AN INNOVATIVE APPROACH TO THE DESIGN OF PILE SUPPORTED SFRC SLABS

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Abstract
Pile supported concrete slabs, have until recently, and in most cases, been made as heavily reinforced concrete slabs with increased shear and flexural capacity in a square around the pile. The shear reinforcement has primarily been stirrups or additional flexural reinforcement (bars or welded fabrics). The normal ways of calculating the need of reinforcement are to divide the slab into strips and obtain moment equilibration or to use yield line theory. Another way of constructing these suspended pile supported slabs is to exchange part of the main reinforcement with steel fibres. The latter reinforcement solution has now been used for floors in several major building projects totalling hundred thousands of square meters. To add extra economical advantage, the system may be designed as solely a steel fibre reinforced concrete (SFRC) slab. In fact, it is possible to design such floors using ordinary yield line theory. The SFRC slab will result in an attractive floor solution when the pile distance is moderate. A thicker floor is needed in cases where the loads or the pile distance increase. One way of reducing the slab thickness is to consider the arch action, a built-in resistance of the floor to carry loads through horizontal restraints.

1. Introduction

Floor slabs, in foundations, are mainly sorted into two categories, concrete slabs on grade or pile supported concrete slabs. This article refers to the latter category of slabs. In Sweden, pile supported steel fibre reinforced concrete slabs have been used, with good results, in such different areas as car reassembling factories (new Saab 9-3), storage and office floors to two major Swedish car manufacturers, and floors to a world leading pharmaceutical industry with laboratories. At the Tumba wholesale trade company in Stockholm, frequent truck driving stands for the lion’s share of the floor usage, making the floor flatness especially important. The system has an economical disadvantage compared to traditionally reinforced concrete slabs due to slightly higher or
equal material costs. This cost difference is, however, compensated in the production phase and the final use of the floor. The reason is that the reinforcement work is decreased dramatically and the over-all quality is often increased [1]. Also the maintenance cost is reduced as the quality increases. The production rate is about 1000 m² floor per production day and in some cases more. To add further economical advantage the system may be designed as an only steel fibre reinforced concrete (SFRC) slab without any traditional shear or flexural reinforcement. In fact, it is possible to design such floors using ordinary yield line theory, if also considering increased shear and punching capacity of SFRC. The design of the SFRC slab will, however, lead to a thick floor in cases where the loads or the pile distance increase. The SFRC slab will therefore result in an attractive floor solution only when the pile distance is moderate and the loads are limited. One way of reducing the slab thickness is to consider the arch action, a built-in resistance of the floor to carry loads through horizontal restraints. In the previous system, it is obvious that the steel cages constituted by the traditional reinforcement inside the square makes a frame around each panel (inscribed by four piles) and thereby a surrounding and supporting frame. On the other hand, a pile-supported floor consisting of hundreds of square panels makes the slab surrounded by an “infinite support” against each arch action, except at the panels forming the edge field of the slab. A recent Ph.D. dissertation at the Royal Institute of Technology has investigated the arch effect, Nilsson [2]. The investigation indicates that the arch effect may have a large influence on the load carrying capacity of steel fibre reinforced shotcrete linings. Probably, this result can be used also for suspended pile supported SFRC slabs. This hypothesis may explain why the constructed Swedish SFRC floors have no visible or developed yields cracks and are of excellent quality even though the ultimate strength should have been overridden in some cases. One question is if the arch action also influences the structural behaviour in the serviceability limit state providing possibilities for increasing loads or decreasing thickness. However the results from Nilsson [2] relates to the ultimate strength capacity of concrete linings with regard to arch action. This paper shows how it can be transferred to pile supported slabs.

2. New floor laying techniques

The development of new floor laying techniques has been driven in the recent years by the damages that often tend to occur. The clients want floors with no faults. New machines and laying methods have given space for large monolith casting techniques. In Sweden a number of production and custom fitted SFRC piled floors have been constructed in the past three years. The first author has designed the floors summarized in Table 1 which may be used as reference floors to the method in section 3. Piled slabs are produced with less fabric reinforcement compared to traditional techniques when SFRC are combined with traditional reinforcement. The laser-screed machines together with concrete dumpers make the construction of the floor more industrialised and help the contractor to produce super-flat and large panels at the same time. The square slab pouring technique with dilatation joints as the only joint-system leave the floor only to take actions from the service loads, if dilated at moderate lengths of 20-45 m.
Table 1: Cases where the combined reinforcement system has been used in Sweden.

<table>
<thead>
<tr>
<th>Case</th>
<th>Year</th>
<th>Area (m²)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ARP, Arendal, Göteborg.</td>
<td>2001</td>
<td>600</td>
<td>Loads 15 kN/m² and 30 kN, ( pd = 4 ) m, ( t = 260 ) mm, K35, 35 kg/m³ Dramix RC-65/60-BN.</td>
</tr>
<tr>
<td>EXEL/SAAB, Hedeng, Trollhättan.</td>
<td>2001/02</td>
<td>28.600</td>
<td>Loads 50 kN/m² and 105 kN, ( pd = 3 ) m, ( t = 300 ) mm, K35, 35 kg/m³ Dramix RC-65/60-BN.</td>
</tr>
<tr>
<td>AHLSELL, Hallsberg.</td>
<td>2002</td>
<td>10.000</td>
<td>Loads 15.3 kN/m² and 60 kN, ( pd = 3.5 ) m, ( t = 240 ) mm, K35, 35 kg/m³ Dramix RC-65/60-BN.</td>
</tr>
<tr>
<td>BILTEMA, Jönköping.</td>
<td>2001</td>
<td>8000</td>
<td>Loads 4 kN/m² and 15 kN, ( pd = 5.7 ) m, ( t = 240 ) mm, K35, 35 kg/m³ Dramix RC-65/60-BN.</td>
</tr>
<tr>
<td>WHOLE SALE TRADE, Botkyrka.</td>
<td>2002</td>
<td>28.600</td>
<td>Loads 20 kN/m² and 30 kN, ( pd = 5.1 ) m, ( t = 275 ) mm, K35, 35 kg/m³ Dramix RC-65/60-BN.</td>
</tr>
<tr>
<td>SILVAN, Örebro.</td>
<td>2002</td>
<td>3.300</td>
<td>Loads 30 kN/m² and 50 kN, ( pd = 3.7 ) m, ( t = 250 ) mm, K35, 35 kg/m³ Dramix RC-65/60-BN.</td>
</tr>
<tr>
<td>NORDIC HUB, Malmö.</td>
<td>2002</td>
<td>5.000</td>
<td>Loads 4 kN/m² and 10 kN, ( pd = 5.5 ) m, ( t = 210 ) mm, K35, 35 kg/m³ Dramix RC-65/60-BN.</td>
</tr>
<tr>
<td>PLD NORDIC, Nykvarn.</td>
<td>2002</td>
<td>6.000</td>
<td>Loads 15 kN/m² and 30 kN, ( pd = 4.8 ) m, ( t = 250 ) mm, K35, 35 kg/m³ Dramix RC-65/60-BN.</td>
</tr>
<tr>
<td>ASTRA NEXIUM IV, Gärtuna.</td>
<td>2002</td>
<td>8.000</td>
<td>Loads 13-140 kN/m² and 250 kN, ( pd = 6.0 ) m, ( t = 400 ) mm, K35, 35 kg/m³ Dramix RC-65/60-BN.</td>
</tr>
<tr>
<td>ICA MAXI, Haninge.</td>
<td>2003</td>
<td>3.000</td>
<td>Loads 7 kN/m² and 30 kN, ( pd = 4.0 ) m, ( t = 215 ) mm, K35, 35 kg/m³ Dramix RC-65/60-BN.</td>
</tr>
<tr>
<td>NORDBY SHOPPING CENTRE, Nordby.</td>
<td>2003</td>
<td>25.000</td>
<td>Loads 7.5 kN/m² and 30 kN, ( pd = 4.0 ) m, ( t = 210 ) mm, K35, 35 kg/m³ Dramix RC-65/60-BN.</td>
</tr>
<tr>
<td>HORNBACH, Göteborg.</td>
<td>2003</td>
<td>18.000</td>
<td>Loads 30 kN/m² and 75 kN, ( pd = 4.42 ) m, ( t = 255 ) mm, K35, 35 kg/m³ Dramix RC-65/60-BN.</td>
</tr>
<tr>
<td>BAUHAUS, Göteborg.</td>
<td>2003</td>
<td>10.500</td>
<td>Loads 6 kN/m² and 47 kN, ( pd = 3.5 ) m, ( t = 200 ) mm, K35, 35 kg/m³ Dramix RC-65/60-BN.</td>
</tr>
<tr>
<td>BULTEN, Kungälv.</td>
<td>2003</td>
<td>5000</td>
<td>Loads 30 kN/m² and 30 kN, ( pd = 3.8 ) m, ( t = 200 ) mm, K35, 35 kg/m³ Dramix RC-65/60-BN.</td>
</tr>
<tr>
<td>BAUHAUS, Västerås.</td>
<td>2003</td>
<td>10.500</td>
<td>Loads 12 kN/m² and 30 kN, ( pd = 3.5 ) m, ( t = 250 ) mm, K35, 35 kg/m³ Dramix RC-65/60-BN.</td>
</tr>
</tbody>
</table>

\( pd \) = pile distance, \( t \) = concrete thickness, K = compressive cube strength grade.

3. Combined reinforcement in slabs on piles

When designing a regular suspended slab a great deal of reinforcement bars will be enclosed in the structural system. The c-square (inside the area of negative moment) around the pile head will be jam-packed by reinforcement bars. The rest of the slab will also have a lot of reinforcement (around 60 kg/m³ if optimised). This will make the concrete set under the bars as the pour and compaction of concrete often are problematic, especially when double reinforcement and stirrups are needed. Less fabric steel will give an easier way of construction. The combined system of SFRC and reinforcement bars, reduces the problems significantly, see the principle Figure 1. The slab is calculated according to the yield line theory with help of the virtual work principle. Material factors and flexural strengths are used according to the Swedish Concrete Association [3].
The design follows the regulations in *BKR* [4] and *BBK* [5]. The method has proved to compete and give trustworthy designs in the construction of pile supported suspended slabs used in several realized projects, see Table 1.

![Diagram of a combined steel and steel fibre reinforced concrete slab on piles.](image1)

**Fig. 1** – The principle of a combined steel and steel fibre reinforced concrete slab on piles.

**4. Fibre only reinforced slabs on piles**

A fibre only reinforced floor system, (Fig. 2), is investigated concerning moment and shear.

![Diagram of a solely fibre reinforced slab on piles.](image2)

**Fig. 2** – The principle of solely fibre reinforced slab on piles.

The yield line models are the same as those used by *Nilsson* [2] and is in turn based on *Kinnunen & Nylander* [6] given in the *Swedish Concrete Handbook* [7]. The circular failure pattern, yield line type A, is here described as one quarter of the total yield line. Alternatively, a straight yield line, type B, may occur, in the line of piles and parallel to that line in the middle of the panels. Both models are described in Table 2. At the slab corner, any redistribution of forces is impossible and the failure is therefore regarded as elastic, which gives the same moment $M_d (3)$ as in the mid span of a simply supported beam, where $q_d =$ design value of distributed loads, $l_{pd} =$ design value of pile distance.
Table 2: Yield line models used in mid panels of concrete slab. The type A model is a cut out modified to the four piles illustrated. The theories are according to Nylander & Kinnunen [6].

<table>
<thead>
<tr>
<th>YIELD LINE TYPE A</th>
<th>YIELD LINE TYPE B</th>
</tr>
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<tbody>
<tr>
<td>![Diagram A]</td>
<td>![Diagram B]</td>
</tr>
</tbody>
</table>

\[
M_d = q_d \frac{l_{pd}^2}{4\pi} = \frac{P_{ul} t}{4\pi} \quad (1)
\]

\[
M_d = q_d \frac{l_{pd}^2}{16} = \frac{P_{ul} t}{16} \quad (2)
\]

\[
M_d = q_d \frac{l_{pd}^2}{8} \quad (3)
\]

At the slab edge, the plastic field moment will be the largest moment in the slab if the pile distance is the same all over the slab. This is not a good solution; however, if the pile distances are reduced (\(l_{red}\)) at the edges to two thirds of the interior panel pile distance, the field moments in edge panels approximately decrease to the magnitude of the yield moments of type A in the interior slab panels. The panels will then have same thickness all over the slab, which simplifies the design when the need of strength in the slab is constant. Equation 4 then achieves this edge moment.

\[
M_d \approx q_d \frac{l_{red}^2}{12} \quad l_{red} = \frac{2}{3} l_{pd} \quad (4)
\]
Design for shear

The shear strength is calculated with the formula given in the Swedish Concrete Association’s guidelines, \[3\], setting the percent of reinforcement to zero. The formal shear strength \( f_{v1} \) is given by Equation 5, where \( \xi \) = crack risk factor, \( f_{ct} \) = pure tensile strength of concrete.

\[
f_{v1} = \xi 0.45 f_{ct}
\]  
(5)

The ultimate shear strength of the section is the eccentricity \( \eta \) factor times the control perimeter \( u_1 \) of the yield cone and the formal shear strength \( f_{v1} \) from Equation 5.

\[
V_u = \eta \cdot u_1 \cdot f_{v1}, \quad \eta = \frac{1}{1 + \frac{2|\epsilon|}{b \cdot d}}, \quad u_1 = \pi(2r + d_{eff})
\]  
(6)

In Equation 6 the effective thickness \( d_{eff} \) equals the slab thickness \( h_{slab} \), as the slab is only reinforced with steel fibres, \( e = \) eccentricity, \( b = \) strip width (here the control perimeter). According to the Swedish Concrete Association, the shear capacity is given by summing the contributions from concrete and fibres in Equation 7.

\[
V_{tot} = V_u + V_f = (f_{v1} + f_{v\text{fibre}}) \cdot bd = \\
\xi \cdot 0.45 \cdot f_{ct} + 0.41 \cdot \tau_f \cdot F_f \cdot bd
\]  
(7)

Above the size effect factor \( \xi \) is involved and it is normally given by

\[
\xi = 1.6 - d \quad 0.2 \text{ m} < d \leq 0.5 \text{ m}
\]  
(8)

where \( d = h_{slab} \) is the thickness of the slab according to previous statement.

When having all needed information on the floor we can make a calculation of some significant parameters regarding the final design. The moment and shear capacities for a light duty industrial floor, where the uniformly distributed characteristic loads are for instance \( G_k = 5 \text{ kN/m}^2 \) and \( Q_k = 10 \text{ kN/m}^2 \), and the design load is \( q_d = 1.0 \times 5 + 1.3 \times 10 = 18 \text{ kN/m}^2 \), are calculated for an increasing pile distance. The results are graphed in Figures 3 and 4 for a SFRC slab at fibre dosages \( A = 30 \text{ kg/m}^3 \), \( B = 40 \text{ kN/m}^3 \) and \( C = 50 \text{ kN/m}^3 \). Figures 3 and 4 show a possibility to construct floors, with pile distance 2.4 m with 30 kg/m³ and 2.9 m when the fibre content is 50 kg/m³, with no moment or shear failure. Design values are used for a C30/35 concrete with thickness 250 mm.
Fig. 3 – Moment capacities and moments $M_e$ for edge, $M_c$ for corner, $M_{m}$ for straight yield lines (type B), $M_p$ for support (type A) v/s pile distance for a solely steel fibre reinforced concrete slab on piles.

Fig. 4 – Shear capacity and design shear load, $V_d$ v/s pile distance for a solely steel fibre reinforced concrete slab on piles.
5. Arch effect in slabs

Compressive arch action, as described by Nilsson [2], which is in turn briefly described in this section is based on the work of Birke [8].

A piled slab, which will go to failure in either type A or type B, described in the previous section, is considered. In ultimate limit state, the cracked slab will have a residual strength, if reinforced with steel fibres, which hold the slab together as a chain of bricks (compare with block pavements). The vertical point load $P$ that is acting on the slab, may still loading the slab after cracking and results in a horizontal reaction $H$ in the support. The interlocking may lead to increased load capacity, if the supports are capable to resist the outward pressure from the slab, compare with Figure 5.

![Fig. 5 – A beam or slab is interlocked by the compressive reactions from the fixed supports. Only rotation of the supported ends is allowed, in the above force-reaction model.](image)

As long as the difference in height between the reaction forces, at the distribution points at edges, and the load point is positive the slab will have an increasing load bearing capacity. The angular rotation of the slab increases the horizontal pressure at the distribution points, but also makes the tensile stresses larger in the slab. However, when the difference in height vanishes, as the slab deforms, the slab will come nearer to the maximum capacity and the turning point. It happens when the two pressure shafts bypass the line parallel to the edge points.

At the negative moment in top at support and at the positive moment at bottom of the slab middle field the slab will crack and therefore has need of a residual material strength to be able to take loads from other panels. The crack opening may be controlled by residual strength to some extent. The residual strength is not of significant importance on the maximum load bearing capacity but is an important factor to obtain structural stability in the slab in ultimate and serviceability limit state. Because of the large capacity, due to arch action, the moment capacity contributed by the residual strength becomes negligible, as the slab ends rotates. An approach for ultimate limit state design, that considers the crack opening, must however involve the residual strength and the crack width of an increased and rotational opening of crack mouth. The maximum load bearing capacity contributed by arch action is not derived within the article, for the equations behind the graphs in Figure 6 and Figure 7 I refer to Nilsson [2]. At 4 m the slab will fail in shear but the ultimate load capacity from arch effect according to Figure 6 is more than twice the design value from the yield line design. The continuous slab
will have twice as large reactions, as a slab with fixed ends, if the loads are evenly distributed over the slab.

Fig. 6 – The type A failure capacities using yield line theory and arch action of an inner field slab part with thickness $t = 250$ mm at fibre dosage = 35 kg/m$^3$, of Dramix RC-65/60-BN, and concrete C30/35.

Fig. 7 – The type B failure capacities using yield line theory and arch action of an inner field slab part with thickness $t = 250$ mm at fibre dosage = 35 kg/m$^3$, of Dramix RC-65/60-BN, and concrete C30/35.
6. Concluding remarks

Speeding up the construction phase it is of great interest for all involved participants in a building process. Reducing reinforcement work is of special interest. Using steel fibre only could make that possible, and reducing the costs significantly in addition. However, this is not a reality yet. For most cases the pile distances are between 4 and 6 m according to Table 1. The article shows that only small pile distances and loads could be used when making a traditional calculation with yield line theory for a piled slab with steel fibre only. However, the results in section 5 indicate that a pile-supported slab could take loads even if large cracks have developed. Probably the slab will have large deflections but this may not be decisive in all cases. More research on the use of arch action, and its significance in serviceability limit states is needed.

References


