Newsletter no. 2 – SFRC Consortium May 2012

Summary

This second newsletter describes the first demonstration project, a load carrying foundation slab, carried out at Eternitgrunden in Aalborg. It includes the design basis, results from the trial and full scale casting, and subsequent verification of the design basis based on mechanical testing of large beams.

Two designs were prepared, a conventional solution without steel fibers and a combined reinforcement solution (CombiSlab) including both conventional reinforcement and steel fibers. Both were designed to fulfil the maximum crack width requirement of 0.2 mm.

The aim of mechanical testing was to compare the crack pattern of the two solutions under identical load conditions. The results showed that the CombiSlab solution provides similar or enhanced capacity up to crack widths of 0.2 mm.

From an economical and environmental point, the CombiSlab solution compared to the no-fiber solution shows that it is possible to obtain steel and cost savings of approximately 50 % and 25 %, respectively.

Fig. 1: Casting of foundation slab.

First demonstration project – a foundation slab

The first demonstration project was carried out at Eternitgrunden in Aalborg, Denmark. The project involved the casting of a foundation slab for a new rainwater basin. The rainwater basin is part of a large development project where an old industrial area is transformed into a new, modern and well integrated part of the town containing offices, apartments, commercial areas and educational facilities.

A total of 380 m^3 of steel fiber reinforced self-compacting concrete was cast and the entire casting took 12 hours to complete. An overview of the timeline and activities of the demonstration project is given below.

Fall 2010	MT Højgaard was selected as main contractor at Eternitgrunden. The foundation slab for the rainwater basin was in line with the selected applications in the SFRC consortium. Approval was given from the building owner and the authorities to change the design into a combined reinforcement solution.
Jan 2011	To assess potential cost savings, the slab was designed with and without steel fibers by COWI and Bekaert.
Jan-Mar 2011	The SCC mix composition was developed and tested at Unicon in Aalborg and DTI in Taastrup.
6 Apr 2011	Trial castings were carried out at MT Højgaard facilities in Aalborg.
27 Apr 2011	Full scale casting at Eternitgrunden.

Table 1: Timeline and activities.

Design

It was found that the crack width requirement w_{max} = 0.2 mm for cracks resulting from restraint is governing for the reinforcement design.

Crack width limit	: 0.2 mm
Concrete	: C40
f_{ctm} (28 days)	: 3.5 N/mm^2
$f_{ctR,S}$ (28 days)	: 1.5 N/mm^2
$f_{R,1}$ (28 days)	: 4.0 N/mm^2
Thickness / cover	: 400 mm/35 mm

$f_{R,1}$ = the residual (post crack) flexural tensile strength, corresponding to the residual (post crack) axial tensile strength $f_{ctR,S}$ (i.e. if a section can take an axial tensile stress of 1,5 N/mm², it can take a flexural tensile stress of 4,0 N/mm²).

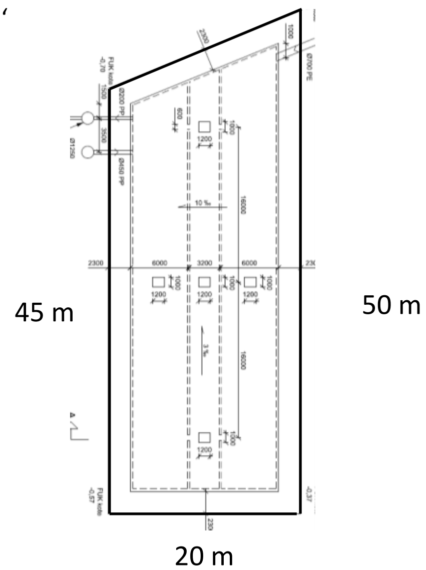


Fig. 2: Dimensions of foundation slab.

Conventional reinforcement solution

The design of the conventional reinforcement solution was based on EN 1992-1-1 ("EC2") with Danish national annex to EC2.

This resulted in a reinforcement solution consisting of Y16 at 100 mm in both directions at top and bottom and stirrups along all edges.

Combined reinforcement solution

The combined reinforcement solution is based on the SLS design approach of EN 1992-1-1 ("EC2"), the German national annex to EC2 and the DAfStb technical rule on steel fibre concrete. Expressing a complex interrelation in simple terms, the latter two documents allow applying the effect of steel fibres on EC2.

$$w_k = s_{r,max} \cdot (\varepsilon_{sm}^f - \varepsilon_{cm}) \qquad \text{eq. 7.8, EC2}$$

For crack width design in particular, the crack design equations for reinforced concrete are amended by the residual post crack strength which is provided by the steel fibres (Table 2).

EC2+NA Germany
(reinforced concrete)

$s_{r,max}$

$(\varepsilon_{sm}^f - \varepsilon_{cm})$

DAfStb
(combined reinforcement)

$s_{r,max} = s_{r,max} \cdot (1 - \alpha_f)$

$(\varepsilon_{sm}^f - \varepsilon_{cm}) = (\varepsilon_{sm}^f - \varepsilon_{cm}) \cdot (1 - \alpha_f)$

Table 2: Crack design equations.

To ensure that for all design situations the same relative concrete age is taken into account for both first crack and post crack strength, the relative value α_f is used instead of $f_{ctr,S}$. α_f is defined as the ratio of the residual uniaxial post crack strength $f_{ctR,S}$ over the uniaxial first crack strength f_{ctm}.

$$\alpha_f = f_{ctR,S} \,/\, f_{ctm}$$

Figure 3 illustrates the stress distribution and forces acting in a reinforced section (left) and a combined reinforced section (right) both prior to and after cracking.

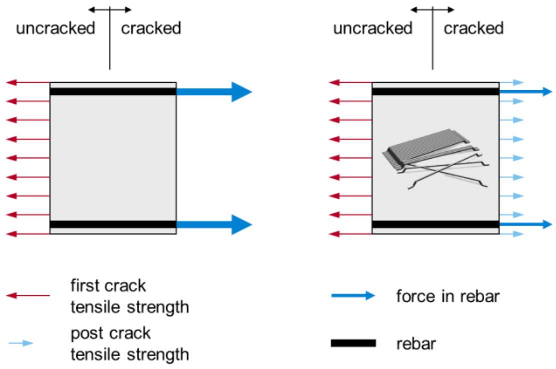


Fig. 3: Stress distribution and forces in a reinforced section (left) and a combined reinforced section (right).

The SLS design for the combined reinforcement was carried out with the Bekaert software "Dramix® Combislab". It is a tool especially developed for SLS design in accordance with the DAfStb technical rule on steel fibre concrete.

In order to align the design assumptions of the original EC2 design with the pre-defined design situations of the Bekaert tool, the combined solution was designed stepwise:

In the first step, a Dramix® Combislab design was carried out for reinforced concrete whereby the effect of fibres was not taken into account. The input parameters were adjusted in such a way that both the results of the original COWI design and the Bekaert design matched. In this way it was assured to finally compare two different solutions on the same basis.

In the second step, the same input parameters have been used for a calculation which took the effect of fibres into account.

The calculations have shown that – for the SLS design - restraint deformations are governing over load induced stresses.

By adding steel fibres, the bar diameter could be reduced significantly while the calculated crack width was kept at 0.2 mm.

In addition, the stirrups along the slab perimeter could be skipped due to the reinforcing effect of the fibres. Thus the reinforcement layout was simplified in addition.

Combined reinforcement solution:

- Y10 at 100 mm in both directions at top and bottom.
- 30 kg/m^3 Dramix® RC-80/60-BN – equivalent to $f_{R1,m}$ = 4.0 N/mm² in C40/50.
- no stirrups

The important material properties f_{ctm} and $f_{R1,m}$ respectively (the input value to $f_{ctR,S}$) have been verified by specific material property testing on the final concrete mix. It was found that both f_{ctm} and $f_{R1,m}$ had been slightly underestimated. A higher f_{ctm} would normally call for an increased amount of reinforcement, no matter if conventional or combined reinforcement. In the case of combined reinforcement, however, the higher concrete tensile strength f_{ctm} was compensated by the also higher value of the post crack strength $f_{R1,m}$ or $f_{ctR,S}$ respectively. Table 3 summarizes the assumed material properties, the requirements and the actual material properties.

assumed	required	actual (QC)	conclusion
[MPa]	[-]	[MPa]	[-]
f_{ctm} = 3.5	$f_{ctm} \geq f_{ctm,QC}$	$f_{ctm,QC}$ = 4.0	not OK[1)]
$f_{R1,k}$ = 2.4	$f_{R1,QC} \geq f_{R1,k}$	$f_{R1,QC}$ = 3.1	OK
$f_{R1,m}$ = 4.0	$f_{R1,m,QC} \geq f_{R1,m}$	$f_{R1,m,QC}$ = 5.2	OK
$f_{ctR,S}$ = 1.5		$f_{ctR,S}$ = 1.7	OK
1) compensated by higher $f_{R1,m,QC}$			

Table 3: Material properties, the requirements and the actual material properties.

Trial casting

The trial casting was carried out 6th April 2011. The purpose of the trial casting was to gain experience with casting of steel fiber reinforced Self-Compacting Concrete (SFRSCC) for this type of application. This was achieved through the casting of a trial slab (10 m^3). Furthermore, it was decided to cast two large beams, one with the traditional reinforcement solution and one with the combined reinforcement solution. The aim of these castings was to obtain full scale specimens to compare the two solutions under controlled loading conditions, in this case four point bending (see Large beam testing).

	Trial slab	Beam 1	Beam 2
Form [m]	5x5x0.4	5x0.9x0.4	5x0.9x0.4
Concrete	SFRSCC	SFRSCC	SCC
Steel fibers RC-80/60 BN	30 kg	30 kg	0 kg
Reinforcement	Y10 per 100 (t/b)	Y10 per 100 (t/b)	Y16 per 100 (t/b)

Table 4: Trial castings.

Fig. 4: Trial castings.

Fig. 5: Trial castings.

Full scale casting

The full scale casting was carried out on 27 April 2011. It was a wind still day with clear sky. The casting lasted from 06:30 to 18:30. 55 truckloads (7 m^3 per batch) of concrete were delivered amounting to a total of 385 m^3 concrete corresponding to a casting rate of 32 m^3/hour. The concrete was delivered from the Unicon factory nearby and typically it was delivered within half an hour after mixing. A GPS was mounted on the pump outlet in order to continuously monitor the pump hose position during the casting. The casting was initiated in one corner and progressed from side to side in the longitudinal direction.

Fig. 6: Full scale casting.

Fig. 7: Full scale casting.

Fig. 8: Full scale casting.

Observations

In general, the full scale casting went well. In particular, after the first couple of hours, the casting proceeded smoothly. The concrete was delivered on time and the specified casting rate of approximately 30 m^3/hour was obtained. The casting showed the importance of a frequent job site control and a high level of communication between the casting crew, pump operator and the concrete supplier.

One of the challenges during the casting was to avoid fiber accumulation on the reinforcement grid, which in severe cases may cause delamination and weak layers below the reinforcement if no actions are taken. The risk of fiber accumulation increased when the pump hose was kept for too long at the same position because the fibers would start to form a nest. However, it is very likely that fiber accumulation would not have been an issue if the ratio between free spacing and fiber length would have been just a little bit higher i.e. above 1.5. The casting procedure also proved to have a strong influence on the risk of fiber accumulation e.g. it was possible to obtain a free flow situation by moving the pump hose from side to side. Table 5 shows some rules of thumb to avoid fiber accumulation based on the grid spacing/fiber length ratio.

During the trial casting, a poker vibrator was used in the parts where fiber accumulation occurred. Subsequently, core samples were drilled out from the trial slab to examine the fiber distribution. Variations between the top, middle and bottom were observed, but within acceptable limits. Crushing the whole samples showed that the total fiber content corresponded to the specified 30 kg/m^3.

Grid spacing/ fiber length	Comment	Example [mm]
> 2.0	Constant pump hose position is OK	150/60 (y10)
~ 1.5	Ok only if moving the pump hose	100/60 (y10)
<< 1.5	Accumulation of fibers very likely	

Table 5: Recommended values of grid spacing over fiber length to avoid accumulation of fibers on reinforcement grid when casting SFRSCC.

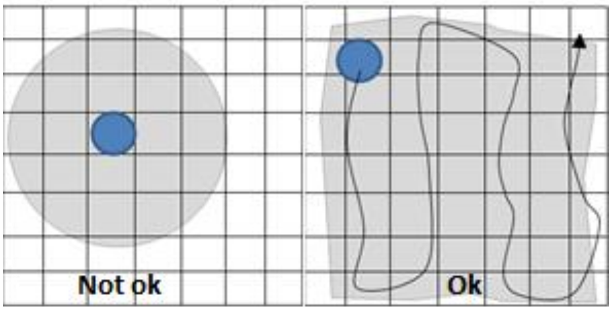


Fig. 9: The effect of pump hose handling on the risk of fiber accumulation on top of the reinforcement grid.

Also, the type and placement of grid spacers is important to consider in relation to fiber accumulation. At the trial casting a rectangular type of spacer was applied, which allowed the concrete to flow freely. However, at the full scale casting, triangular shaped spacers were applied. The triangular shape results in free spacing below 100 mm, which in some places caused fiber accumulation. To ensure the integrity of the structure, the casting crew had to move the pump hose carefully on each side of the spacers. Finally, as pointed out by the casting crew they would have preferred, if possible, to have the spacers orientated in the same direction as the concrete flow direction i.e. the concrete would flow parallel to the spacers.

Fig. 10: Different type of reinforcement grid spacers.

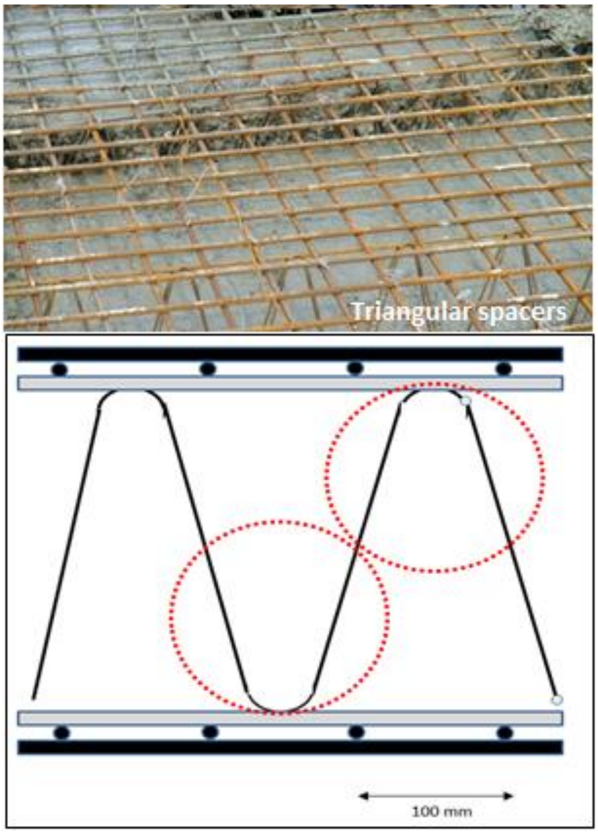


Fig. 11: Critical areas when using triangular shaped reinforcement grid spacers.

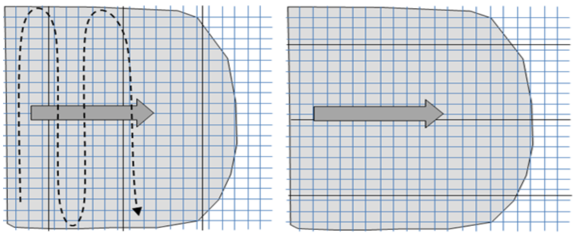


Fig. 12: The reinforcement grid spacers were orientated perpendicular to the concrete flow direction (left). Preferred spacer orientation (right).

Flow properties

The flow properties of the SFRSCC were measured using the manual slump flow test and the 4C-Rheometer (http://www.dti.dk/21743). The latter is designed to measure the rheological properties yield stress and plastic viscosity.

The yield stress applied at the trial casting was in the range from 80-130 Pa corresponding to slump flow values from 490 to 540 mm (on dry plate), and the plastic viscosity was in the range from 60-100 Pa˙s after pump corresponding to a medium viscosity according to the definition given in the Danish guideline on execution of SCC (www.dti.dk/23767). Based on the observations, the flow properties proved useful for this type of casting.

For job site control it was decided to set target values for the slump flow as given in Table 6. Due to different base plate conditions between the 4C-Rheometer (dry plate) and the standard slump flow test (moist plate), the target values for the 4C-Rheometer is somewhat lower than the manual slump flow.

	4C-Rheometer	Manual
Slump flow	500-550	570-620

Table 6. Slump flow target range for full scale casting.

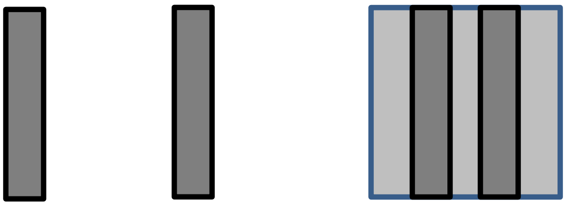
The first 6 truckloads had a relatively low slump flow (480 mm, 4C-Rheometer), which was also noticed by the casting crew. For the rest of the casting, the slump flow was generally within the target values with a few exceptions below 500 mm and above 550 mm. During the casting, there was continuous communication between the casting crew and the persons testing the flow properties. The observations made by the casting crew confirmed the target values set for this casting. When the concrete became too stiff (below 500 mm) it was more difficult to penetrate the reinforcement grid and when it was too fluid in the range of 600 mm (4C-Rheometer) they found in more difficult to control the front of the concrete and it would flow too far away from the position of the pump hose.

	4C Rheometer		Manual slump flow	
	Before pump	After pump	Batch plant	After pump
Sl. flow [mm]				
Average	532	521	546	575
Standard deviation	34	38	41	40
t_{500} [sec]				
Average	4,5	4,6	5,2	2,6
Standard deviation	1,0	1,8	2,1	0,9
Pl. visc. [Pa˙s]				
Average	79	68		
Standard deviation	16	30		
Yi. stress [Pa]				
Average	72	80		
Standard deviation	27	29		
Air cont. [%]				
Average			6,4	5,9
Standard deviation			1,2	0,9

Table 7. Fresh concrete properties.

Large beam testing

A total of four large beams (5.0 x 0.4 x 1.0 m3) were produced from the trial casting. Two were cast and two were cut from the trial slab.



Trad solution	CombiSlab	CombiSlab
Cast beam	Cast beam	Cut beams from trial slab
SCC	SFRSCC, 30 kg/m^3	SFRSCC, 30 kg/m^3
Y16 per 100	Y10 per 100	Y10 per 100

Fig. 13: Large full-scale beams (400x1000x5000mm).

The aim was to compare the crack pattern of the CombiSlab solution to the original no-fiber solution under identical load conditions and to assess if the CombiSlab solution fulfills the maximum crack width requirement (SLS design). However, from an experimental point of view, it is very difficult to establish a combined loading condition representative of the loading condition at Eternitgrunden, which is a combination of bending and restrained shrinkage. Therefore, the beams have only been subjected to four-point bending with constant moment length of 2.4 m. Figure 14 and 15 shows the experimental setup and pictures from the testing.

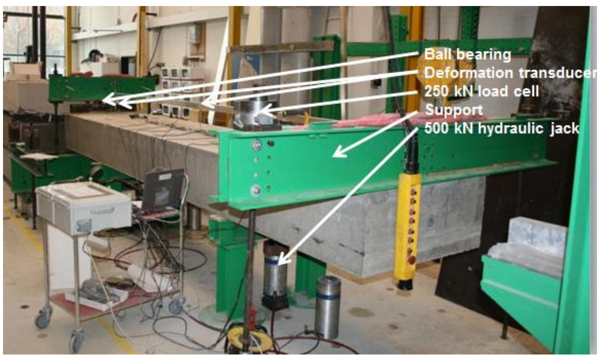


Fig. 14: Experimental setup.

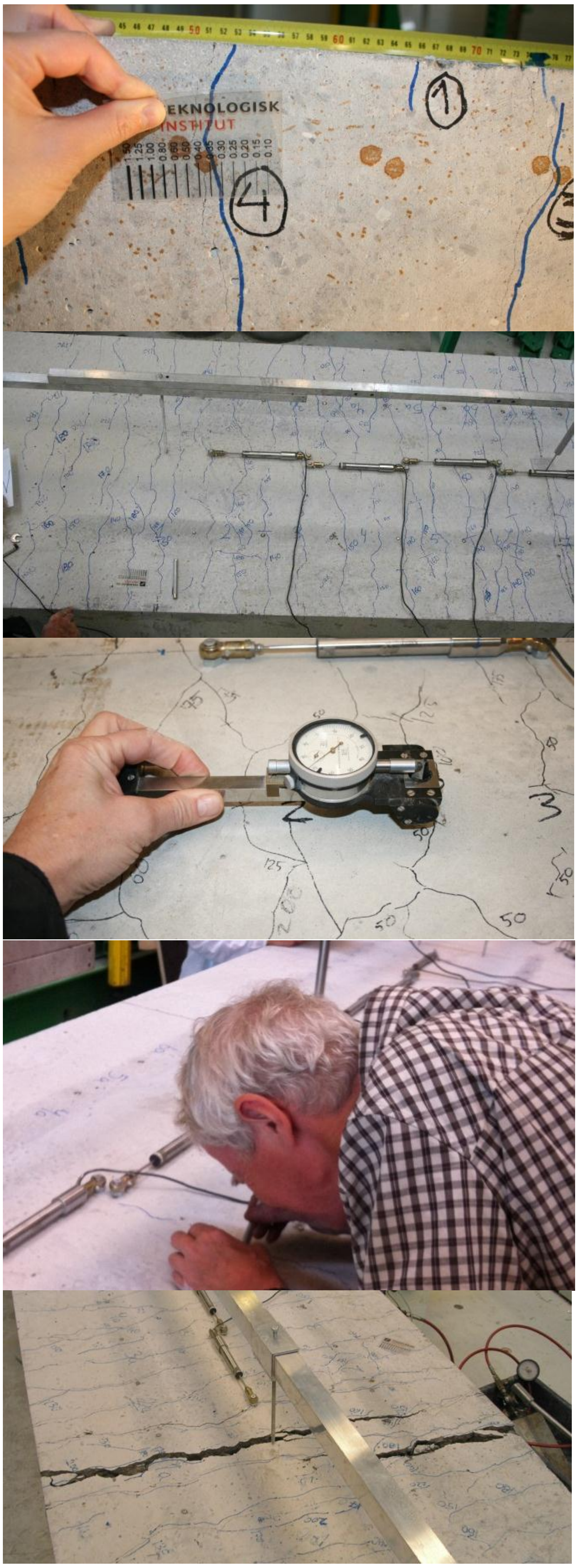


Fig. 15: Manual crack pattern detection.

The load deflection curves are shown in figure 15. The deflection represents vertical deflection in the constant moment area. The behavior of the two solutions is quite similar up to a load of approximately 150 kN corresponding to moment of 180 kNm. The beams with the CombiSlab solution were loaded until complete failure. The normal beam with 16 mm bars were loaded until yielding of the bars, however, to avoid any damages to the experimental setup, the load was released before complete failure occurred. For the CombiSlab solution, it is interesting to see that the fibers contribute to the bending capacity if compared to the expected bending capacity of a beam with only 10 mm bars. It is likely that the yielding of 10 mm bars in a beam without fibers would begin at a load of approximately 110 kN.

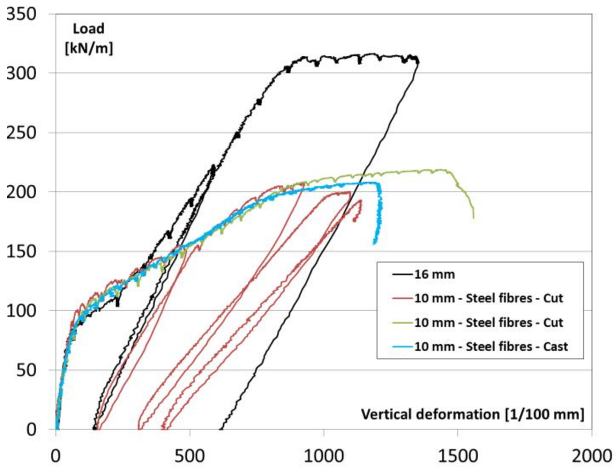


Fig. 16: Load deflection curves.

For each beam, the crack pattern was monitored at different load steps. At each load step, all the cracks were detected, and the crack width and crack distance were measured. Figure 17 shows the maximum crack width detected at the different loads. The results show that the cracks widths in the CombiSlab solution is somewhat lower or equal to the conventional solution up to a load of approximately 125 kN corresponding to a moment of 150 kNm. This indicates that the CombiSlab solution provides similar or enhanced capacity in the service limit state (SLS) compared to the conventional solution without steel fibers. The average distance between the cracks in the CombiSlab and conventional solutions was approximately 100 and 150 mm, respectively.

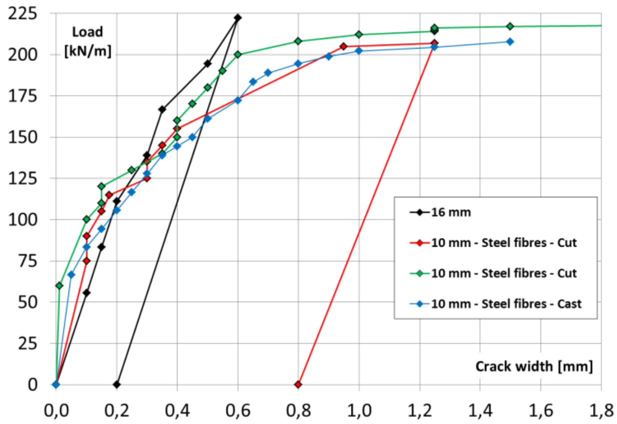


Fig. 17: Manuel measurements of crack widths.

For three of the beams, the so-called Aramis system was used to measure the crack patterns. It is based on advanced image analysis and can provide very accurate and precise crack measurements, it is able to measure cracks that the eye cannot detect, and it can generate videos to give a very good overview of the crack pattern development. It works by placing a high-resolution camera over the area of interest. Then, the area is colored by white spray paint followed by black paint to produce an infinite number of virtual measuring points. The image analysis software can then detect and follow the position of each marker. From this analysis, it is possible to calculate deformations, crack widths etc. To verify the accuracy, the maximum crack width of the Aramis was compared to the manual measurements and the results showed almost perfect agreement (Fig. 17).

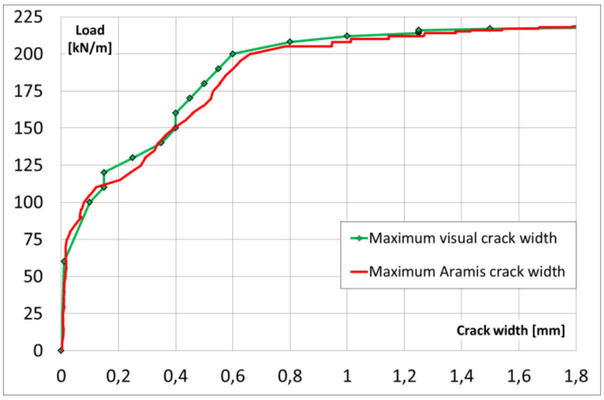


Fig. 18: Correlation between manual measurements and the Aramis system based on image analysis.

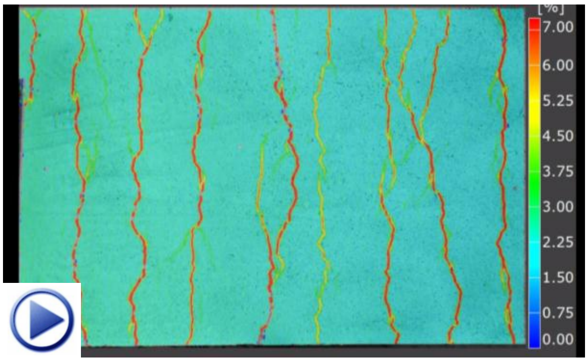


Fig. 20: Aramis video.

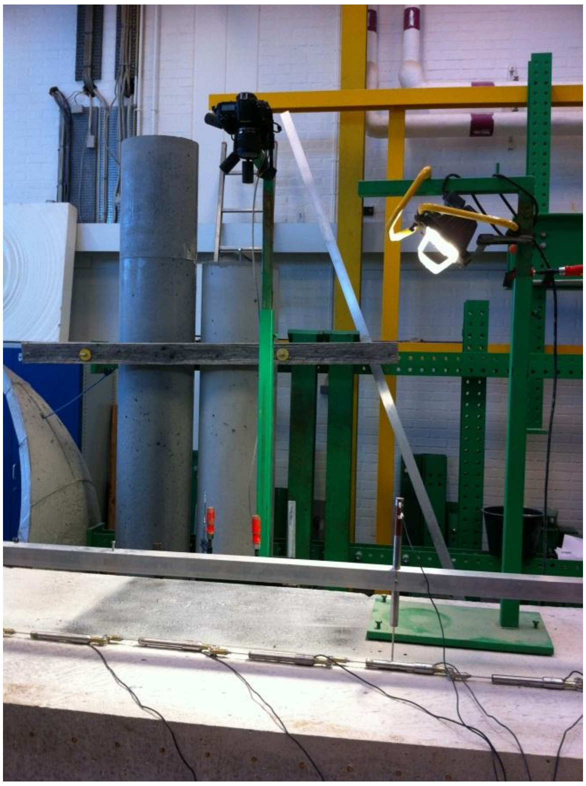


Fig. 19: Aramis setup.

Cost analysis

The specified solution contained mesh reinforcement Y16 per 100 mm in both directions at top and bottom, and stirrups along all edges. In the CombiSlab solution the meshes were reduced to Y10 at 100 mm in both directions at top and bottom, and the stirrups were no longer necessary due to the introduction of steel fibres in the concrete.

Table 8 shows the unit prices assumed for the conventional reinforcement and the steel fibres. For the conventional reinforcement the unit price include placing, and for the total amount an extra 15% of steel have been included for overlap of meshes.

Reinforcement	Price (all incl.) [DKK/kg]
Y16/100	8.0
Y10/100	9.5
Stirrups (Y16 C100)	12.0
Steel fibres (RC-80/60-BN)	20.0

Table 8. Assumptions used for cost comparison.

Conventional solution	Weight [Kg]	Price [DKK]
Y16/100	70,815	566,524
Stirrups (Y16 C100)	6,602	79,218
Total	77,417	645,742
CombiSlab	Weight [Kg]	Price [DKK]
Y10/100	27,631	262,495
Steel fibres (80/60)	11,334	226,670
Total	38,965	489,166

Table 9. Cost estimates and steel consumption.

As a conclusion, the total savings of going from a traditional double mesh solution to a CombiSlab solution were 156,000 DKK or approximately 25%. The total steel savings was 38,452 Kg or approximately 50%.

Conclusion

The first project to demonstrate the use of steel fiber reinforced self-compacting concrete (SFRSCC) was carried out at Eternitgrunden in Aalborg. For a 380 m^3 foundation slab, the use of a combined reinforcement solution, CombiSlab, resulted in steel and cost savings of approximately 50 % and 25 %, respectively. From an execution point of view, the main challenges proved to be the risk of fiber accumulation. However, in future projects the risk of fiber accumulation could be eliminated through careful considerations of the casting procedure, choice and placement of grid spacers, and the grid spacing/fiber length ratio.

The use of steel fibers in SCC may potentially provide the same positive impact on the working environment as normal SCC. In particular, if the need to move the pump hose to avoid fiber accumulation can be avoided.

Upcoming demonstration projects will include measurements of the working environment.

Coming up

In the coming period, many of the activities are linked to the next demonstration projects including the casting of an underpass and overpass in connection to the new Slagelse bypass. Also, investigations have been started up to study the potential benefits of SFRSCC in prefab beams in relation to shear and bending capacity.

Further information

Please contact project manager:
Lars Nyholm Thrane
lnth@dti.dk
+45 72 20 22 15

Website: www.steelfibreconcrete.com