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FIBRE REINFORCED CONCRETE WALLS AND SLABS: IN SITU PROPERTIES DETERMINED ON BEAMS

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Abstract:

Most of the generally accepted test methods for determining the residual tensile strength, the main FRC design parameter, are based on bending of laboratory beams. Considering differences between the laboratory test methods and real structures, major uncertainties are due to anisotropic fibre orientation and the actual fibre content. One method proposed in the Norwegian guidelines for design, execution and control of steel fibre reinforced concrete, is applied in several field test programs the last years. It is based on beams 150xhx600 mm sawn out from structures (of thickness h) exposed to four-point bending. Furthermore, fibre counting in critical sections to determine the so-called orientation factors, which again can be used to determine a direction-dependent residual tensile strength, have been conducted. Utilizing this method, both favourable and unfavourable fibre orientation can be accounted for. A method for fibre counting on drilled cylinders is also used and evaluated. Results from three field test series are referred in this paper, and the investigated parameters are: (1) horizontally vs vertically cast elements, (2) horizontal vs vertical beams in wall elements, (3) Vibrated vs self compacting concrete, and (3) influence of casting point location in walls

Keywords: Concrete structures, fibres, in situ, testing, self-compacting concrete

1 Introduction

Even if the use of fibre reinforcement in concrete has been increasing the last decades, and many R&D projects have been carried out, there are still important limiting factors. One is the relatively large uncertainty due to the in-situ mechanical properties of real fibre reinforced concrete (FRC) structures. Most of the generally accepted test methods for determining the residual tensile strength, which is the main design parameter, are based on bending tests of laboratory beams. Considering the differences between these test methods and real structures, scale effects are present, and for FRC in particular it is shown in previous works that the statistical scatter in the post-cracking properties of real structures can be rather large, and that the major explanation is anisotropic fibre orientation caused by the casting process Døssland 2008. However, the way to handle it is hardly treated at all in the research literature.

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The Norwegian contractor Veidekke AS has been initiator and driving force for new production methods, and was early to use fibre reinforcement actively in their projects. One aim has been to determine whether and how non-bearing interior walls can be made with use of fibres as the only reinforcement, so that the normally used double grid can be omitted. This could imply a considerable cost saving and simpler progress in concrete construction. This paper outlines the experience from several years of investigation where fibre-reinforced SCC and VCC have been used on both walls and slabs, on site and in laboratories.

2 The Norwegian Test Method

A variant of the widely used Japanese four point beam test (JCI-SF4) is recommended in the Norwegian design rule draft [Thorenfeldt et. al. 2006] with 150 x 150 x 600 mm un-notched beams. The midpoint deflection is measured and from this the toughness and the equivalent flexural strength can be calculated.

The residual strength after cracking is taken as $f_{res}=0.37f_{t,eq}$, where $f_{ft,eq}$ is the average equivalent bending strength recorded between 0.5 and 2.5mm deflection. The factor 0.37 expresses the difference between the tensile stress in the uncracked section and the equivalent tensile stress in the cracked section. This is based on the assumption that the depth of the compressive zone in the cracked stage is 1/10 which results in a ratio between the section modulus in the uncracked and cracked state of 0.37.

3 Beams from wall and slab elements

A series of full-scale wall (4x2.4x0.15m) and slab elements (2.65x2.65x0.15m) were cast to investigate the orientation and distribution of fibres in real structures. One wall and one slab element were made with vibrator compacted concrete (VCC), and one wall and one slab element were made with self compacting concrete (SCC). Afterwards, 36 small beams (150 x 150 x 600 mm) were sawn from the elements and exposed to four point bending according to the Norwegian test method, [Døssland (2008)]. Both concretes had water/cement ratio 0.59, and 0.7 volume % (56kg/m^3) 60 mm long steel fibres. The matrix volume was 339kg/m^3 and 367 kg/m^3 in the VCC and the SCC, respectively. The VCC's 28 days compressive cube strength was 60.7N/mm^2, while the corresponding SCC strength was 59.0 N/mm^2.

The fibres were added in the concrete lorry, mixed a couple of minutes at the concrete plant, and additionally mixed during the transport. Finally, the concrete was poured through a concrete funnel. One week after casting, square 600x600 mm elements were sawn from the walls and slabs as illustrated in Figure 1, and three beams cut from each element. The beams were stored under wet sacks covered by plastic sheets until testing, and while half of the beams were tested at 28 days, the remaining were tested at later ages.

To determine the actual fibre amount crossing the failure zone, a block from each beam was sawn about 9 cm (1.5·fibrelength) from the failure zone. Then the fibres over the cross-section were counted, and afterwards the sawn block was crushed and all fibres were gathered. The results (v_f [%]) are shown in Table 1. The fibre volumes in the crushed blocks were close to the added fibre volume for all beams, which implies an even fibre distribution in the structures. The volume was only controlled in one of three beams for element P11, P21, W11, W12, W21 and W22. For the remaining elements, the volume was controlled in all three beams.

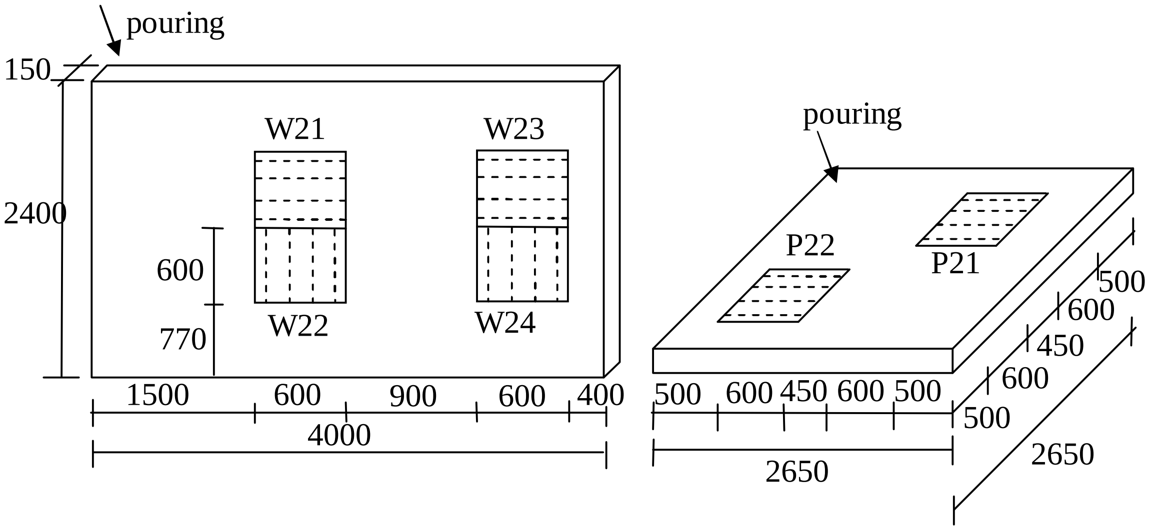

Fig. 1: Elements sawn from wall W2 and slab P2 with SCC. Similar elements were sawn from wall W1 (W11, W12, W13, W14) and slab P1 (P11, P12) with VCC.

Tab 1. Fibre counting results for each element.

		Fibre volume v_f[%]	ρ [%]	α	η
			0.35	0.5	0.33
P11	VCC	0.67* / *0.62	0.49	0.79	0.72
P12	“	0.68	0.25	0.37	0.25
P21	SCC	0.71 */ 0.72**	0.40	0.56	0.42
P22	“	0.71	0.56	0.78	0.71
W11	VCC	0.74 / *0.81	0.41	0.56	0.44
W12	“	0.75 / *0.85	0.35	0.47	0.33
W13	“	0.77	0.52	0.68	0.58
W14	“	0.79	0.38	0.48	0.34
W21	SCC	0.71 / *0.74	0.40	0.57	0.43
W22	“	0.68 / *0.63	0.25	0.37	0.24
W23	“	0.70	0.23	0.33	0.22
W24	“	0.72	0.44	0.62	0.49

*) Fibre content in one of three beams (showed after the slash). To estimate the average value, the fibre content in the two remaining beams is assumed to be equal to the added volume.

Table 1 also presents the different parameters which can be determined from the fibre counting, i.e. the section ratio ρ, the fibre orientation factor α, and the capacity factor η. The section ratio ρ is defined as the area of fibres per unit concrete area:

$$r = n_f A_f / A_c$$

Under isotropic conditions ρ is $0{,}5v_f$. Furthermore is the fibre orientation factor α, defined as the ratio between the section ratio and the fibre volume as:

$$\alpha = \rho/v_f = n \cdot A_f/(A_c \cdot v_f)$$

It can be shown theoretically that α =0,5 under isotropic conditions, 0,64 when the fibres are plane oriented while it is 1,0 when all the fibres are uni-directed.

Numerous analytical and semi-empirical expressions for the effect of fibres on the mechanical properties of FRC are presented in the literature [Døssland 2008]. In the present approach the influence of fibres after cracking is considered in a rather direct way. Compared to for instance the comprehensive work by Li et al. (1991), several simplifications related to modelling of single fibres are made. Theoretically, the residual strength can be expressed as:

$$f_{ftk,res} = \eta\ v_f\ \sigma_{average}$$

In this equation $\sigma_{average}$ is the average stress in all fibres intersecting the crack with arbitrary orientation and anchor length, while η is the capacity factor which physically describes the ratio between the fibres normal force resultant in the current situation and the corresponding force in a situation with only uni-directed fibres. For uni-directed fibres η=1, for plane orientated fibres η=1/2 and for isotropic orientated fibres η=1/3.

Some advantages by the present model, compared to other approaches (i.e. RILEM, DIN 1045), is that it is physically explainable, linearly related to the fibre content, and that anisotropic fibre orientation relatively easily can be accounted for.

To utilize systematic anisotropic fibre orientation in calculations it is necessary to relate the capacity and the orientation factors, and a simplified solution is [Thorenfeldt, Fjeld et al 2006]:

$$\eta = 2/3\ \alpha \qquad \text{when } 0.3<\alpha<0.5$$
$$\eta = 4/3\ \alpha - 1/3 \qquad \text{when } 0.5<\alpha<0.8$$

The upper and lower limit of 0.3 and 0.8 is set because an orientation that exceeds these limits is highly unlikely in practical applications.

Studying the results in Table 1 once more, it can be concluded that while the measured fibre volume is in reasonably good agreement with the theoretical, this is certainly not so for the other parameters, which show that there is a considerable scatter regarding the fibre orientation. For instance is it seen that in element P12 with VCC the fibre volume is close to the added fibre content, while the capacity factor is very low, indicating that the main part of the fibres is orientated parallel to the cross-section. The average orientation factor for element P11 is more than twice the corresponding factor for element P12. The average orientation factors in the four elements from the VCC wall were higher for the horizontally sawn beams than the vertically sawn beams. For the SCC wall, the orientation factor is also higher for the horizontally sawn beams near the casting point, but highest for the vertically saw beams on the other end of the formwork.

Dupont (2003) considered the influence of the form walls in this context, and divided beam cross-sections in three different zones. In the middle an isotropic orientation corresponding to orientation factor α_1=0.5 was assumed. Secondly the orientation factor is determined as α_2=0.6 for the area close to one wall, and finally the orientation factor is α_3=0.84 for the corner areas. With a wall thickness of 150 mm and Dramix 65/60 steel fibres, the theoretical orientation factor $\alpha_{Dramix65/60}=0.54$. The average orientation factor for all beams in the VCC wall is 0.55, which is close to the theoretical factor although the scatter is rather large

The relation between the residual strength from the measured response and the orientation factor from fibre-counting is quite convincing for all beams. It is clear that the fibres are not isotropic orientated. Moreover, the average residual strength was higher for the horizontal beams than for the vertical beams.

The fibre-orientation for the corresponding SCC-wall was mainly horizontal in the elements closest to the casting point, while the fibres were more vertically orientated in the elements further away. This is also verified by the residual strength which is largest for the horizontally sawn beams near the casting point, and largest for the vertically sawn beams in the other end. In general the orientation of the fibres in SCC is strongly dependent on the concrete flow during casting [Døssland 2008].

Considering the results from the horizontally cast slab elements, Figure 2, an important observation is that the fibre orientation factors and the concentrations in the two elements sawn from the VCC slab were very different from each other, with average orientation factors 0.70 and 0.37 for element P_{11} and P_{12}, respectively. As already discussed, the fibre content in the controlled blocks from element P12 was close to the added fibre volume, which implies that an unfavourable fibre orientation causes the low post-cracking strength, not an absence of fibres. The uneven fibre orientation must have originated from the vibration and the casting work. The average residual strength for the two elements sawn from the SCC slabs, on the other hand, were quite similar as illustrated in Figure 2b.

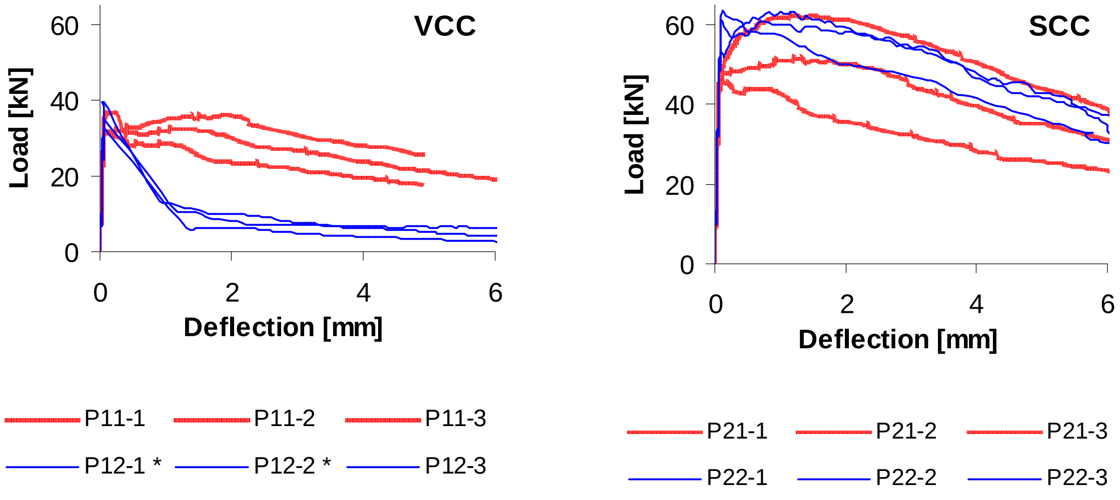

Fig. 2 Load-deflection curves for the 12 beams taken from the two plates. The residual strengths determined from the average equivalent bending strength are: $f_{res,P11}=1.28$, $f_{res,P12}=0.46$, $f_{res,P21}=2.01$, $f_{res,P22}=2.55$ N/mm^2. *) Two beams were tested upside down.

Residual strength from fibre counting

The experimental residual strength can be compared with the corresponding theoretical value: $f_{ftk,res} = \eta \, v_f \, \sigma_{average}$, when the capacity factor η is estimated from fibre counting. This stress is mainly determined by the fibre concrete bond, including the anchorage capacity of end hooks, and is in addition limited by the fibres tensile strength.

Due to the relation between bond and compressive strength, the residual strength depends on the concrete strength. Although the concrete types used here have similar compressive strength, it is still clear that the average post-cracking stress in the fibres is different, approximately 300 N/mm^2 for the VCC and 500 N/mm^2 for the SCC. The results are illustrated in figure 3, which directly shows experimental versus theoretical residual strength.

One main reason for the scatter between the theoretical and experimental residual strength is that the fibre-counting of the block taken 5-10cm away from the crack differs from the fibre orientation and fibre concentration in the actual failure zone. Another reason is the chosen representative cross-section for the theoretical residual strength included in η. In Figure 3 the whole cross-section is included. Obviously, the number of activated fibres increases as the crack develops. Hence the cross-section area of fibres contributing is not constant, and therefore it is difficult to choose a representative cross section area of activated fibres between 0.5 and 2.5 mm deflection, corresponding to the residual strength determined from the equivalent bending strength.

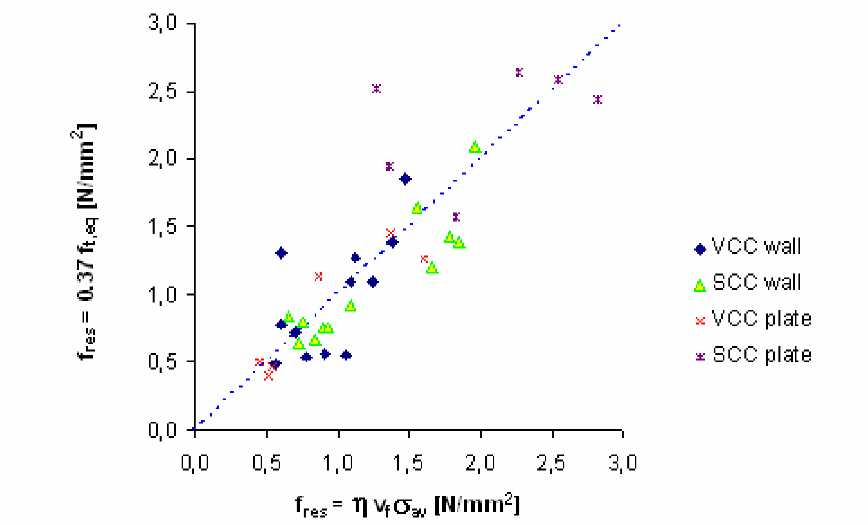

Fig. 3 Theoretical residual strength from fibre-counting vs. Experimental values. Here $\sigma_{average,VCC}$=300 N/mm^2 and $\sigma_{average,SCC}$=500 N/mm^2.

4 Fibres as minimum reinforcement

This chapter is related to fibres as minimum reinforcement in none load-bearing walls. As in the previous chapter, beam tests have been used to determine the residual tensile strength for concrete with different fibre types. The background for this part of the assessment and the selection of materials used in the experiments are based on a literature study, where steel and polypropylene fibres have been considered. The tests have been carried out with self compacting concrete (SCC), and test methods and range of use for SCC have also been studied.

The test program included 10 walls (L/H/h=5/0.6/0.15 m) cast in the laboratory on top of two plastic sheet layers separated with form oil to ensure free horizontal movement. As a supplement a full size wall at a building site was made. The three reinforcement types were: Dramix RC-80/50-BN(42 kg/m^3=0,54%), Barchip Kyodo (7 kg/m^3 =0,78%) and ordinary mesh reinforcement (2 layers K189=40 kg/m^3). Shrinkage of the walls was measured through the hardening and drying phases of the concrete walls, and the results showed, not surprisingly, that there was no significant influence of the reinforcement type.

The walls were cut into beams (150 x 150x 600 mm) for determination of residual tensile strength. The comparison between the three reinforcement types showed that the double mesh reinforcement K 189 (40 kg/m^3) gave larger residual tensile strength than 42 kg/m^3 steel fibres steel and this amount of steel fibres gave larger residual strength than 7 kg/m3 synthetic fibres.

The fibres in the cross-section area were counted directly, and the results showed that the orientation factor α, defined above, is considerably higher than the theoretical value of 0,5 for the horizontal beams. Furthermore, for the vertical beams, the orientation factors are considerably lower than the same theoretical value. The full scale wall at the building site showed a more even distribution of the orientation factor, which shows that the formwork, the geometry and the concrete flow may be important factors for the fibre orientation.

5 Synthetic fibre reinforced concrete walls

The work in this section focuses on to which extent, wall pouring methods affect the orientation and distribution of synthetic macro fibres added to ready-mixed self compacting concrete (SCC). The consisted of 5 walls (9,2 x 2,55 x 0,2 m) and the concrete was placed by crane, bucket and funnel with hose, with three different filling points at one end of the wall (1), at the midpoint of the wall (2), and finally at both ends and the mid-point (3).

After hardening 9 cylinder specimens were drilled from each wall to determine the fibre-content and the orientation on various locations in the walls by manual counting.

In the laboratory, the fibres were counted on the surfaces of the test specimens to register and evaluate the fibre orientation and distribution. This work included an investigation of whether or not the method described in section 3 for concrete cubes can be used for cylinders. Four cylinder cores were crushed and the fibre content gathered and weighted. The results of these differ from the estimated fibre volume. Although there are few test pieces, the test shows that there is a need for further investigations of whether the method developed for cubes apply for cylinders.

The results indicate that the concrete-wall pouring-method probably have an effect on fibre orientation. However, the variations are not large, and none of the pouring methods appear to be unsuitable. An important observation is that all cores in the bottom of the walls have the main fiber-direction in the longitudinal direction of the walls. This may suggest that the effect of the surface to a certain extent prevents whirl in the concrete, and that the conditions are similar to small beams and thin walls. This is beneficial since the experience shows that most cracks are vertical, starts 30-40 cm above the wall bottom and expands upward.

There are considerable variations in the fibre distribution throughout the wall. The deviations between added fibre amount and fibre washed out from the concrete at the construction site, shows that there are variations within the batch that will have an impact on the distribution in the wall. In order to determine the casting methods influence on the distribution it is important to know exactly the added amount. To achieve this, it is necessary to take samples continuously, from each batch. Furthermore, to ensure sufficient control, is necessary to establish improved routines for concrete manufacturer and contractor for production, transport and execution.

Based on the present results, pouring from the middle of the wall is recommended for walls. This method is being used by Veidekke AS today and is incorporated as a daily routine. According to the Norwegian Concrete Association's recommendations, the flow distance is within a range where separation is avoided (assuming a wall-length <10 m).

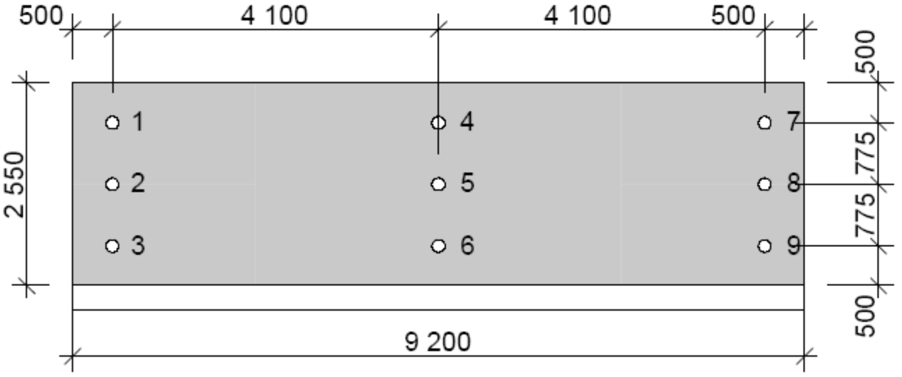

Fig. 4 Placement of drilled cores 1 – 9 from each of the 5 walls

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References

[1] Døssland Å.L. Fibre reinforcement in load carrying concrete structures, PhD-thesis, Department of structural engineering, NTNU, Trondheim, Norway, April 2008

[2] THORENFELDT E.V., FJELD, S. et. al. Steel Fibre Reinforcement in Concrete, Guidelines for design, execution and control, Sintef, Norway, 2006 (in Norwegian).

[3] Li, V.C., Wang, Y., Backer, S. (1990) Effect of inclining angle, bundling and surface treatment on synthetic fibre pullout from a cement matrix, Composites, Volume 21, no.2. pp 132-140.

[4] Dupont, D. (2003): Modelling and experimental validation of the constitutive law (σ-ε) and cracking behaviour of steel fibre reinforced concrete. PhD thesis TU Leuven, Belgium.