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# Structural design of raft foundations with combined reinforcement

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**Abstract**:  After years of research and development detailed design methods, guidelines, and codes to design and construct steel fibre reinforced concrete structures are available. These documents offer a framework for designing and constructing a huge range of raft foundations and waterproof/fluid-tight structures in steel fibre reinforced concrete with or without traditional reinforcement in a very efficient way.

**Keywords**:  SFRC (steel fibre reinforced concrete), Constitutive law, EC2 (Eurocode 2), German standard (DAfStb-guideline steel fibre reinforced concrete), combined reinforcement (combination of steel fibres and traditional reinforcement)

## 1. Introduction

The use of SFRC is traditionally associated to industrial floors, tunneling, precast and minor residential applications. Nowadays the design and execution of advanced structural applications like raft foundations with SFRC or with combined reinforcement is possible due to the available codes and standards [1-5], which have been published after years of extensive committee works. Beside facilitating the construction work and reducing the execution time, adding steel fibers leads to economical, durable, and sustainable solutions. Design formulas are predominantly built on EC2 [2] and MC 2010 [3], amending and complementing the existing ones with the contribution of SFRC and verified by extensive full-scale testing. The additional performance of SFRC can be utilized for reducing slab depth and basic reinforcement and/or for eliminating shear studs with the objective to work out most efficient solutions. This paper will elaborate on the design methods of the German standard and present some examples of executed raft projects.

## 2. Design and construction of raft foundations

### *2.1 The German standard for SFRC*

The German standard [1], which is considered as an amendment and supplement to the National Annex (NA) of EC2 in Germany, has been used as a basis of design for the following project examples. It provides the rules for design, quality control and execution of steel fibre concrete structures with or without conventional reinforcement. It has a full legislative nature and contains the necessary changes and additions to all relevant standards to fully incorporate steel fibre concrete. The German standard comprises:

Part 1: Design and construction

Part 2: Specification, performance, production, and conformity

Part 3: Execution

In 2011, the German standard [1], meanwhile there is a new edition from June 2021, was nationally approved in Germany and was notified to the European Union. It is meant to be used as addition to the standards for concrete DIN EN 206-1 [6], DIN EN 13670 [7] and concrete structures DIN EN 1992-1-1 [2]. Following design method in chapter 2.2 to 2.4 is based on this German standard.

### *2.2 Constitutive law and design for bending*

The bending moment capacity of SFRC sections is calculated using the following stress-strain diagram and constitutive law (Figure 1 and 2). 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.

- o $\varepsilon_c^f < -3.5‰$ (concrete in compression)
- o $\varepsilon_{ct}^f < -25‰$ (steel in tension)

- The steel fiber effect is considered by a post crack tensile strength throughout the area in tension

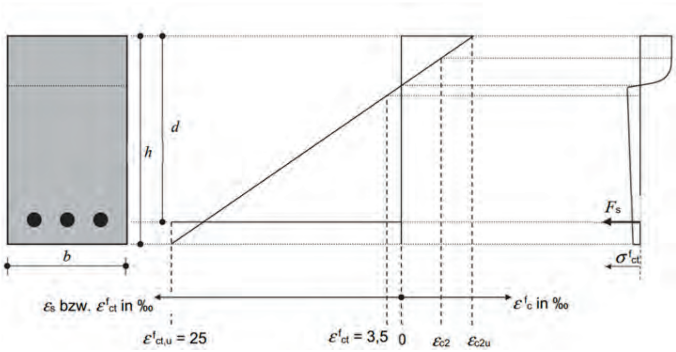


Figure 1 Stress strain diagram [1],[2]

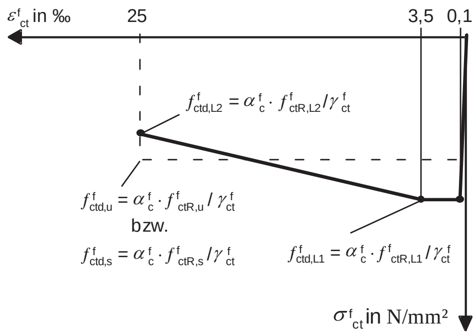


Figure 2 Constitutive law [1],[2]

The applied constitutive law united material safety factor, factor of geometry, orientation factor and long-term factor. They are aligned and fully compatible with the underlying reinforced concrete standards.

### 2.3 Shear and punching shear design

The effect of the steel fibers to shear and punching shear resistance is considered by an additional component. Steel fibers act as shear reinforcement over the entire cross section of the structure. The shear capacity of the structure is increased as a function of the post crack performance of the steel fiber concrete. This can lead to a large reduction or a complete elimination of conventional shear reinforcement.

#### 2.3.1 Shear:

The German standard takes the increased shear resistance due to steel fiber concrete into account by introducing an additional element $V_{Rd,cf}$ into the equations of conventional shear design.

$$V_{Rd,c}^f = V_{Rd,c} + V_{Rd,cf}$$ (without conventional shear reinforcement)

$$V_{Rd,s}^f = V_{Rd,s} + V_{Rd,cf} \leq V_{Rd,max}$$ (with conventional shear reinforcement)

where

$V_{Rd,c}^f$ design shear resistance of the SFRC member without shear reinforcement [kN]

$V_{Rd,s}^f$ design shear resistance of the SFRC member with shear reinforcement [kN]

$V_{Rd,cf}$ design value of the shear resistance due to the steel fiber effect [kN]

$$V_{Rd,cf} = \frac{a_c^f \cdot f_{ctR,u}^f \cdot b_w \cdot h}{\gamma_{ct}^f}$$

$a_c^f$ 0.85 (factor aligned with $\gamma_{ct}^f$, allowing for long term effects)

$\gamma_{ct}^f$ 1.25 (material safety factor, aligned with $a_c^f$)

$b_w$ is the width of the element

$h$ is the overall depth of the cross-section

$f_{ctR,u}^f$ is the calculated post-crack tensile strength in the ultimate limit state, including effects from member size and fiber orientation

$V_{Rd,s}$ is the design value of the shear force which can be sustained by the yielding shear reinforcement

$V_{Rd,max}$ is the design value of the maximum shear force which can be sustained by the member, limited by failure of the compression struts.

$V_{Rd,cf}$ is a linear function of the post crack tensile strength $f^f_{ctR,u}$ and h. In this respect, the shear capacity of SFRC becomes especially important for thick sections.

### 2.3.2 Punching shear

For slabs or foundations made of SFRC without traditional punching shear reinforcement, the punching shear resistance can be calculated as the following:

$$v^f_{Rd,c} = 2 \cdot d/a \cdot v_{Rd,c} + v_{Rd,cf} \leq v_{Rd,max}$$

where

$v^f_{Rd,c}$ punching shear resistance per unit area of the SFRC [N/mm²]

$v_{Rd,c}$ punching shear resistance of concrete per unit area according to EC2 [N/mm²]

$v_{Rd,cf}$ punching shear resistance per unit area due to the steel fibre effect [N/mm²]

$v_{Rd,max} = 1{,}4 \cdot v_{Rd,c}$ according to EC 2

$v_{Rd,cf} = 0{,}85 \cdot \frac{\alpha^f_c \cdot f^f_{ctR,u}}{\gamma^f_{ct}}$ with definition as above

$v_{Rd,cf}$ is a linear function of the post crack tensile strength $f^f_{ctR,u}$ within the critical perimeter. The resistance becomes considerably effective and can fully replace traditional punching shear studs.

## 2.4 Design for crack width limitation

The approach for crack width design corresponds to the method used for structural concrete introduced in EC2. The formulas of EC2 are amended by the post crack tensile strength provided by the steel fibre concrete. This is done by introducing the factor $\alpha_f$ as the ratio of the post crack tensile strength to the first crack tensile strength of concrete. The basic principle is that due to increasing post crack strength the released force at crack formation decreases as the fibres carry a part of the released force. Consequently, the reinforcing steel needs to transfer only the gap of the force back into the concrete. Therefore, the area of reinforcing steel, as well as the required anchorage length, is reduced.

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

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

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

where

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

$\varepsilon^f_{sm}$ is the mean strain in the reinforcing steel

$\varepsilon_{cm}$ is the mean strain in the concrete between cracks

$\alpha_f$ is the ratio of the post crack tensile strength over the first crack tensile strength, including effects from member size and fiber orientation

$d_s$ is the diameter of the reinforcing steel

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

$\sigma_s$ is the stress in the reinforcement

$f_{ct,eff}$ is the mean value of the effective tensile strength of the concrete

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

## 3. Project case studies

### *3.1 Massive raft foundation with focus on constructability and time optimisation*

Carl Zeiss AG was investing in an expansion to their plant in Germany between 2011 and 2012 by constructing several new offices and production facilities. The expansion of the SMT-department (Semiconductor Manufacturing Technology) is a keystone for the future development of the company. In this facility they will manufacture the next generation lithography-optics powered by extreme ultraviolet light. The devices operate in a wavelength range of 13.5 nm. To build and operate such equipment a special production environment is required. Focus here is on the massive raft foundations, which represented a challenge for the design, planning, execution, and tight timeline. The building structure consists of a thick raft foundation, supporting the precast concrete structure. One of the essential requirements is a very low sensitivity to vibrations. The dynamic analysis and the vibration tests have been carried out by a specialized engineering office. Due to the vibration criterion a 150cm and 220cm thick, monolithic foundation slabs was required. Special attention had to be paid to restraint originating from the dissipation of hydration heat and shrinkage. The requirement was a calculated crack width of 0.2mm under service conditions.

The design office statix GmbH was assigned to work out the structural design. The task was complex, especially due to the severe dynamic aspects. A monolithic foundation slab was required. Due to the required depth of the foundations (150cm / 220cm) and length of more than 90m without joints, special planning and detailing considerations were necessary. The design of these foundations was done in collaboration with the engineers of Bekaert (Office Neu-Anspach, Germany). The essential idea was to reduce the amount of reinforcing steel so that BAMTEC® rolled mesh reinforcement could be used and all shear reinforcement could be eliminated. With the rolled meshes the required installation time had been decreased significantly. The fibre concrete performance class was limited to balance design values to an economic and practical workability level. Based on the design results a steel fiber concrete with the performance class C25/30, L1.5/L1.5 (25kg/m³ Dramix® 3D 80/60BG) was chosen as starting point. The required amount of the basic reinforcement was determined by considering the use of reinforcement rolls in an efficient way (d=12 mm/115 mm/115 mm). Besides the steel savings, there are important advantages concerning time, quality, durability, and ease of execution. The construction process and the logistics demanded a very good organization of the casting procedure. During the 80 hours of continuous concreting, 120 m³ concrete was poured each hour. The steel fiber concrete was mixed in a mobile 3 m³ mixing plant which was installed next to the construction site. The slabs were divided into three layers and casted “fresh on fresh”. A delay of only 3 hours was allowed between casting the next layer so that a monolithic slab without additional shear connection could be achieved. Three concrete pumps with 58 m radius and 6 truck mixers were needed to feed the slab with concrete.

Figure 2: Easy reinforcement layout

Figure 1: Casting of the foundation raft

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The construction of the raft foundations with Dramix® steel fibers lead to several economical and practical advantages. More than 50% of conventional reinforcing steel could be replaced. A congested reinforcement layout could be avoided in favor of easy concrete placement and proper compaction. Shear and punching shear reinforcement were eliminated and instead of heavy bars, the application of rolled reinforcement elements became possible. Significant saving in construction time could be achieved due to the simple reinforcement layout. Additional efforts for mixing and handling the fibers were very limited. All expectations to the raft foundations were met, all deadlines were kept, and cost and material savings were achieved. The use of combined reinforcement made the difference. In the past years, several additional expansions of Carl Zeiss SMT followed; for each foundation slab the same solution as formerly described was applied. Design efforts were provided by Bekaert engineers in cooperation with the design office [8].

### *3.2 Rafts for multi-story buildings with focus to slab depth optimisation*

SFRC has already been used in foundation slabs of residential buildings for many years. In the past the option to build with SFRC was enabled by general approvals; those approvals however were limited in scope. The German standard has replaced the need of general approvals for those foundation slabs in Germany and thus has also removed boundaries so that raft foundations of any size and requirement can be designed and built in SFRC/combined reinforcement. The main idea for adding steel fibres as additional component is to achieve efficiency by utilizing economic advantages, higher sustainability, and simplified way of construction.
The resistance of a slab is mainly determined by slab depth, concrete strength class and reinforcement. Steel fibres are another reinforcing element which can be added in different levels of fibre concrete performance to balance design values to level best efficiency.

Focus here is on slab depth optimization. Many raft thicknesses of multi-story buildings with underground parking are governed by punching requirement of the columns. To counteract either increase of slab depth or installation of shear studs are usually foreseen. In those projects where installation of shear studs was avoided by sufficient slab depth a reduction of depth can be achieved by using SFRC as steel fibres act as shear and punching reinforcement (chapter 2.2). An extra shear strength, up to $v_{Rd,max} = 1{,}4 \cdot v_{Rd,c}$ , according to EC2 can be reached by applying a reasonable amount of high-end steel fibres. A thinner slab will result in less required reinforcement for crack width limitation and reduced earthworks. In most cases this essential amendment in design is providing the most efficient economical advantage since those steel fibres applied are also contributing in all other ULS and SLS verifications.
Project “City Prag” Stuttgart, Germany is only example of projects for which the optimisation of slab depth and the balance between traditional reinforcement and steel fibres lead to considerable savings.

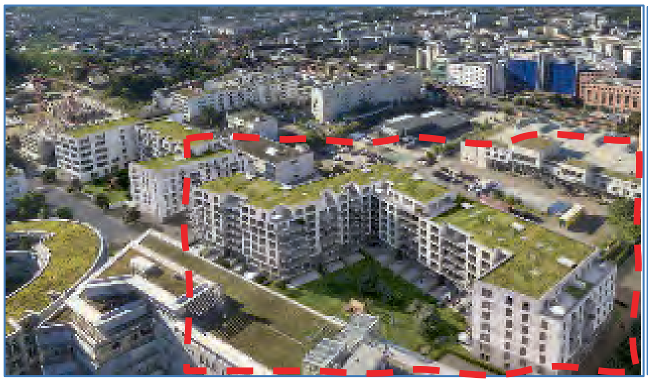

Figure 4: Urban development, ‘City Prag’ Stuttgart

Figure 5: Casting of one part of the raft foundation

Quite some raft foundations for office blocks, residential and multi-storey buildings were executed in combined reinforcement to generate savings and higher sustainability. In those cases where punching requirement was fulfilled by using shear studs and a confined reinforcement layout, the use of steel fibres have replaced those shear studs and simplified the reinforcement layout. In cases where the punching resistance of the slab has been achieved with longitudinal reinforcement only, it was possible to reduce slab depth next to replacing a part of traditional reinforcement, resulting in an even a bigger efficiency mainly due to material/ time saving and higher sustainability.

### *3.3 Raft foundation with focus on water-impermeability and fluid-tightness function*

#### 3.3.1 Fluid-tight raft with secondary barrier function for the chemical industry

Strict laws to protect our environment present special challenges to engineers and designers. Thus, due to requirements in §61 of the Water-Resources-Law (WHG), "plants for storage, filling, production and treatment of substances hazardous to water need to be designed, constructed, maintained and operated in a proper way without causing risk at any time of adverse changes in the properties of underground-water. This principle is often applied to buildings in the chemical industry, as large quantities of water-harming substances are produced and stored there. The use of liquid-tight concrete is regulated in a separate standard, the DAfStb guideline “concrete structure when handling substances hazardous to water” abbreviated BUmwS [9]. The purpose of this guideline is to design a structure in such way that assures the liquid-tightness and thus prevent penetration of a specific medium at any time. The basis for the verification of “liquid-tight” is the degree of penetration depth of a medium into the concrete. The penetration depth depends on the type and viscosity of the liquid. It dictates the required height of the compression zone in the concrete. In case of alternating crack-inducing bending moments in one section a further increasing factor to the required compression zone height will be applied. The positive influence of steel fibres on the properties of concrete is used in BUmwS [9] above all to increase the tightness of the uncracked and cracked concrete [10], the stress absorption in the cracked state and the increase of wear resistance. While traditional reinforcement only affects the surface area of the cross-section, especially in thick structures, steel fibres are distributed and act over the entire cross-section effectively. In addition, cracks inside the cross-section can also be controlled and prevent crack development. The risk of separation cracks in the structure is thus significantly reduced. The principle of this project for a BASF tank foundation (tank-cup) [11] was to prevent any separation crack under restraint deformations, to limit cracks under load to 0,1mm and to apply the mandatory thickness to the structure to obtain the required height of compression zone in every section under alternating crack-inducing bending moments. Due to high stresses of liquid pressure, wind loads and temperature, the walls of the “tank-cup” were post-tensioned whilst the raft foundation was executed in combined reinforcement. The design effort of the foundation was provided by Bekaert engineers in cooperation with the design office in charge.

Figure 6: Raft foundation before concreting the SFRC

By using a high-performing steel fibre concrete (performance class L 2.1/2.1 with 25kg/m³ Dramix® 5D 65/60BG) the thickness of the structure could be optimized and the degree of reinforcement significantly reduced. The effect of the steel fibres was considered in the design of ULS, the SLS and for liquid-tightness. The result was an economic, durable, practical and very reliable solution.

### 3.3.2 Water-impermeable raft foundation Vinzent R22

Vinzent is the name of the office-residential building in the city center of Munich, which is planned as timber-hybrid construction. Execution started in September 2022 and shall be finalized by 2024. The building has 3 underground parking floors and 6 levels above ground [12]. A Sustainability-certification LEED Gold is targeted. This project is a typical multi-story building, similar to those projects presented in chapter 3.2; however, main challenge here was to find the most suitable solution for the raft foundation to achieve a highest sustainability level with the underlying conditions. The building pit lays 10 m under the ground water level and hence a 10 m high pressure level need to be considered for the design whilst the foundation slab is foreseen as white-basin construction (water-impermeable structure). At the same time the most sustainable solution was targeted. To satisfy the sustainability requirement it was decided not to counteract the water-pressure purely by weight of the slab but to limit the slab depth to 100 cm and rather to anchor it with Gewi-piles into the ground. Typically, one basic condition for white-basin constructions is to avoid or limit restraint as good as possible. So, there was a certain contradiction as the amount of back-pilling was inducing quite a high level of restraint and therefore increase the risk for separation cracks. Thus, the concept was to limit the cracks to a level where a self-healing effect can be accounted for whilst considering the unbeneficial situation, fully restraint at mature concrete age, in the design. One main trigger to use combined reinforcement was to ensure the most effective solution for the water impermeability requirement. As the effect of the steel fibres has considerably reduced the amount of basic reinforcement mainly for the governing crack width design, both the economical and the sustainable advantages were acquired on top. Precise analyses were undertaken to compare economics and sustainability of the original solution (structural concrete) to the alternative solution of combined reinforcement as this was of quite high importance for the LEED Gold target.

Figure 7: South-West view of “Vinzent”

Figure 8:Pit with temporary water-retainment

The raft foundation was casted in combined reinforcement. The design solution of Bekaert engineers in cooperation with the design office Seidl&Partner was successfully implemented. Not a single spot of water leak was detected. The life cycle assessment for Cradle to Gate analysis was undertaken with the One-click LCA tool. 325 tons of traditional reinforcement were reduced to 170 tons. A saving of 155 tons of traditional reinforcement and some amount shear studs was achieved by using 80 tons of Dramix® 5D 65/60BG fibres instead. From logistical point of view, it was also a meaningful advantage, that 155 tons less steel reinforcement had to be transported into the city center of Munich. The benefit of using SFRC resulted in a reduction of >= 75 tons of $CO_2$ emission. To illustrate that number more comprehensible we may say this equals the $CO_2$ amount which can be absorbed by 75 mature trees over a period of 50 years.

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## 4. Conclusions

The application area for SFRC and especially for combined reinforcement has been considerably extended. The German standard, a national recognized document, provides suitable design methods to facilitate the use of steel fibres and is due to its recognition also accepted in other countries outside of Germany.

The new Eurocode version which will be implemented in few years from now will contain a separate annex ”L” for designing and constructing with SFRC; this annex is based on the German standard and the ModelCode 2010. This development will accordingly enable all European member states and those countries who are intending to adopt the EC2 as national standard to use SFRC/combined reinforcement for structural applications too. Using high-end steel fibres allow achieving a robust post-crack tensile strength and a ductile material behavior and retain a good concrete workability.

Thanks to widely gained experience and full-scale tests as well as code development the advantages of the synergy effect between steel fibers and reinforcing steel can be utilized. For raft foundations in combined reinforcement those numerous advantages mainly economic advantages, higher sustainability, easier constructability, and considerable time savings can be mostly achieved.

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