery, the arch segment manufacturer must ensure a control plan is set up. This may be subcontracted to a competent third party, and must be designed to demonstrate conformity to the required technical specifications.

These procedures should be based on standard EN 14889-1, concrete. Steel fibres. Definitions, specifications and conformity.

4.1.2 - Storage of fibres
Fibres are delivered in sacks or “big bags”, so storage must ensure the following:
• conservation pursuant to the supplier’s specifications (in particular for fibres that are not protected against corrosion and for fibres that have had preparatory treatment, e.g. fibres assembled in panels),
• use in the same order that the batches were accepted, in order to ensure proper traceability,
• if packaging is specific and specially adapted to the dosage unit for a given batch, it is imperative that the storage conditions preserve the packaging integrity. Any item with damaged or suspect packaging must be isolated and not declared compliant until fresh packaging and inspection has been carried out.

4.2 - Concrete mixing plant
4.2.1 - Component dosing
The concrete mixing plant and its equipment, in particular for dosing, must comply with the requirements specified in one of the documents quoted at the head of this chapter, taking into account the reference priorities specified in the Particular Technical Specifications (CCTP).

These include the provisions concerning:
- the storage and dosing of concrete components (the tolerances for which are set forth in General Technical Specifications (CCTG) Fascicle 65),
- the operation of the concrete plant (automation and controls),
- the materials control programme (EN 206-1: Table 23 EN 13369: D1).

The document PR NF EN 14650 (October 2005) “Precast concrete products - General rules for factory production control of metallic fibered concrete” presents the specific procedures for fibres, in line with the provisions of EN 206-1 and EN 13369 (it refers to these for components other than fibres).

4.2.2 - Fibre dosing
Preferably, fibres should be dosed using specific equipment, connected by means of PLCs and controls to the concrete plant’s command-control unit.

This specific equipment should operate by dosing the fibres by weight.

All suitable measures should be taken to carry out monitoring of the stock of fibre available in the doser, ensuring that reloading takes place outside automated dosing cycles and does not interrupt these cycles, in order to ensure batch integrity.

By analogy with the usual provisions covering concrete component dosing, the following points should be adopted and specified in the control plan:
• ensuring dosing accuracy such that the measured results of the quantity of fibres by weight fall within the following bounds:
  - a maximum of 20% of results beneath the nominal value, with a limit value of -5%
  - at least 80% greater or equal to the nominal value
• controlling the equipment’s dosing accuracy at regular intervals: during installation, reinstallation and after any major repairs, and in any event at least once a year.

If in doubt:
• carry out a visual inspection once a day to check the proper operation of each stage of dosing and transfer to the mixer.

In the case of a concrete plant operating regularly with several models of fibre, the arch segment manufacturer must take measures regarding changeover from one model to another without any risk of error or pollution between models (with the use of different bowls or an emptying and cleaning process when the model is changed, checking the components used for transfer to the mixer).

---

1 - Chapter 3.3 of standard NF EN 14650 recommends a dosage tolerance of +/-5% of the required quantity for all quantities of concrete greater or equal to 1 m³.

Section 6.6 of the document “Quality Assurance Guidelines for the use of Steel Fibre Reinforced Concrete (SFRC)” [6] recommends a tolerance of 3% for fibre doses and refers to EN 206-1 for other components. However, a dosage minimum should also be guaranteed; this is the reason for specification of the dispersion positioning.

TUNNELS ET ESPACE SOUTERRAIN - n°238 - Juillet/Août 2013 321
4.2.3 - Introduction and mixing of fibres

The choice of mixer and the procedures for introducing fibres will determine the uniformity of the mix and proper distribution of the fibres. A part of water quantity is mobilized by the fibres (steel or polypropylene possibly) that significantly influences workability.

The mixing equipment must be able to provide high shear for fresh concrete. Particular attention must be paid to horizontal-shaft mixers with regard to the quality of the fibre mixed obtained.

The shape of the blades must not result in any buildup of fibres.

The mixer must be large and powerful enough to ensure nominal batches are produced properly. A minimum size for any partial batches (which should be no more than 50% of the nominal volume) should be established. These operating capabilities should be demonstrated during the concrete suitability test.

The quality plan must specify the conditions in which fibres are introduced and mixed:

- the point in the general concrete component introduction cycle
- the speed or duration of fibre introduction
- the minimum mixing duration after the end of fibre introduction (whether wet or dry process)
- the maximum mixing time (where applicable, and in the event of a proven risk of segregation)

The effectiveness of the operating cycle should be demonstrated during the concrete suitability test.

Note: in recent production experience, in the case of firm concrete, fibres are introduced with the aggregates (the fibre feed system pours the fibres onto the weighing belt or into the aggregate hopper feeder). This recommendation also features in section 6.7 of the Quality Assurance Guidelines for the use of Steel Fibre Reinforced Concrete (SFRC) [6].

For more plastic or fluid concretes and/or high doses, the fibres may be introduced once the mix has been made uniform (with water and additives).

4.2.4 - Installation of concrete

The choice of the modes of concrete transport and installation must take account of the fibres. Consequently, procedures minimising the risk of segregation and absence of coating and minimising the path of the fibre reinforced concrete in the formwork are to be preferred; procedures between the mixer and the arch segment formwork should not be stacked.

Any interruption in the supply of fresh material for a single element must be avoided, as must any supply from a number of different feeds that have not been re-treated. Any use of internal or external vibrating rods must be the subject of specific study given the major incidence of this procedure on the distribution and orientation of fibres.

For suitability testing, the concrete to be assessed must have been installed in the mould and followed the path specified for production to be evaluated.

Blagis tunnel - SFRC casting.

Blagis tunnel - 3 point-failure test on a beam sawed out of a test segment.

4.2.5 - Equipment monitoring and control

In addition to the procedures for controlling the dosing equipment, the mixer and where applicable, the concrete transfer equipment (overhead conveyors, belts or skips) must be monitored especially closely taking into account the potential impact of the use of fibres on wear of shielding and blades and disruption due to fibre buildup in joints of any moving parts (doors, door seals, etc.).

The frequency of cleaning operations must also be adjusted appropriately (an important detail).

4.2.6 - Concrete suitability tests

Pursuant to the table shown in § 3.3.2.3, in addition to procedures designed to evaluate traditional concrete (see standard EN 206-1 and fascicle 65), concrete suitability testing should include additional procedures relating to the incorporation of fibres and the execution of a prototype allowing the quantitative value of the K factor regarding fibre orientation (§3.2 stage 3 above) to be taken into account.

The additional procedures relating to fibres include the following:

- measuring concrete consistency
- measuring the fibre content of fresh concrete
- measuring the fibre content of hardened concrete
- evaluating the spatial distribution of fibres
- execution of the test piece pursuant to the tests specified in chapter 3 "Dimensioning of SFRC arch segments"

Measuring the fibre content of fresh and hardened concrete is covered by standard NF EN 14721+A1 "Precast concrete products. Test method for metallic..."
fibre concrete. Measuring the fibre content in fresh and hardened concrete"  
This reference should be quoted as per the tests specified in chapter 3 “Dimensioning of SFRC arch segments”; NF EN 14651+A1 “Precast concrete products. Test method for metallic fibre concrete. Measuring the flexural tensile strength”

The suitability test programme must specify the number of specific tests relating to fibres, as appropriate for the objectives and the number of batch types and/or planned finished product types. All SFRC manufacturing and installation processes, including curing and maturing, should be the subject of an execution procedure validated by the project owner at the end of the suitability test, certifying that the properties specified and/or required to substantiate the mechanical properties of the elements have been obtained. This stage constitutes a critical point.

4.3 - Production controls

4.3.1 - Control plan

The control plan must supply details of all the aspects specified above:

- acceptance of fibres
- control of the equipment

It should be supplemented with measures governing control of the procedure, including the following:

- concrete mixing
  - visual inspection
  - evaluation of a proper mix
  - once a day (plus continuous surveillance at the pouring station to ensure there are no fibre balls, etc)
- consistency of concrete
  - cf suitability (same test)
  - once a day
- installation of concrete
  - visual inspection
  - evaluation of proper compacting
  - once a day
- strength
  - compression test specimen
  - checking strength after 28 days (other periods and/or intermediate periods may be specified)
  - adopt frequencies and adjustments thereto as shown in Table 13 of EN 206-1 for concrete for which production control is certified (once a week minimum)
- structural strength
  - fibre-reinforced concrete test specimen (according to the main dimension of the segment)

- fibre content of fresh concrete
  - adopt frequencies and adjustments thereto as shown in Table 13 of EN 206-1 for concrete for which production control is certified (once a week minimum) – the specimen used should correspond to a single sample

4.3.2 - Conformity criteria

In addition to the customary conditions for acceptance of design, suitability and control tests for compressive strength, consistency and density of concrete, the following criteria should be applied to assess conformity of tests with regard to the tensile strength of SFRC:

Characterisation (design test): The characteristic curve (i.e. one that will be exceeded in 95% of cases) derived from characterisation tests (on moulded prisms) to which the K factor has been applied must be above the characteristic behaviour curve used for the project, to which an affinity value of 1.05 has been applied, at all points.

Suitability: The characteristic curve (i.e. one that will be exceeded in 95% of cases) derived from characterisation tests (on moulded prisms) to which the K factor has been applied must be above the characteristic behaviour curve used for the project.

NOTE: Characterisation and suitability stages may be combined, with cut and moulded test specimens carried out at the same time in order to determine the K factor. However, separate steps may be indispensable if it is necessary to detail specific properties that do not depend directly on the fibre dose or its effect (resistance to the environment, for instance, chemical attacks relating to the soil, compression strength when fresh, etc.).

With regard to “design assisted by testing” as detailed in Model Code 2010 § 7.12, suitability tests using prism specimens could be replaced by full-scale experiments performed on prototype arch segments that are representative of the design stress intensity for the project. The margins to be adopted in this approach are set forth in Model Code 2010 § 7.12. In the light of the resources required, this approach should be envisaged only for major projects, new products or when optimisation of a given solution is being sought.

Control: The mean curve resulting from the moulded prism tests to which a K factor has been applied must be higher than the behaviour curve used for the product. In addition, each individual curve resulting from the moulded prism tests to which a K factor has been applied must be higher at every point than the beha-
viour curve used for the project to which an affinity value of 0.95 has been assigned.
The K factor (which uses both moulded test specimens and prism samples taken from the representative element) must be determined on the basis of enough actual samples to enable the statistical effect within the arch segment to be taken into account (a minimum of six prisms in areas in which the tensile stress and bending stress behaviour of elements is critical).

5 - References

[6] Quality assurance guidelines for the use of Steel Fibres Reinforced Concrete – project funded by the European Community under the Industrial and Materials Technologies Programme (Brite – EuRam III)