THE SUSPENDED FOUNDATION SLAB OF THE *SWEDBANK ARENA* IN STOCKHOLM (SWEDEN) : 16,000 m^3 (21,000 cu yd) OF STEEL FIBER REINFORCED CONCRETE

Xavier Destrée, Consultant, Structural Engineer, ArcelorMittal, Luxembourg.
Hans Oscarsson, Project Manager, Swerock AB, Sweden.
Mats Pettersson, Sales manager, ArcelorMittal Scandinavia.

SYNOPSIS

Steel fibre-only structural reinforcement at a rate of 40-50kg/m³(66-82lb/cu yd) has been used as the sole method of reinforcement of heavily loaded suspended slabs cast on the ground on the one hand and foundation slabs supported by a grid of piles on the other hand. Typical applications include warehouses, factories, office and condominium buildings, towers and, as shown in this paper, sport arenas. The span to depth ratio is between 8 to 22. The 60,000 seating capacity Swedbank Arena in Solna (Stockholm, Sweden) is a project located on a site which does not show any available ground bearing capacity so that the site has been piled completely prior to installing the foundation slab. The pile grid lies between 3m (20ft) and 7m (25ft) distance and the slab's thicknesses equal 300mm(12in) and 350mm(14in). The suspended foundation slab consists of 16,000cu.m(20,700cu yd). worth of steel fiber reinforced concrete, the total area being 50,000m²(550,000sq.ft): the grass area for the soccer game or as exhibition and concert hall, the technical rooms, and the external parking area, respectively highlighted in green, pink and orange in Fig.3.

1. INTRODUCTION

The Swedbank Arena, as shown in Fig.1, will become in 2012 Europe's most modern football stadium and shall host the largest sporting events in Scandinavia. The section view of the arena in Fig. 2 shows the piled slab under the grass area in green as well as the technical rooms. During events such as concerts, artists from around the world will perform in front of 65,000 spectators. Because the surface of the pitch can be changed quickly from grass to ice to gravel, large sports events and high audience shows will take place in the Swedbank Arena.

The highest level of comfort for all is guaranteed by a retractable roof, wide seats, an outstanding visibility, and large screens together with cutting edge sound and scene facilities.
Security is such that, at full capacity, the stadium can be evacuated in 6 minutes time.
Swerock AB has been awarded the building contract to complete the arena in less than two years, which is a tight schedule to meet regardless of the severe winter conditions prevailing generally over the Stockholm region.

The steel fiber reinforced concrete (SFRC) suspended foundation slab offered significant advantages in terms of cost savings and shorter schedule when compared to traditional rebar reinforcing. The same advantages were also decisive parameters for the ground suspended slab of the Bolton arena, (Cheshire, UK) built in 2001 to host the Commonwealth Games that took place in 2002.
Thanks to the use of steel fibers instead of reinforcing bars in the ground suspended slab, almost 2500 metric tons of steel (5500kip) have been saved together with 42,000 labor hours worth of cutting, bending and placing traditional steel, without mentioning in detail how much crane and concrete pump time have been saved also.

An overall view of the foundation slab is shown in Fig. 2. The general pile lay-out is shown in Fig.3 where the grass area, the technical rooms, the external parking area and a long culvert cover are enlighted in green, pink, orange and yellow. The piles are made of prefabricated prestressed concrete and are hammered down to 20m (66ft) depth at a rate of up to 50 pieces per day, per machine used.

2. FOUNDATION SLAB

The slab is mainly divided in four areas where the pile grid and loading conditions vary. Each pile has a traditional pile head made of reinforced concrete of 1.15m (3ft10in) by 1.10m (3ft8in) size and 500mm (1ft8in) thickness. The four different areas are as follows:
- The grass area is above a pile grid underneath of 3m (10ft) by 3m (10ft).
The most onerous loading case is a 600kN (132kip) unfactored live load imposed onto each center of square of the grid or a uniformly distributed loading of 40kN/m² (800psf).
The slab of 120m (400ft) x 80m (265ft) size is 350mm (13 3/4 in) thick and is reinforced by 45kg/m³ (75lbs/cu.yd³) ARCELORMITTAL HE+1/60 steelfibers.
HE+1/60 are loose steel fibers of 1mm steelwire diameter, 60mm (2in1/2) long with hooked ends and of 1475N/mm² (210ksi) tensile strength. Steel fibers were added into the concrete at the batching plant.
The C40-50 (f'_c=5700psi) mix design of the whole slab in the four different areas includes 425kg/m³(721lbd/cu.yd) of Type I Cement for all external areas and Type II for the grass area and all technical areas. A mix design of 0-16mm(0-2/3 inch) continuous aggregate grading together with W/C<0.45 has been defined in order to ensure a high durability and freezing-thawing cycles resistance.
The passings at 250, 500 and 1000 µm (1/100in, 1/50in and 1/25in) sieve are respectively 10%, 20% and 30%.
A high range water reducer has been used as the flowing concrete was not poker vibrated during its installation.
All the steel fiber reinforced concrete mixes were of XF4 type (EN206 standard) and have been perfectly workable and suitable under all pumping conditions.
The grass area has been divided into 6 equal jointless pours of 40m (131ft) x 42m (138ft).

-The technical rooms have a variable pile grid in size with a maximum of 5.20m (17.3ft) x 5.20m (17.3ft) and the slab is 300mm (12in) thick.
The dosage rate is 50kg/m³(83lbs/cu.yd) of HE+1/60 steel fibers.
The most onerous loading conditions are a uniformly distributed loading of 10kN/m² (200psf). In some areas, electrical ducts embedded in a concrete channel with a self-weight of 62.5kN/m (4.2kip/ft) hang underneath the slab so that local top and bottom rebars are also included between the adjacent piles.
Other areas by the technical rooms are only lightly loaded by uniformly distributed loading of 5kN/m²(100psf) so that the pile grid is extended up to 7.40m (24.66ft) x 7.22m (23.66ft).The slab thickness and the dosage rate of steel fibers remain respectively 300mm (12in) and 50kg/m³(83lbs/cu.yd).
The slab is in numerous locations locked to various foundation pads and ground beams so that both free shrinkage and thermal contraction movement cannot take place.
Although additional top rebars 16mm (0.63in) diameter and at 200mm (8in) spacing are included around and along the hard spots in order to control cracking, cracks are expected to develop in these locations.

-The external area, indeed a parking area, is above a pile grid of 3.82m (12.5ft) x 3.82m(12.5ft) and its slab is of 300mm (12in) thickness with 45kg/m³ (75lbs/cu.yd) dosage rate of HE+1/60. The slab is subjected to a 310kN (68kip) truck axle dynamic loading.

- A culvert area, enlighted in yellow in Fig.3, where the 300mm (12in) thickness of steel fiber reinforced concrete at 45kg/m³(75lbs/cu/yd) HE+1/60 dosage rate has been installed above concrete planks spanning 3.00m (10ft). A layer of 16mm (0.63in) diameter bottom rebars by 200mm (8in) spacing has been included. The culvert is subjected to a truck axle loading of 350kN (77kip).

3. DESIGN

As an example, a typical design of the slab in the grass area is given in this section.
The slab is 350mm (13.77in) thick. The ultimate case is checked when a point load
P = 600kN (132kip) is being imposed.
The verification of the design is accomplished by using Johansen 's yield line model shown in reference 1, p.24 and p.47, where one single span can show, in the worst and most onerous case, three parallel yield lines near the columns with M_L negative and at mid span, where M_L is positive.
Near to the columns, the negative yield lines are located at a distance equal to half the depth of the slab from the external face of the column or pile heads as shown in Fig.4.

A one-way yield line pattern, as shown in Fig.4, is selected as it provides the lowest estimate of the ultimate point loading intensity.

The net span L_{rs} as defined in reference 6, is the distance between the parallel yield lines and L is the length between centroids of piles:

L = 3.0m (10ft)

L_{rs} = L - 1.10m - 0.35m = 1.55m (5ft2in), where 1.10m (3ft8in) is the size of the pile head.

The plastic resisting moment of the section M_L is calculated starting from f_{tu}, the plastic tensile strength derived from round indeterminate simply supported slab tests as shown in Fig. 5 and showing a fan pattern of yield lines as outlined in references 2, 3 and 4 as shown in Fig. 6 where:

$$M_L = P_{ult} / 2\pi \qquad (1)$$

$$M_L = f_{tu} * 0.45 * h^2 \text{ where } f_{tu} = 2.25 \text{N/mm}^2 \text{ (328psi)} \qquad (2)$$

in case of 45kg/m³(73lbs/yd³) dosage rate of HE+1/60 and h = 350mm(13.78in), when one assumes a rectangular stress block in compression over 10% of the cross sectional depth and a rectangle tensile stress block of f_{tu} stress intensity distributed over the remaining 90% of the cross sectional depth.

Hence,

M_L = 124,80 kNm/m(27kip.ft/ft).

The material factor for steel fiber reinforced concrete is taken equal to 1.5 and the loading factors for its own weight and live loads are respectively 1.35 and 1.5, as in the Eurocode.
The equilibrium equation where γ_c is the volumic weight of concrete is as follows and is verified:

$$(1.5 \text{ x } P \text{ x } L_{rs})/(8 \text{ x } L) + (1.35 \text{ x } \gamma_c \text{ x } h \text{ x } L_{rs}^2 / 16) < M_L / 1.5 \qquad (3)$$

$$(1.5 \text{ x } 600 \text{ x } 1.55)/(8 \text{ x } 3.00) + (1.35 \text{ x } 24 \text{ x } 0.35 \text{ x} 1.55^2)/16 < 124.80/1.5$$

58.125 + 1.70 = 59.83 < 83.2 kNm/m or,
12.95 < 0.018 kipft/ft

Such analysis means that a lowest estimate of a center point loading ultimate intensity is of 1900kN(418kip) resulting from 600kN x 1.50 x 1.50 x 83/59 where 1.5 are material and loading factors, and can be compared to the full scale testing results of Ternat (1994) and Townsville (2001) as reported in reference 5 and where both slabs of 160mm thickness (6.5in) and 3.10m (10ft4in) span resisted 450kN(99kip).

A comparison is quickly made as follows to predict a possible experimental ultimate loading of the grass area:

$450kN \times (3.1/3.00)^2 \times (350/160)^2 = 5.11 \times 450kN = 3000kN(660kip)$

When assuming no size effect, the real global safety factor of the slab can be determined and is equal to 3000kN/600kN = 5.

In the service condition, it is needed to verify that the flexural stress in the slab does not exceed at least 4.5N/mm² (640psi) so that no flexural cracking can develop under the most onerous service loading conditions.

Therefore rapid experimental design formula(5),(6) were used and have been developed and derived from the full scale tests in references 2 ,3 ,4 and 5 when the span to depth ratio does not exceed 20.
The formula gives an estimate of the flexural stress under the most onerous loading condition in service:

$$\sigma_c = 12 \times P \times (L_{rs}/L)^2 / (n \times h^2) \tag{4}$$

$$n = \{(1 + 0.85 \times \log (h/0.18)\} \times (11.57 - 1.21 \times L_{rs}) = 12.07 \tag{5}$$

Hence, σ_c = 1.299MN/m² (185psi) < 4.5MN/m² (640psi) and thus a first cracking loading intensity of 600kN x 4.5/1.299 = 2078 kN (458kip) is found. Indeed in reality 5500kN(1211kip) cranes have been operated on the slab and no cracks were observed.

The suspended slab resistance exceeds the capacity of the deep foundations. In case of an uniformly distributed loading p, the expression of σ_c becomes as follows:

$$\sigma_c = 6 \times p \times (L_{rs}/L)^2 / (n \times h^2) \tag{6}$$

The rapid method here does not replace a complete finite element analysis but indeed has been proved very safe for the last 14 years of practical applications including 200 million square feet worth of SFRC ground suspended slabs.

From the full scale tests results in references 2, 4 and 5 when the span to depth ratio does not exceed 20, it is observed that the punching-out failure mode is never critical and thus punching strength is not discussed here.

4. APPLICATION.

The steel fiber reinforced concrete has been pumped in all areas and a 50m (55yd) boom pump was used. The grass area concrete has been installed with laser screeder machines as shown in figure 7.
All other areas have been installed by hand with straight edges, bull floats and power trowelling.
The surface tolerance is of 5mm (0.2in) gap underneath the 2m (6ft8in) long straight edge.
Construction joints are of the Tera-joint type as shown in figure 8 and worked really well.

5. CONCLUSIONS

While both design and installation of the steel fiber reinforced concrete has been going on already during several months, one can observe that is completely trouble free. Indeed, very few shrinkage cracks have appeared despite all installation happening in the open air and despite the fact that in many locations the slab has been tied to ground beams and foundations pads where some form of cracking is inevitable and was thus expected.
The grass area slabs were subjected to high intensity of 5500kN (1211kip) crane loadings, but no flexion stress crack developed.
Although the Swedbank Arena project is far from being the first very large successful structural foundation slab involving ArcelorMittal steel fibers, it is another practical demonstration that steel fiber reinforcing is a proven, viable and highly competitive alternative solution against traditional rebar reinforced concrete.
The Swedbank Arena foundation slab is a typical example of a reinforced ready mixed concrete application.

6. REFERENCES

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[3] Structural Application of Steel Fibers as principal reinforcing : conditions –

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[6] Traité de Génie Civil, E.P.F.L.Vol.8, Favre, Jacoud, Burdet, Charif. Dimensionnement des structures en béton, Presses Polytechniques Romandes. pp372-376.

Tables and Figures

Fig.1: Aerial view of the Swedbank Arena

Fig.2: a section of the Swedbank Arena

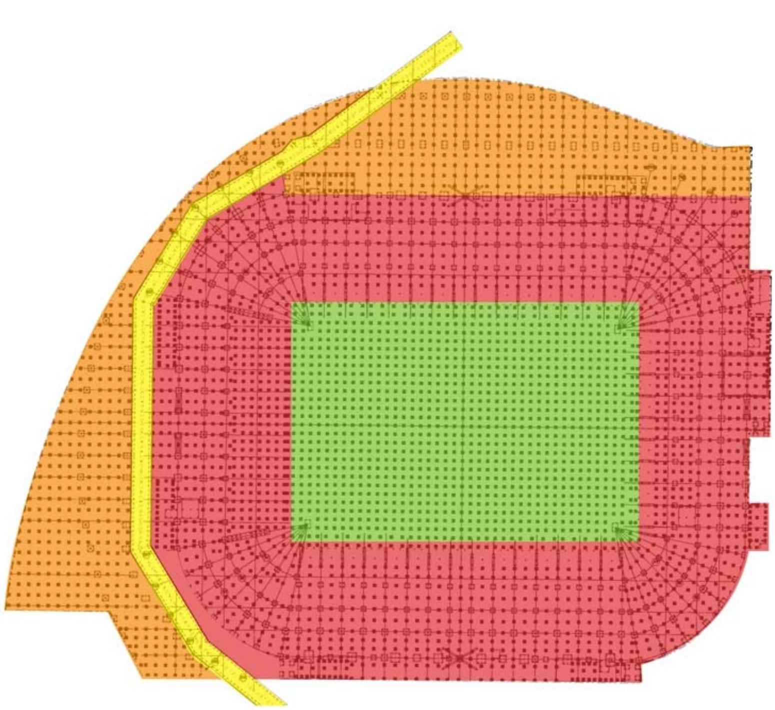

Fig.3 pilelay-out and 3 different slab areas in colours

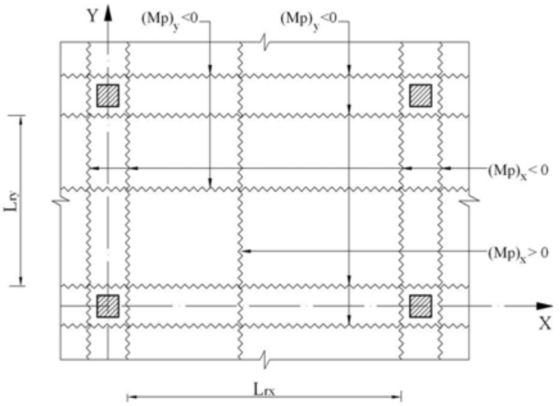

Fig.4 : Typical yield line patterns in one way and two ways.

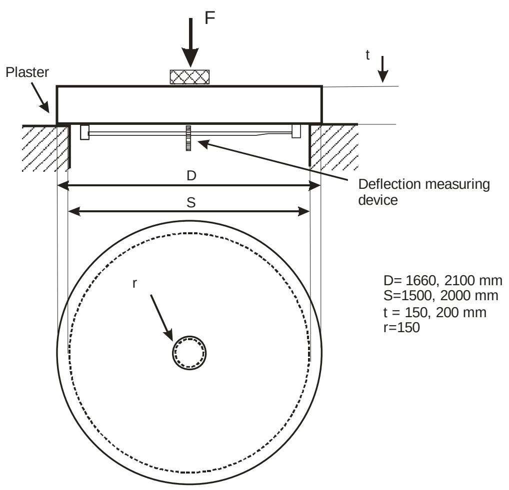

Fig.5: details of a round indeterminated simply supported slab test set-up.

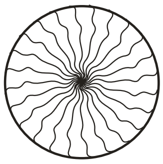

Fig.6: Typical fan pattern of yield lines of a round indeterminated slab.

Fig.7 Laser screeder and hand laying of the slab

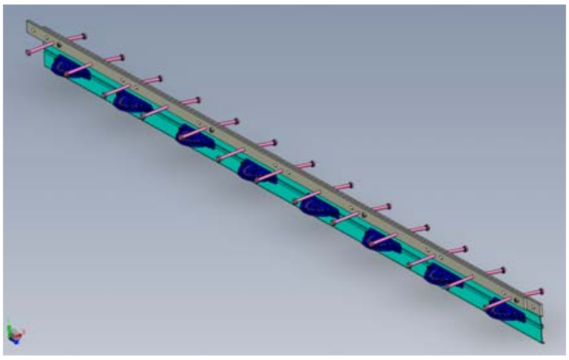

Figure 8 Tera-joint as construction joint