Codes for SFRC structures – A Swedish proposal

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ABSTRACT: Despite both technical and economical advantages, the use of Steel Fibre Reinforced Concrete (SFRC) has been limited to certain areas, e.g., shotcrete for rock strengthening and slabs-on-grade. In order to facilitate its design and increase its use, design recommendations are necessary. The Swedish Concrete Association has tried to promote the use of SFRC by issuing recommendations both for general applications and for industrial concrete floors. This paper summaries the Swedish proposal to a possible Code for SFRC structures. It deals with basis of design, determination of material properties, slabs-on-grade, pile-supported slabs, and overlays.

1 INTRODUCTION

Steel fibre reinforced concrete (SFRC) has both technical and economical advantages, e.g., improved ductility and corrosion resistance and substantial reduction of laborious reinforcement work. Despite its extensive and long-term use in specific areas, e.g., underground shotcrete structures and industrial floors, it has not conquered the general market of concrete structures. One reason is that the major international and national concrete codes do not cover SFRC structures. In Sweden, the Swedish Concrete Association (SCA) developed its first recommendations for SFRC in 1995 (SCA, 1997). At that moment, they were considered to be cutting-edge recommendations. Currently, the 3rd edition of the recommendations is developed. It covers modernizations and extensions. Very soon, SCA will publish recommendations on industrial concrete floors (SCA, 2008). They cover both plain, conventionally reinforced and SFRC concrete floors and both slabs-on-grade, pile-supported slabs, and overlays. Pile-supported slabs are generally regarded as a load-carrying structure and since the Swedish code for concrete structures does not cover SFRC solutions without conventional reinforcement (“SFRC only”) have not been possible to design. The new SCA recommendations have tried to fill this gap and have consequently developed guidelines for pile-supported slabs of SFRC only. The guidelines also present straightforward methods to design SFRC floors and overlays for crack control. Together, the two SCA reports will facilitate the proper design and probably increase the future use of SFRC structures.

Table 1. Partial safety factors according to SCA (1997).

<table>
<thead>
<tr>
<th>Structure</th>
<th>Design state</th>
<th>ULS – uncracked</th>
<th>SLS – uncracked</th>
</tr>
</thead>
<tbody>
<tr>
<td>Floors &amp; pavements</td>
<td>1.2</td>
<td>1.2</td>
<td>1.0</td>
</tr>
<tr>
<td>Other cast-in place structures</td>
<td>1.5</td>
<td>1.4</td>
<td>2-R/100</td>
</tr>
<tr>
<td>Concrete products</td>
<td>1.5</td>
<td>1.5</td>
<td>2-R/100</td>
</tr>
<tr>
<td>Precast elements</td>
<td>1.5</td>
<td>1.3</td>
<td>2-R/100</td>
</tr>
</tbody>
</table>

Note: R = residual strength factor according to Section 3.2. For tension: R = R2, for flexure: R = R1.

2 BASIS OF DESIGN

2.1 Partial safety factors

According to Swedish concrete code (BBK 04, 2004), there are four safety factors: (i) $\eta = \text{factor considering systematic difference between material properties of the control test specimen and that of the real structure}$, (ii) $\gamma = \text{factor for load-carrying capacity}$, (iii) $\gamma_n = \text{factor for safety class (see Section 2.2)}$, and (iv) $\zeta = \text{crack safety factor (} \zeta = 2 \text{ for plain concrete)}$. The first two are usually given as a product $\eta \gamma_n$. The partial safety factors are listed in Table 1.

2.2 Security classes for industrial floors

Sweden uses a concept of security classes for all kind of structures (BKR, 2003). The security class...
Table 2. Proposed partial safety factors for industrial floors according to SCA (2008).

<table>
<thead>
<tr>
<th>Structural system</th>
<th>$H \leq 5 \text{ m}$</th>
<th>$H &gt; 5 \text{ m}$</th>
<th>$H \leq 5 \text{ m}$</th>
<th>$H &gt; 5 \text{ m}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slab-on-grade</td>
<td>1.0</td>
<td>1.1</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Pile-supported slab</td>
<td>1.0</td>
<td>1.1</td>
<td>1.0</td>
<td>1.1</td>
</tr>
</tbody>
</table>

Note: $H =$ storage height.

is dependent on the risk of severe injuries. There are three classes 1–3 with connecting partial safety factors $\gamma_n = 1.0$, $\gamma_n = 1.1$, and $\gamma_n = 1.2$. Industrial floors are either constructed as slabs-on-grade or pile-supported slab. The risk of severe injuries is usually low, but might increase in high buildings and on pile-supported slabs. The following safety factors have been proposed (Table 2):

3 DETERMINATION OF MATERIAL PROPERTIES

3.1 Determination of flexural strength through flexural bending tests

The flexural strength is determined through four-point bending of a slender steel fibre reinforced concrete beam (Fig. 1). During the test, the cracking load $F_{cr}$, the ultimate load $F_u$, and the residual load $F_{res}$ are determined as the average load between predefined displacements (usually between 5.5 and 10.5 times the displacement $\delta_{cr}$ at cracking $[F_{res,1}]$, but in cases of increased ductility demands also between 5.5$\delta_{cr}$ and 15.5$\delta_{cr}$ $[F_{res,2}]$ or even between 5.5$\delta_{cr}$ and 20.5$\delta_{cr}$ $[F_{res,3}]$). For each specimen, the flexural strength at cracking $f_{cr}$, the ultimate flexural strength $f_{u}$, and the residual flexural strength $f_{res}$ are computed by the following equations (Fig. 2):

$$f_{cr} = \frac{F_{cr}}{b \cdot \frac{h}{2}}$$  \hspace{1cm} (1)

$$f_{u} = \frac{F_{u}}{b \cdot \frac{h}{2}}$$  \hspace{1cm} (2)

$$f_{res,i} = \frac{F_{res,i}}{b \cdot \frac{h}{2}}; i = 1, 2, 3$$  \hspace{1cm} (3)

SFRC is usually subjected to relatively large scatter. To reduce the scatter, large numbers of expensive tests would be necessary. A pragmatic solution is to define the characteristic values as 90 percent of the lowest value in test series on three specimens, e.g.,

$$f_{cr,k} = 0.9 \cdot \min(f_{cr}, f_{cr2}, f_{cr3})$$  \hspace{1cm} (4)

3.2 Determination of derived material properties

Most material properties, e.g., compressive strength, modulus of elasticity, and shrinkage, are almost the same for SFRC as for plain concrete. Consequently, the values of plain concrete can be used. However, for flexural strength and tensile strength, the differences are essential. In Swedish design of SFRC, the following expressions can be used for cracked SFRC in ULS:

$$f_{ud} = \frac{f_{u,k}}{\eta \gamma_n \cdot \gamma_u}$$  \hspace{1cm} (5)

$$f_{ul} = \frac{0.37 \cdot f_{u,k,i}}{\eta \gamma_n \cdot \gamma_u}$$  \hspace{1cm} (6)

The design values have to be determined for specified ductility demand. This is done by specifying type of residual strength $f_{res,k,i}$. Default value is $i = 1$.

The following expressions are used for uncracked SFRC in ULS:

$$f_{ud} = \frac{f_{ud,k}}{\eta \gamma_n \cdot \gamma_u \cdot \zeta}$$  \hspace{1cm} (7)
In the SLS, both $\eta_\gamma m = 1.0$ (Table 1) and $\gamma_n = 1.0$. The following expressions can be used:

\[
\begin{align*}
 f_{ld} &= \frac{f_{\text{neck}}}{\zeta} \\
 f_{ld} &= \frac{0.6 \cdot f_{\text{neck}}}{\zeta}
\end{align*}
\]

In the SLS, both $\eta_\gamma m = 1.0$ (Table 1) and $\gamma_n = 1.0$. The following expressions can be used:

\[
\begin{align*}
 f_{ld} &= \frac{f_{\text{neck}}}{\zeta} \\
 f_{ld} &= \frac{0.6 \cdot f_{\text{neck}}}{\zeta}
\end{align*}
\]

Finally, the residual strength factor $R_i$ (measured in %) can be determined as follows:

\[
R_i = 100 \cdot \frac{f_{\text{res},i}}{f_{\text{neck}}}
\]

### 3.3 Comparison between Swedish test method and EN 14651

The international test method EN 14651 (2005) consists of three-point bending test on notched SFRC specimens. The difference between the Swedish test method and EN 14651 are described in Table 3. In cases where transformations are necessary, the following relationships may be used:

\[
\begin{align*}
 f_{hr}(SE) &= f_{frj}(EN) \\
 f_{frj}(SE) &= f_{frj}(EN) \\
 R(SE) &\approx 100 \cdot \frac{f_{frj}(EN)}{f_{frj}(EN)}
\end{align*}
\]

For definitions of the EN parameters, see EN 14651.

### 4 SLABS-ON-GRADE

#### 4.1 Mechanical loading

The design for mechanical loading in ULS may either be determined by assuming cracked state and yield-line theory or by assuming uncracked state and theory of elasticity (see Section 4.3). In the first case, the following condition apply:

\[
F_d \leq g(m_u)
\]

where, $F_d$ = design load, $g(m_u)$ = load-carrying capacity for relevant yield-line pattern, and $m_u$ = moment capacity according to:

\[
m_u = \frac{f_{ld} \cdot h^2}{6}
\]

where, $h$ = slab thickness. In order to take restrained shrinkage or thermal movements into account, $f_{ld}$ should be determined by Eq. 5 with increased ductility demands, i.e., residual flexural strength $f_{\text{res},2}$ or $f_{\text{res},3}$. Solutions for $g$ for various loading cases were originally developed by Losberg (1961).

#### 4.2 Restraint

Concrete floor slabs cast-in to columns, piles, foundations, walls or other connecting structural elements lead to high degrees of restraint. Restraint is also developed though friction to the base or subbase. Restraint stresses develop simultaneously with restrained shrinkage or thermal movements. The restrained shrinkage stress $\sigma_{ct}$ may be estimated by the following equation:

\[
\sigma_{ct} = \psi \cdot \frac{E_c \cdot e_{cs}}{1 + \phi}
\]

where, $\psi$ = degree of restraint (full slip $= 0 \leq \psi \leq 1$ = complete restraint), $E_c$ = modulus of elasticity of concrete, $e_{cs}$ = free concrete shrinkage, and $\phi$ = creep coefficient.

#### 4.3 Combined loading

Generally, SFRC slabs are subjected to both mechanical and restraint loads. In the cracked state, Losberg’s hypothesis (Losberg, 1961) stating that restrained stresses vanish as soon as the reinforcement yields is used also for the SFRC slab. Consequently, only mechanical loads have to be considered on the loading side of the design equation 15. Restraint is, as stated above, taken into account be increasing the ductility demands of the SFRC. In uncracked SFRC, the following equation apply:

\[
\frac{\sigma_{cl}}{f_{ld}} + \frac{\sigma_{ct}}{f_{ld}} \leq 1
\]

where, $\sigma_{cl}$ = flexural stress due to mechanical loading and $\sigma_{ct}$ = tensile stress due to restraint loading according to Eq. 17.

#### 4.4 Crack control

SCA (2008) proposes four crack width classes (Table 4). Suitable classes ought to be selected due to the intended use of the industrial concrete floor.

### 5 PILE-SUPPORTED SLABS

#### 5.1 General

In Sweden, there is a continuous discussion on whether the pile-supported slab has to be considered as a load-carrying structure or not. From the beginning, piles and subgrade share the load, but gradually the piles will carry the majority of the load. Eventually, the slab is a load-carrying structure. On the other hand, the risk of injuries is still limited. The Swedish Concrete Association (2008) solved the problem by introducing the safety classes shown in Table 2. There
Table 3. Comparison between flexural test methods according to SCA (1997) and EN 14651.

<table>
<thead>
<tr>
<th>Type of bending</th>
<th>SCA 4-point bending (4PB)</th>
<th>EN 14651 3-point bending (3PB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Notch depth (mm)</td>
<td>0</td>
<td>25</td>
</tr>
<tr>
<td>Span length (mm)</td>
<td>450</td>
<td>500</td>
</tr>
<tr>
<td>Beam length (mm)</td>
<td>500</td>
<td>550</td>
</tr>
<tr>
<td>Beam width (mm)</td>
<td>125</td>
<td>150</td>
</tr>
<tr>
<td>Beam height (mm)</td>
<td>75</td>
<td>150</td>
</tr>
<tr>
<td>Net height (mm)</td>
<td>75</td>
<td>125</td>
</tr>
<tr>
<td>Beam weight (kg)</td>
<td>11.2</td>
<td>29.7</td>
</tr>
<tr>
<td>Slenderness l/h</td>
<td>6</td>
<td>3.33</td>
</tr>
<tr>
<td>Parameters recorded</td>
<td>Mid-span displacement at cracking; Flexural stress at various displacement intervals given by certain multiples of the cracking displacement.</td>
<td>Crack mouth opening displacement (CMOD); Residual flexural stress at certain CMODs (0.5, 1.5, 2.5, and 3.5 mm).</td>
</tr>
<tr>
<td>Advantages</td>
<td>(1) Minor arch effect due to slenderness; (2) Possible multiple cracking due to 4PB; (3) Possible to record strain-hardening; (4) No disturbing shear at central beam third; (5) Low weight.</td>
<td>(1) Less scatter, (2) Predefined crack path; (3) Possible use of the measured CMOD values in fracture mechanics studies.</td>
</tr>
<tr>
<td>Disadvantages</td>
<td>(1) Large scatter; (2) Crack location influence on measured values; (3) Possible load-increasing effect of fibre orientation.</td>
<td>(1) Higher arch action; (2) Complicated stress state at notch (combined flexure and shear, both magnified due stress concentration); (3) No possibility to record strain-hardening; (4) Higher weight.</td>
</tr>
</tbody>
</table>

Table 4. Crack width classes for industrial concrete according to SCA (2008).

<table>
<thead>
<tr>
<th>Crack width class</th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Demands</td>
<td>High</td>
<td>Moderate</td>
<td>Low</td>
<td>No</td>
</tr>
<tr>
<td>Possible exposure classes¹</td>
<td>All</td>
<td>All</td>
<td>XC0 + XC1</td>
<td>XC0 + XC1</td>
</tr>
<tr>
<td>εcs (mm/m)</td>
<td>≤0.5</td>
<td>≤0.6</td>
<td>≤0.8</td>
<td>No demands</td>
</tr>
<tr>
<td>R1 (%)</td>
<td>N/A³</td>
<td>≥70</td>
<td>≥40</td>
<td>≥30</td>
</tr>
<tr>
<td>Curing class²</td>
<td>4</td>
<td>3</td>
<td>3</td>
<td>2</td>
</tr>
</tbody>
</table>

Notes: ¹ = according to EN 206. ² = according to prEN 13670. ³ = SFRC is not recommended, select post-tensioning or heavy conventional reinforcement.

are three competing systems; (i) conventionally reinforced concrete slabs, (ii) SFRC slabs ("fibres only"), and (iii) SFRC slabs with additional conventional reinforcement above the pile heads ("combined reinforcement"). Due to the limited space, only the SFRC slab is dealt with here, despite that the third system often is more competitive at least in cases with high loads and large pile spacing.

The pile-supported slab has to be designed for flexural moment, punching shear, and crack control.

5.2 Flexural moment

Two types of flexural failure modes are possible; (A) circular and radial yield lines around the pile (Fig. 3, top) and (B) straight and parallel lines above and between the pile lines (Fig. 3, bottom). The corresponding design moments can be determined by the following equations (Nylander & Kinnunen, 1974):

\[
m_{\lambda,d} = q_d \cdot \frac{l_{pd}^2}{4 \pi} = \frac{P_u}{4 \pi} \quad (19)
\]

\[
m_{\eta,d} = q_d \cdot \frac{l_{pd}^2}{16} = \frac{P_u}{16} \quad (20)
\]

where, \( q_d \) = design value of the distributed load, \( l_{pd} \) = pile spacing, and \( P_u \) = ultimate pile load. The design condition reads as follows:

\[
m_u = \frac{f_{\eta,d} \cdot h^2}{6} \leq \min \left\{ m_{\lambda,d}, m_{\eta,d} \right\} \quad (21)
\]

where, \( m_u \) = flexural moment capacity of the SFRC slab with thickness \( h \).

5.3 Punching shear

Besides flexural failures, also punching failures are possible especially for piles with small cross section and thin slabs. The shear strength along the control section may be determined by the following equation:

\[
f_{\eta} = \frac{\bar{f}}{1.4} \cdot C \cdot \frac{f_{\eta,d}}{\bar{f}} \quad (22)
\]
where, \( \xi \) = size-dependent factor, \( C \) = coefficient (here: \( C = 0.45 \)), and \( \zeta \) = crack safety factor (here: \( \zeta = 1 - R_2/100 \)). \( \xi \) has the following values:

\[
\xi = \begin{cases} 
1.4 & \text{if } h \leq 0.2 \text{ m} \\
1.6 - h & \text{if } 0.2 \text{ m} < h \leq 0.5 \text{ m} \\
1.3 - 0.4 \cdot h & \text{if } 0.5 \text{ m} < h \leq 1.0 \text{ m} \\
0.9 & \text{if } 1.0 \text{ m} < h
\end{cases}
\]

(23)

5.4 Crack control
The risk of wide cracks is highest in areas above the piles since they are devoted to negative moment. In order to limit the crack width either SFRC with high residual strength factor or additional reinforcement in this area has to be selected. Recommended values dependent on crack width class are given in Table 5.

6 OVERLAYS
6.1 Degree of bond
Bonded concrete overlays constitute a versatile repair alternative for concrete bridge decks, concrete pavements, and industrial concrete floors. In most cases, bond between substrate and overlay is desired in order to provide monolithic action to restore or increase load-carrying capacity and stiffness. Good bond is also beneficial for crack control since it contributes to crack distribution if the vertical cracks develop through the overlay due to differential shrinkage, differential thermal movements, or mechanical loading.

Decisive for the design is the bond between substrate and overlay. We may discern between the following four cases (Fig. 4):

I. Complete bond between substrate and overlay.
II. Deficient or uncertain bond between substrate and overlay. Local debonding zones may exist.
III. Full slip, but still movement friction, between substrate and overlay.
IV. Presence of an intermediate interface layer providing stress-free movement between substrate and overlay.

6.2 Crack control
SFRC is in many overlay cases a superior alternative to conventional reinforcement. The characteristics, expressed as residual strength factor \( R \), of the SFRC is dependent on the bond degree (Table 6).

In the case of complete bond, the crack width may be estimated by the following equation:

\[
w = (1 - R_1 / 100) \cdot n \cdot h_1 \cdot \varepsilon_{cs} < w_{max}
\]

(24)

where, \( n \cdot h_1 = \) average crack spacing, \( h_1 = \) overlay thickness, and \( w_{max} = \) maximum acceptable crack width. The value of \( n \) is in the range of \( 1 \leq n \leq 3 \) (Laurence et al., 2000), \( n = 3 \) may conservatively be selected as default value. If,
Table 6. Design of SFRC for concrete overlays.

<table>
<thead>
<tr>
<th>Bond degree</th>
<th>Description</th>
<th>SFRC characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Complete bond</td>
<td>$R_1 &gt; 70%$ or $w &lt; w_{\text{max}}$ according to Eq. 24</td>
</tr>
<tr>
<td>II</td>
<td>Uncertain bond</td>
<td>$R_1 &gt; 85%$</td>
</tr>
<tr>
<td>III</td>
<td>Full slip but friction</td>
<td>$R_1 &gt; 70%$</td>
</tr>
<tr>
<td>IV</td>
<td>Interlayer</td>
<td>Conventional reinforcement or specific investigation.</td>
</tr>
</tbody>
</table>

e.g., $\varepsilon_{cs} = 0.8 \text{ mm/m}$, $h_1 = 0.10 \text{ m}$, and the maximum allowable crack width is $w_{\text{max}} = 0.1 \text{ mm}$, a SFRC mix with $R_1 = 60\%$ will fulfil the demands ($w = 0.40 \times 3 \times 0.10 \times 0.8 = 0.096 \text{ mm} < w_{\text{max}} = 0.1 \text{ mm}$).

7 CONCLUDING REMARKS

SFRC has an ability to increase the productivity and the working environment in the construction sector. Today, the use is mostly limited to underground shotcrete structures and industrial concrete floors. The Swedish Concrete Association has worked with SFRC since the mid 1990s. This paper summarises its recommendations. By applying them, the use may be increased without jeopardizing safety. Especially the recommendations for pile-supported slabs and bonded concrete overlays are innovative. The paper also covers a comparison between the Swedish and the EN test methods to determine material strength properties of SFRC. The conclusion is that the Swedish 4PB method has more advantages, but proposed transformations between the output parameters in the two test methods will enable the user (client, designer, or researcher) to make the choice.

REFERENCES

Bissonnette