FIBRE REINFORCED CONCRETE IN STRUCTURAL APPLICATIONS

POUILLON Steven [1]

Abstract

Structural steel fibre reinforced concrete (SFRC) applications differ mainly from well-known fibre applications like industrial floors by the more constructive aspect of these. Foundation slabs are an example of such a structural fibre reinforced concrete application, in which steel fibres are the main or the complementary reinforcement to take up bending moments and the shear stresses. In combination with conventional reinforcement, steel fibres are also very effective to control the crack width. The steel fibre contribution can be calculated following different codes and guidelines, like the DAfSTb-richtlinie [1], which is a guideline at code level in Germany (The DAfSTb-richtlinie adds the required rules for SFRC to DIN EN 1992-1-1/NA [2], which is the German national annex of the Eurocode 2 – EN 1992-1-1) The use of steel fibres leads to a significant reduction of traditional reinforcement and an optimization of the building process. The advantages of this construction method and the basis of design are explained in detail with reference to some European example projects, like the extension of the Carl Zeiss AG factory in Oberkochen (Germany) [3] and the Crop's Clad Rack construction (Freezer type) in Ooigem (Belgium).

Keywords: Steel Fibre Concrete, Structural Application, Standards, DIN EN1992-1-1

1. Introduction

Steel fibres are used these days as main and complementary concrete reinforcement in an increasing number of applications. Well known and well established applications are for example industrial floors on grade, stabilizing temporary shotcrete linings in tunnels and precast sewer pipes. More recent developments can be seen in the domain of concrete foundations, liquid tight slabs and piled industrial floors.

These developments are steered and boosted by the numerous design guidelines, standards and codes published in the last years. Moreover, the CEN (European Committee for Standardization) is currently revising the structural Eurocodes, whereas the EN 1992-1-1 focuses on the design of concrete structures. Under impulse of the recently finalised ModelCode2010 and the already in place German DAfSTb-guideline as part of the DIN EN1992-1-1/NA, steel fibres will be – with high probability – included as structural reinforcement material in the upcoming version of Eurocode 2.

[1] POUILLON Steven, N.V. Bekaert S.A., Bekaertstraat 2 postal code 6050, B-8550 Zwevegem, Belgium, steven.pouillon@bekaert.com

This essay will describe the DAfStb-Richtlinie (DIN edition), which is since March 2011 an addition to the approved German national annex to EN 1992-1-1. This standard contains the design rules to design SFRC structures. The approach of this standard will be demonstrated throughout this essay.

2. Trend: quality, certification, standardization

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 and ASTM C1018 – 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 test standard is mostly used in Europe, but also widely accepted outside Europe. The performance of the SFRC 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, 2003). 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 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.

A new milestone was reached in 2014 when the final version of the Model Code 2010 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 serve as the source code for this work.

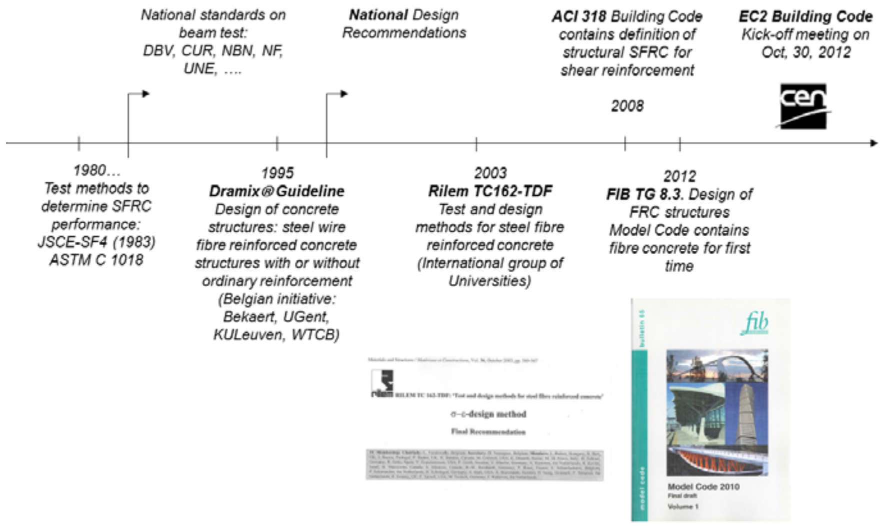

Fig. 1: Evolution of SFRC test and design standards from 1980 to present

3. DAfStb-Richtlinie Steel fibre concrete

In this chapter, the DAfStb-Richtlinie Steel fibre concrete is presented. This document provides the required rules for design, quality control and execution of steel fibre concrete structures with or without conventional reinforcement. In March 2011, the DAfStb-Richtlinie (Version 2010) was nationally approved in Germany and its states. Meanwhile, the DAfStb-Richtlinie (Version 2012) has been notified to the European Commission and can be used as an addition to the relevant European standards for concrete DIN EN 206-1, concrete structures DIN EN 1992-1-1/NA and execution DIN EN 13670 in conjunction with their national annexes for Germany. It has a full legislative nature and contains the necessary changes and additions to all relevant main standards in order to fully incorporate steel fibre concrete. The DAfStb-Richtlinie consists of three parts:

- Part 1: Design and construction
- Part 2: Specification, performance, production and conformity
- Part 3: Execution

The scope of the DAfStb-Richtlinie covers the design and construction of SFRC structures with or without conventional reinforcement and up to a compressive strength class of C50/60. Steel fibres with a positive mechanical anchorage – to avoid bond creep – and according to EN 14889-1, system „1“ for structural uses, are mandatory. No other fibres but steel fibres can be used. Self compacting concrete, shotcrete and light weight concrete are not included in the scope. The DAfStb-Richtlinie focuses on structural applications and has a little additional restriction for the use of combined reinforcement if compared to conventional reinforced concrete.

It is important that static systems with a post crack load bigger than the first crack load are

- hyperstatic systems (redistribution of internal forces and moments is possible),
- systems designed with combined reinforcement and/or
- systems on which an external compression force is applied.

3.1 Material characterization

It is common practice to classify materials based on (some of) their characteristics, like it is done for concrete. Concrete is classified into compressive strength classes (e.g. C30/37). This classification is done based upon a strict test, executed under specific circumstances in a controlled environment and quality system.

SFRC is classified by the guideline into performance classes based on residual flexural strength, which is tested by means of a flexural beam test. This flexural beam test results in a load-displacement curve, from which the residual flexural strength at deflection points δ_{L1} = 0,5mm and δ_{L2} = 3,5mm can be derived. A minimum of 6 beams is needed to obtain the performance classes L1 and L2, which correspond to the respective characteristic values of the residual flexural strength at the respective deformations.

It is important to stress that this performance class classifies the material “steel fibre reinforced concrete” and not just the steel fibres. The concrete and the steel fibres work together, and are therefore inseparable and both mutually influence the performance. This is also reflected in the way the SFRC is specified. As an example:

C30/37 – L1,2/0,9 – XC1 – WO

where C30/37 indicates the compressive strength class, L1,2/0,9 indicates the SFRC performance class 1,2 for small deformations (SLS) and the SFRC performance class 0,9 for big deformations (ULS), XC1 indicates the exposure class and WO indicates the humidity class.

The performance classes L1 and L2 are now the input to determine the stress-strain characteristic of the SFRC cross-section (§3.2), which is subsequently the input to calculate the section and system resistance with regard to bending, shear and punching in ULS (§3.3) and to perform a crack width calculation in SLS (§3.4).

3.2 Constitutive law

The constitutive law expresses the stress-strain relationship of the SFRC in the tension zone for cross-section design at ULS. There are two constitutive laws described in the DAfStb-Richtlinie (stress block and tri-linear). The ratio L2/L1 determines which one can/needs to be used. The one where L2/L1 >0.7 – the tri-linear law - is presented in Fig. 2:

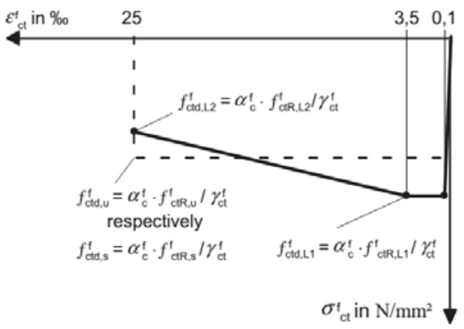

Fig. 2: The tri-linear stress-strain curve of SFRC in the tension zone for cross-section design at the ultimate limit state (except for non-linear methods) (the dashed line represents the stress block)

The determination of the design strength $f^f_{ctd,L1}$ and $f^f_{ctd,L2}$ (or alternatively, for the stress block, $f^f_{ctd,s}$ and $f^f_{ctd,u}$) is done by multiplying consecutive factors with the characteristic residual flexural strength (or the performance class L_i):

- a conversion factor β: to convert flexural strength into uniaxial strength (0,25-0,44 depending on the ration L2/L1 according to Bild P.1, [1]),
- a size factor κ^f_G: to take into account the effect of member size on the coefficient of variation,
- a fibre orientation factor κ^f_F: to take into account fibre orientation (e.g. for horizontally casted slabs, κ^f_F is generally determined to be 1.0 for bending and tensile loads)
- a long-term factor α^f_c=0,85: to take into account long-term effects on the residual tensile strength of SFRC
- a partial safety factor ${}^1\!/_{\gamma^f_{ct}} = {}^1\!/_{1,25}$

$$f^f_{ctd} = \frac{\alpha^f_c \cdot \kappa^f_G \cdot \kappa^f_F \cdot \beta \cdot L}{\gamma^f_{cf}} \tag{1}$$

3.3 Bending, shear and punching resistance

3.3.1 Determination of the bending moment capacity

The bending moment capacity of the fibre reinforced section can now be calculated using either of the constitutive laws. The ultimate limit state design of a cross-section for bending with or without axial force is based on following assumptions:

- Plain sections remain plain.
- The strain distribution is aligned with the strain distribution of reinforced concrete.

Thus the same boundary conditions as for reinforced concrete apply.

- ε^f_c < -3,5‰ (concrete in compression) (2)
- ε^f_c < -25‰ (steel or SFRC in tension)

In order to calculate the cross-section bending moment capacity, the static equilibrium needs to be determined. Fig. 3 schematically represents the relation between stresses (and resultant forces) and strains. Instead of neglecting the resistance of concrete in the tension zone, the stress-strain relation of the SFRC can be adopted here so the steel fibres take a share in the resistance.

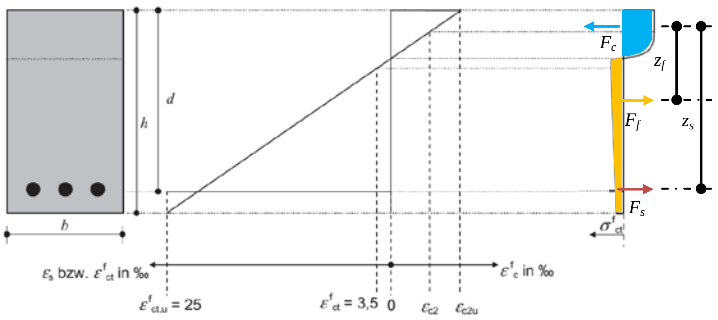

Fig. 3: Static equilibrium of the cross section under bending

The bending moment capacity of the cross section can be written as follows:

$$M_R = F_f \cdot z_f + F_s \cdot z_s \tag{3}$$

3.3.2 Determination of the shear and punching resistance

The effect of the steel fibres onto the shear and punching shear resistance can be taken into account by an additional component in the respective equations. Steel fibres act like a shear reinforcement over the entire cross section of the structure. The shear capacity of the element is increased as a function of the performance of the steel fibre concrete used. This can lead to a significant reduction (or even a complete elimination) of conventional shear reinforcement. Installation of stirrups or shear rails can be omitted in such a case. The DAfStb-Richtlinie takes the increased shear resistance due to steel fibre concrete into account by introducing an additional element $V_{Rd,cf}$ into the equations for conventional shear design. This holds for both slabs with and without conventional shear reinforcement:

$$V^f_{Rd,c} = V_{Rd,c} + V_{Rd,cf} \text{ (without conventional shear reinforcement)} \tag{4}$$

$$V^f_{Rd,s} = V_{Rd,s} + V_{Rd,cf} \leq V_{Rd,max} \text{ (with conventional shear reinforcement)} \tag{5}$$

where:

- $V^f_{Rd,c}$ is the design shear resistance of the steel fibre concrete member without shear reinforcement
- $V^f_{Rd,s}$ is the design shear resistance of the steel fibre concrete member with shear reinforcement

$V_{Rd,cf}$ is the design value of the shear resistance due to the steel fibre effect

$$V_{Rd,cf} = \frac{a^f_c \cdot \kappa^f_G \cdot \kappa^f_F \cdot \beta \cdot L \cdot b_w \cdot h}{\gamma^f_{ct}} \tag{6}$$

where:

- b_w is the width of the member
- h is the overall depth of the cross-section
- other parameters are explained in §3.3.1

$V_{Rd,cf}$ is a linear function of the SFRC performance and h. In this respect, the shear capacity of steel fibre concrete becomes especially important for thick sections.

3.4 Crack width calculation

The crack width design approach corresponds with the method for reinforced concrete introduced in EC2. Following the DAfStb-Richtlinie, the rules of EC2 are amended by the post crack tensile strength provided by the steel fibre concrete. This is done by introducing the factor α_f as the ratio of the post crack tensile strength over the first crack tensile strength. The basic principle is that due to increasing post crack strength the released force at crack formation decreases: The fibres carry a part of the released force. As a consequence, the reinforcing steel needs to transfer only a reduced force back into the concrete.

Therefore the strain in the reinforcing steel, as well as the required transfer length, is directly reduced.

$$w_k = s_{r,max} \cdot \left(\varepsilon_{sm}^f - \varepsilon_{cm}\right) \tag{7}$$

$$s_{r,max} = \left(1 - \alpha_f\right) \cdot \frac{d_s}{3.6 \cdot \rho_{p,eff}} \leq \left(1 - \alpha_f\right) \cdot \frac{\sigma_s \cdot d_s}{3.6 \cdot f_{ct,eff}} \tag{8}$$

$$\varepsilon_{sm}^f - \varepsilon_{cm} = \frac{\left(1-\alpha_f\right) \cdot \left(\sigma_s - 0.4 \cdot \frac{f_{ct,eff}}{\rho_{p,eff}}\right)}{E_s} \geq 0.6 \cdot \left(1 - \alpha_f\right) \cdot \frac{\sigma_s}{E_s} \tag{9}$$

where

$s_{r,max}$ is the maximum crack spacing

ε_{sm}^f is the mean strain in the reinforcing steel

ε_{cm} is the mean strain in the concrete between cracks

α_f is the ratio of the post crack tensile strength over the first crack tensile strength at 28 days, including effects from member size and fibre orientation

d_s is the diameter of the reinforcing steel

$\rho_{p,eff}$ is the effective reinforcement ratio

σ_s is the stress in the reinforcement, calculated without taking into account the steel fibre effect

$f_{ct,eff}$ is the mean value of the tensile strength of the concrete effective at the time when the cracks may first be expected to occur

Specific rules for thick members apply in addition.

For a given crack width, the use of steel fibres can significantly decrease the required amount of reinforcing steel. Additional effects from enabling the use of smaller diameters can be utilized.

By defining the normalized ratio of α_f on the basis of the 28 day strengths and by subsequently multiplying it with $f_{ct,eff}$, the fibre effect is aligned to the concrete age at the time considered for the design.

3.5 Execution and quality control

Quality control and production monitoring are another important aspect. For this purpose, parts 2 and 3 of the DAfStb-Richtlinie provide the rules and principles. The material properties of the steel fibre concrete must be determined by the concrete manufacturer in an initial type test. This comprises the standard properties like compression strength, air content etc. and the performance class which is derived from the characteristic residual flexural strength.

Once the performance class is determined with the mix design to be used, a strict process control is applied in order to make sure the correct concrete properties are delivered. This means that in addition to the quality control requirements of EN 206-1 for fresh and hardened concrete a defined process control for the steel fibres and the mixing of the steel fibre concrete has to be followed. The concrete composition must not be changed. From that point onwards, process control focuses on all steps which are relevant to reproduce the mix of the initial type testing. Controls range from identification of the correct fibre type, following a detailed mixing procedure, using the correct concrete components, allowable tolerances on the concrete composition etc., to homogeneity checks of the steel fibre concrete. Additional beam tests are only required once a year, in case of doubt or as soon as the concrete mix design or its constituents are changed. Wash-out tests to prove concrete homogeneity are the preferred test method and deliver results almost immediately, as compared to beam tests.

4. Structural steel fibre applications

“Structural steel fibre applications” is a term used to address SFRC structures and elements fulfilling a constructive function and mainly differentiates these from the well-known and widely recognized SFRC application “industrial floors”. Such constructions need to withstand often different load cases, like wind loads, earth quake loads and various life loads. Examples of structures falling in this category are residential and industrial raft slabs, industrial floors on piles and clad rack foundations. All these applications can be designed fully in accordance to the DAfSTb richtlinie and DIN EN 1992-1-1/NA.

This chapter presents 3 references designed accordingly.

4.1 Residential raft slab: IBV Nový Martin

The first application discussed in this paragraph is a residential raft slab, constructed with combined reinforcement in Martin, Slovakia in 2013. The slab was especially designed in SLS (service limit state). It was required to limit the average expected crack width to 0,15mm in the 34m x 12m slab. The loads themselves are mainly carried by strip foundations under the most heavy loaded areas (walls, columns…). In order to fulfil the strict SLS requirements, the slab of 170mm thick C20/25 concrete was reinforced with 25 kg/m³ Dramix® 4D 65/60BG in combination with a top mesh layer 8/8/150/150. The Dramix® 4D 65/60BG is a fibre of 60mm long, 0,9mm diameter, a tensile strength of 1500MPa and shaped with an improved anchorage. This special design maximizes its SLS performance in concrete. A total cost reduction of 10% was realised compared with a traditional reinforced slab design, due to material, time and global financial savings.

Fig. 4: Residential raft slab: IBV Nový Martin reinforced with Dramix® 4D 65/60BG

4.2 Industrial raft slab: Carl Zeiss AG factory in Oberkochen (Germany)

A second application presented here is a heavy industrial raft slab, as a part of the Carl Zeiss AG factory in Oberkochen, Germany. This factory consists of clean rooms, an additional service level for the ventilation ducts and other technical installations. At the side, a multi-story office is directly connected to the main area. Due to very severe vibration limiting criteria, a monolitic heavy raft slab was required. The slab needed to be on average 150cm thick. Complementary, the average crack width was limited to 0,3mm, which was a challenge to obtain for such a thick slab. A combined reinforcement (30 kg/m³ of Dramix® 3D 80/60BG and mainly rolled reinforcement (Bamtec(R) 12/12/100/100, at the top and at the bottom) fulfilled the ULS loading, vibration requirements and SLS requirements. Besides the steel savings with respect to a simulated traditional solution, there are important advantages concerning quality, durability, ease of execution, applicable construction methods and timings too. With the chosen reinforcement layout, all benefits could be utilized for this foundation slab. A comparison is made in the table below between the combined solution and the traditional solution.

Tab.1: Comparison of combined reinforced concrete solution and traditionally reinforced concrete solution for the 150cm thick slab

Basic reinforcement	Ø12/100, both directions, top + bottom Bamtec(R) rolls	2 x Ø14/100, both directions, top + bottom bars
Steel fibre content	30 kg/m³ Dramix® 3D 80/60BG in the 2 middle layers	-
Shear reinforcement	-	Shear Studs

Fig. 5: Casting of foundation raft slab of the Carl Zeiss AG factory in Oberkochen

4.3 Clad rack foundation: Crop's, Ooigem, Belgium

The last example of a structural fibre reinforced application is a clad rack foundation slab. A clad rack building is a building consisting of a structural racking system. The walls and roof are cladded to the racks. Doing so, the rack structure is not only carrying the stored goods, but must also withstand external loads like wind load, snow load and earthquake load. The clad rack foundation for the Crop's building in Ooigem, Belgium, has a height of over 30m. 2 important load cases are mainly determining the slab design: the situation where heavy wind is present on the moment that the racks are empty and the situation where the racks are fully filled with goods. The first situation causes high bending moments at the bottom of the edges of the slab where the wind is lifting the edges upwards. Therefore, the edges are made much thicker (80cm – 50cm elsewhere) with supplementary bottom reinforcement. The other situation mainly causes high internal bending moments under the rack legs. To meet the stability requirements the slab is reinforced with steel fibres (25 kg/m³ of Dramix® 5D 65/60BG), a top mesh 10/10/150/150 and a bottom mesh 8/8/150/15.

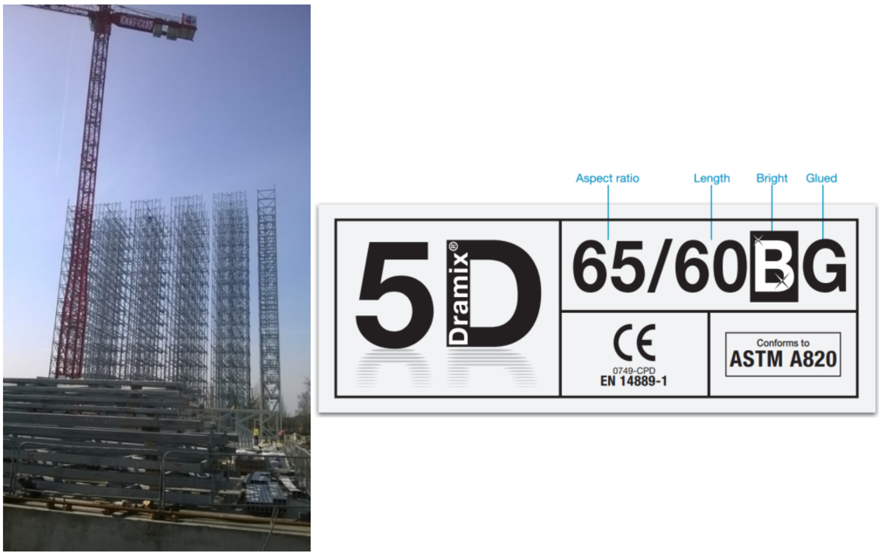

Fig. 6: Clad rack building Crop's, Ooigem, Belgium. Reinforced with Dramix® 5D 65/60BG.

5. Conclusions

Structural fibre reinforced concrete applications differ mainly from well-known fibre applications like industrial floors by the more structural aspect of these. Foundation slabs are an example of such a structural fibre reinforced concrete application in which steel fibres are the main or the complementary reinforcement to take up bending moments and the shear stresses. In combination with conventional reinforcement,the well known benefits of steel fibres on the reduction of crack width can even be utilized in a numerical model. The steel fibre contribution can be calculated using the German version of the Eurocode 2 (DIN EN1992-1-1/NAD) together with the DafStb guideline Steel Fibre Concrete. The use of steel fibres leads to a significant reduction of traditional reinforcement and an optimization of the building process. The advantages of this construction method and the basis of design are explained in detail with reference to some European example projects, like the extension of the Carl Zeiss AG factory in Oberkochen (Germany) and the Crop's Clad Rack construction (Freezer type) in Ooigem (Belgium).

References

[1] DAfStb Richtlinie Stahlfaserbeton 2012-11, *DAfStb technical rule Steel Fibre Concrete*.

[2] DIN EN 1992-1-1/NA, *Design of concrete structures - Part 1-1: General rules and rules for buildings.*

[3] POUILLON, Steven, VITT Gerhard. *Hybrid concrete in heavy mat foundations*. FRC Joint-ACI-FIB International Workshop, 2014.