Dramix® Steel fibres in residential foundation slabs in Czech Republic: design approach

S Pouillon 1

1 N.V. Bekaert S.A., Bekaertstraat 2, B-8550 Zwevegem, Belgium

E-mail: Steven.pouillon@bekaert.com

Abstract. Steel fibres are used more and more in structural concrete elements, like residential foundation slabs. The development of high performant steel fibres (e.g. Dramix® 4D and 5D), the evolution in standardization and the demand coming from construction companies and investors are pushing this trend. Engineers are using the yield line method to design steel fibre concrete structures in an easy and economical way, especially if the structure has a regular load layout mainly containing wall loads and point loads. The load configuration, soil characteristics and material characteristics determine the final solution.

1. Introduction
Dramix® steel fibres become more and more the preferred concrete reinforcement material in a wide range of residential and industrial structural applications in Czech Republic. Bekaert expanded his steel fibre product range with Dramix® 4D and 5D fibres, especially developed to reinforce structural concrete elements. Already for more than 20 years, steel fibres are used to reinforce most of the Czech concrete industrial floors on grade. But very recently, engineers, contractors and investors are often opting for this material to also reinforce their concrete structural elements: residential and industrial foundation slabs, industrial slabs on piles and crack width controlled slabs.

2. From well-known steel fibre application to structural steel fibre applications
Various developments have boosted the use of steel fibre concrete in structural applications. As a result of 3 years fundamental research, Bekaert launched a range of high performing steel fibres (4D and 5D). These steel fibres make it possible to design structural applications with steel fibre reinforced concrete (SFRC), economically and technically safe. Secondly, various standardization committees have created a technical and juridical framework for engineers to design structural steel fibre concrete structures in a safe and legal way. And last but not least, the practical and economic advantages of steel fibre reinforcement – as they are experienced in floors and other standard applications – remain valid and very appreciated by all stakeholders in the new applications.

2.1. Outperforming new Dramix® steel fibres
Steel fibres increase the ductility of the concrete by bridging cracks and transferring tensile stresses over these cracked zones. Many different parameters influence the performance of the steel fibre concrete: the tensile strength of the steel wire, type of anchorage, ductility of the wire, the dosage of steel fibres and of course the concrete class and quality. Bekaert has grouped its Dramix® products into 3 families: 3D, 4D and 5D (More information about the different characteristics can be found in
[1] and [2]). The steel fibres belonging to the 3D family are the standard ones (e.g. 3D 80/60BG, 3D 65/60BG and 3D 45/50BL) and are mainly used to reinforce industrial floors on grade (jointed floors, jointless floors), tunnels and precast elements. The newly developed Dramix® steel fibres, the families 4D and 5D, are especially designed to reinforce structural concrete elements. The main difference between the 4D/5D family and the 3D family is the significantly increased performance in serviceability limit state (4D) and ultimate limit state (5D). The combination of type of anchorage (more end hooks), stronger wires (up to 2200 MPa) and more ductile wires (up to 7% of elongation) are key in this increased performance.

![5D 4D 3D Dramix Fibres](image)

**Figure 1.** The logos and shape of the 3 Dramix® fibre families

### 2.2. Evolution in standardization [3]

Steel fibre reinforced concrete has been the subject of much research over the last 40 years. In line with the knowledge built up, guidelines and standards have been developed gradually.

In the early 1980’s, the SFRC test standards – JSCE-SF4 [4] and ASTM C1018 [5] – were in place and widely used. These standards – still topical – describe how SFRC can be tested in order to determine the performance of this material under bending conditions. During such a test, a SFRC prism is tested under bending, until a crack is formed with a specific crack opening. The performance is expressed as “flexural toughness” and represents the energy dissipated during the test. An equivalent post-crack flexural stress is derived from the flexural toughness. Many European countries developed their own national SFRC test standards, based upon the two pioneer standards. Actually, the EN14651 [6] test standard is mostly used in Europe, but also widely accepted outside Europe. In some countries, like Czech Republic, local standards (ČSN P 73 2452 [7]) are as well valid. The performance of the SFRC in EN14651 is expressed directly in flexural post crack stresses at specific crack mouth openings. The term crack mouth opening – and not crack opening - is used because a notch is made at the center bottom of the beam. This, in order to force the beam to crack in the middle. In 1995, the first design guideline was published: “Dramix Design Guideline”. This document contained the first basic design rules in order to design concrete structures with steel fibres. This document was a result of a cooperation between N.V. Bekaert S.A., the Belgian universities KULeuven and UGent and the Belgian building research institute WTCB. This design guideline served as the basis for some national design recommendations. A deeper investigation was done by a group of international universities brought together by RILEM (RILEM TC162-TDF [8]). This cooperation resulted in a test and a design method. A structured approach – material characterization, performance indicators, constitutive law – was worked out and fully backed up by theory and experiments. Also overseas, in 2008, ACI 318 [9] incorporated steel fibres as a structural element to take up shear forces in concrete elements.

Different countries (e.g. Germany, Sweden and Italy) also published in the meantime national design guidelines and/or codes, often as an add-on of EN1992-1-1 [10]. A new milestone was reached in 2014 when the final version of the Model Code 2010 [11] was published. Steel fibres are fully incorporated in this state-of-the-art concrete design guideline. This document was also the trigger for the launch of TC 250/SC2/WG1/TG2(CEN); this task group works on the integration of steel fibres
into the future EN1992-1-1. The ModelCode2010 and the DAfSTb-guideline [12] serve as the source code for this work.

2.3. Practical and economic advantages of steel fibre concrete in structural applications

The practical and economic advantages are mainly a consequence of the low reinforcement complexity that can be obtained when using steel fibres and the fact that the ‘reinforcement’ is pre-mixed in the concrete.

The first is very clear when a fibre only solution is proposed. In that case, there is no need for complex drawings and for long site preparations, which is reducing the cost in each stage of the project (design and execution). Furthermore, errors in the drawings and errors during the reinforcement placing are almost eliminated. When a fibre only solution is technically not possible, engineers will always try to combine standard meshes – and avoid (thick) diameter bars – combined with steel fibres. The latter optimizes the crack control (less total reinforcement steel needed compared with a traditional solution) and increases the bending moment capacity significantly. Additionally, due to the strong shear and punching resistance of steel fibre concrete, shear and punching reinforcement can often be omitted.

The second is clearly facilitating the logistics. Instead of transporting to and storing the reinforcement on site, the steel fibres are delivered together with the truck mixer. Direct pouring from the truck mixer or using a pump is still possible with steel fibres.

3. Residential foundation slabs

Different type of residential foundation slabs exist: small (e.g. 50m²) to big (e.g. 1000m² or more), regularly versus irregularly shaped, lightly loaded versus highly loaded, on pile foundations or at grade… In particular – but not exclusively – the lightly to medium loaded residential foundation slabs on grade are very suitable to reinforce with (only) steel fibres. The advantages are evident:

- Fast execution (no mesh/rebar installation, little detailing work)
- Easy logistics (no storage of meshes on small construction sites)
- Easy design
- Economic

In general 2 load types are acting on a regular residential foundation slab: wall loads ("line load") and column loads ("point loads"). These loads can be positioned in the middle of the slab or at the edge/ corner of the slab. Other important input parameters for a design are the soil characteristics (bedding modulus and bearing capacity - which can be assumed homogeneous over the small surface) and the characteristics (long-term E-modulus, thickness and maximum long-term compressible strength) of the insulation under the complete slab or only at the perimeter (if applicable).

**Figure 3.** Example of the preparation and construction of a residential foundation slab (left) and a typical load configuration on a such slab (right)

### 4. Design of a foundation slab on grade

A typical SFRC design follows below mentioned flow:

- **Resistance of the material**
- **Material characterization and behaviour** what is the performance of the fibre concrete
- **Occurring material stresses**
- **Model and calculation:** occurring bending moments, shear and punching...

**Figure 4.** Design flow of SFRC structures

#### 4.1. Material characterization and behavior

SFRC can be characterized using different methods or following different standards. Common tests standards in Europe are the EN14651 [6] (3-point bending test with notch) and the DAfStb [12] (4-point bending test). Also the Czech standard ČSN P 73 2452 [7] is suitable to follow when determining the performance of SFRC. It is although important that the material characterization and the model used to describe the behavior (constitutive law) are in correspondence with each other. The constitutive law and rules to derive the stress-strain curve from residual flexural strength values are inseparably linked with the type of test used to develop them. So e.g. is a 4-point bending test the basis
for a design according the DAfStb Steel Fibre Concrete Guideline and the 3-point bending test EN 14651 the basis for a design according the ModelCode2010 [11] or Rilem TC162-TDF [8].

Important considerations in the material characterization of SFRC are the number of samples and the way how the characteristic residual strength values are determined. 6 beams is generally regarded as the absolute minimum, taking the natural spread in these type of beam tests into account; it is common to obtain a coefficient of variance of 25% (Reference can be made to SS 812310 [13]). In order to calculate the characteristic value, reference can be made to the international standard ISO 12491 [14]. The estimation of the lower mean value (when the standard deviation of the population is unknown) is given by:

$$
\bar{x} - t_p \cdot s / \sqrt{n}
$$

where

- $s$ is the sample standard deviation;
- $t_p$ is the fractile of the t-distribution for $v = (n - 1)$ degrees of freedom;
- $p$ is the probability (close to 1) given in table 3 or ISO 12491.

Other methods are described in DAfStb Steel Fibre Concrete Guideline, Annex O.6 for example. Here a log-normal distribution is assumed.

The constitutive law expresses the stress-strain relationship of the SFRC in the tension zone. The characteristic residual flexural stress vs. crack width results of the beam tests are converted in stress – strain values. Together with a material safety factor (1,5 is common for SFRC in structural applications, like concrete in compression), the derived material behaviour can directly be used in the design of the bending moment capacity of a section, shear/punching capacity and in the calculation of crack openings.

The main parameters in the determination of the stress-strain curve are the conversion factor (bending vs. axial tension), the size factor, the orientation factor and the material safety factor.

### 4.1.1. The conversion factor.

The characteristic residual flexural strength values need to be converted in uniaxial tensile strength values. Typical values are presented in the table pod.

| Strain           | Rilem TC162-TDF | DAfStb SFRC Guideline | ModelCode 2010                       |
|------------------|-----------------|-----------------------|--------------------------------------|
| At small strain  | $\sigma_2 = 0.45 f_{R1,k}$ | $\sigma_2 = 0.40 f_{c,t,L1}$ | $\sigma_2 = 0.45 f_{R1,k}$          |
| At ultimate strain | $\sigma_3 = 0.37 f_{R3,k}$ | $\sigma_3 = 0.25 - 0.44 f_{c,t,L2}$ | $\sigma_3 = \sigma_2 - \frac{w_u}{C_{MOD_3}} (\sigma_2 - 0.5 f_{R3,k} + 0.2 f_{R1,k})$ |

$\sigma_1$ is the characteristic tensile strength of unreinforced concrete, $\sigma_2$ is the characteristic tensile strength of SFRC at small strain (typically between 0 %o and 3.5 %o), $\sigma_3$ is the characteristic tensile strength of SFRC (typically around 20%o - 25%o. For the definition of the other parameters, reference is made to the selected standards/guidelines.

### 4.1.2. The size factor.

In many applications, a much bigger cracked section is present than tested in the standard beams. To account for the much smaller standard deviation expected in the actual structure, a size factor is introduced. For bending situations in slabs, following formula can be used in accordance with the DAfStb:

$$
\kappa_G^f = 1.0 + A_{ct}^f \cdot 0.5 \leq 1.7
$$

with $A_{ct}^f$ area of tension zones in the concrete of the cracked cross-sections or plastic hinges in m².
4.1.3. *The orientation factor.* In many applications, a random fibre orientation can be expected (like in general slabs). For some applications (due to their shape, way of casting, concrete consistency…), a significant fibre alignment can be expected (advantageously or disadvantageously). To account for this an orientation factor should be used.

4.1.4. *The material safety factor.* A typical material safety factor for SFRC in tension is 1.5 (DAfStb: 1.25/0.85, ModelCode2010: 1.5).

4.2. **Design of the structure (in U.L.S.)**

The design of a residential foundation slab can be economically performed by using the yield-line theory. Yield-line theory requires to determine the relevant yield-line mechanism together with the corresponding load case.

For residential foundation slabs two major mechanisms are governing:
- folded plate pattern
- fan pattern

While the folded plate is relevant for both line loads (walls) and point loads positioned in a line (row of columns), the fan pattern only applies to point loads.

Shear and punching need to be verified in addition whereby both design situation are usually not governing for steel fibres concrete without additional reinforcement.

This rather simple approach is valid under specific conditions:
- no ground water pressure
- a continuous support with suitable ground
- no shear walls, frames or cores present

4.2.1. **Line load.** A line load (or a line of point loads) at the inner side of the slab will typically create 2 negative yield lines (m_\text{Ed}') and 1 positive yield line (m_\text{Ed}), as shown in the picture pod:

![Diagram](image.png)

**Figure 5.** The yield line system for a line load (inner side of the slab)

The situation in case of a line load at the edge is slightly different and shown in Figure 6.
Figure 6. The yield line system for a line load (edge side of the slab)

The principle is that the load $V_{Ed}$ must be in balance with the soil pressure distribution (described by $\sigma_{gd}$ and $\sigma_{gd'}$) and (excluding the slab death weight), not exceeding the soil bearing capacity $\sigma_{gd,max}$ (equilibrium of vertical forces). The position of the negative yield lines depends on the elastic length $l_{el}$ for the minimum distance (between 0.5$l_{el}$ and $l_{el}$) and the distance to the edge and/or other loads for the maximum distance (to avoid intersection with other yield lines). The respective occurring plastic bending moment ($m'_{Ed} + m_{Ed}$) in the cracked sections (yield lines) can easily be found by the principle of moment equilibrium:

For an inner line load:

$$m_{Ed} + m'_{Ed} = \sigma_{gd'} \cdot \left( \frac{x_i}{2} + \frac{b_w}{2} \right) \cdot x_i + (\sigma_{gd} - \sigma_{gd'}) \cdot \left( \frac{x_i}{3} + \frac{b_w}{2} \right) \cdot x_i + \sigma_{gd} \cdot \frac{b_w^2}{8} - V_{Ed} \cdot \frac{b_w}{8}$$

(3)

For an edge line load:

$$m'_{Ed} = V_{Ed} \cdot \left( x_e + \frac{b_w}{2} \right) + \sigma_{gd} \left( \frac{b_w^2}{2} + p_w \cdot b_w + p_w \cdot x_e + \frac{b_w^2}{3} + b_w \cdot x_e + \frac{x_e^2}{3} \right)$$

$$-\sigma_{gd} \cdot \frac{x_e^2}{6}$$

(4)

The shear forces can be calculated as follows:

$$V_{Ed} = \left[ \left( \frac{\sigma_{gd} - \sigma_{gd'}}{2} \right) \cdot \frac{\left( x_i - d \right)}{x_i} + \sigma_{gd} \right] \cdot (x_i - d)$$

(5)

with $d =$ the slab thickness for SFRC, $d = d_{eff}$ for combined reinforcement)

4.2.2. Point load. The governing yield line system for point loads is the fan pattern. Reference is made to Losberg [15]. The circumferential crack will occur at the top (negative yield line) and the diagonal cracks will occur at the bottom (positive yield lines).

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1 Elastic length: $l_{el} = \sqrt{\frac{E_c h^3}{12(1-v^2)k}}$, with $E_c$ the Youngs Modulus of concrete, $h$ the slab thickness, $v$ the Poisson ratio, $k$ the bedding modulus.
4.3. Design of the structure (in S.L.S.)
Due to the nature of concrete, crack free structures cannot be guaranteed and are normally not required either. Serviceability of a foundation slab can thus be achieved in different ways, depending on the actual requirements, the actual way of constructing and the intended use:
- avoiding of cracks (e.g. applying construction methods to avoid cracks)
- dealing with cracks (e.g. procedure defined prior to construction)
- limiting of cracks (e.g. controlling cracks using combined reinforcement)

5. Example
This paragraph presents an example of a residential foundation slab in Czech Republic. The load analysis (reaction forces from the wall loads and column loads) is shown in Figure 8.

Figure 7. The yield line system for a point load (inner side of the slab). Reference is made to Losberg for all equations.
Figure 8. A cross section of the house (left) and the reaction forces from the wall loads and column loads (in U.L.S.) (right)

5.1. Input parameters

| Table 2. Input parameters |
|---------------------------|
| **Soil**                  |
| Bedding modulus k         |
| Maximum bearing capacity  |
| $\sigma_{gd}$ 200 kN/m²  |
| **Inner wall**            |
| Line load $V_{Ed}$ 132.4 kN/m |
| Wall width $b_w$ 175 mm   |
| Closest other load s 1925 mm |
| **Edge wall**             |
| Line load $V_{Ed}$ 101.1 kN/m |
| Wall width $b_w$ 175 mm   |
| Closest other load s 3875 mm |
| **Edge column**           |
| Point load $V_{Ed}$ 208.4 kN |
| Column dimension $a \cdot b$ 175 mm · 1000mm |
| Closest other load s 3000 mm |

5.2. U.L.S. design: bending moments

As solution, following slab characteristics were determined: 240mm, C30/37 + 30 kg/m³ 5D 65/60BG.

| Table 3. Results |
|------------------|
| Bending moment capacity |
| m_{Ed} 28.4 kNm/m |
| m'_{Ed} 28.4 kNm/m |
| m_{Ed} + m'_{Ed} 56.8 kNm/m |
| Occurring bending moments |
| Inner wall m_{Ed}+m'_{Ed} 15.1 kNm/m |
| Edge wall m'_{Ed} 10.5 kNm/m |
| Edge column m_{Ed}+m'_{Ed} 55.4 kNm/m |
6. Conclusion
Dramix® steel fibres become more and more the preferred concrete reinforcement material in a wide range of structural applications in Czech Republic. Well established standards are guiding engineers in their designs of structural concrete elements with steel fibers. Contractors and investors are experiencing each day the practical and economic advantages of the newly developed Dramix® steel fiber families by Bekaert. Residential foundation slabs, taken as a design example in this article, are highly suitable to be reinforced with the new Dramix® fibre families 4D and 5D; from technical and economic point of view.

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