

# FLOWABLE FIBRE REINFORCED CONCRETE: MATERIALS DEVELOPMENT, FIBRE DISTRIBUTION AND STRUCTURAL PROPERTIES

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## **Abstract**

The paper presents an overview over the activities in the fibre concrete project of the Norwegian research umbrella COIN. The project is heading towards ordinary strength fibre concretes with sufficiently high residual tensile strength so fibres can replace a considerable part of the reinforcing bars. Flowable concretes are targeted to utilize synergies between SCC and fibres due to mechanical properties and work-hours. The residual strength of full-scale structures can deviate considerably from standardized test beams, and prioritized topics are therefore to map relevant cases and understand the reasons. A proposal for Norwegian design-guidelines, closely related to fib's Model Code (2011) is briefly described.

## **Keywords**

Fibre reinforced concrete, materials development, execution, design, test methods, load carrying structures

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## 1. INTRODUCTION AND OBJECTIVES

The fibre project within the Norwegian research programme, COIN (Concrete Innovation Centre, see acknowledgement), has two major objectives: (1) To do R&D work which stimulates and makes use of fibres possible in load carrying concrete structures. (2) To further development and verification of a ductile high tensile strength concrete, exemplified by a target tensile strength: 15MPa. Related to this, efforts have been made to understand why the residual tensile strength in full-scale structures made by flowable fibre concrete can vary from 0.4 to more than 2 times the strength of small standard beams. If this is fully understood, and expressed in regulations, the production of structural elements can be optimized. Fibre reinforced concrete (FRC) can then be used to its potential as a sustainable and cost-efficient construction material.

Ductility in tension, which can be expressed by high residual strength at large crack widths, is considered to be important for two reasons: (1) Fibre concrete should have similar ductility as ordinary reinforced concrete to meet the requirements of load carrying structures. (2) Large tensile ductility is necessary if the full yield strength of ordinary reinforcing bars and the fibre residual tensile strength shall be added without restrictions in the design process which is important for sustainability and cost-efficiency reasons.

To fulfil the objectives, three sub-projects have been established: (A) Materials development, incl. fibre type investigations and performance of structures to achieve the target concrete. (B) Guidelines for design and execution, and (C) Field - and full scale laboratory testing.

## 2. MATERIALS DEVELOPMENT

### 2.1 Previous investigations

One major activity has been to map properties of various fibre and concrete types, as basis for further development and improvement of the fibre concrete technology, Sandbakk [1]. Figure 1 shows results from pullout testing of single fibres, and while Figure 1a considers hooked end steel fibres in two different concretes (38 and 68 MPa compressive strength), Figure 1b concerns 48 mm long straight synthetic fibres with embossed surface in concretes with compressive strength ranging from 24 to 125 MPa. For both fibre types it can be seen that the effect of the concrete quality is large, and it should be noted that nearly all test specimens failed by pullout failure. The exception is the synthetic fibres in the concrete with 125 MPa strength which failed by fibre rupture as seen by the two characteristic vertical stress-slip curves in Figure 1b. The pullout failure type is clearly most favourable for ductility reasons and the fibre and concrete type should be chosen to achieve this type of failure. An important difference is that the steel fibres reach their maximum stress at about 1mm slip, while the synthetic fibres reach their maximum stress at about 2mm slip, which implicates that steel fibres contribute more to crack-width-limitations at service states loads, while the synthetic fibres might contribute to improved ductility at large crack-widths.

The pullout test results were directly used as input to a model for the post-cracking behaviour of beams tested in bending, Sandbakk [1]. Figure 1c shows theoretical and experimental results for the two considered fibre types, and it is seen that the agreement between theory and experiments is reasonably good. When the model is based directly on the input from the pullout tests the stresses will increase with increasing crack width similarly as with the slip in Figure 1. Therefore the stress distribution over the cross section height will typically be as shown in Figure 1d, which is different from what most researchers usually show. The major characteristics of the beam behaviour are that the load decrease at cracking is much larger for the synthetic fibres due to these fibres low E-modulus. Furthermore it is seen that both fibre types result in a relatively stable residual strength at CMOD ranging from 1.5 to 3.0 mm. The shape of the pullout curves are not directly mirrored in the bending tests due to the stress gradients across the tensile zone in the bending problems. However, still it can be concluded that pullout testing can be used to evaluate various fibre types in different concretes.

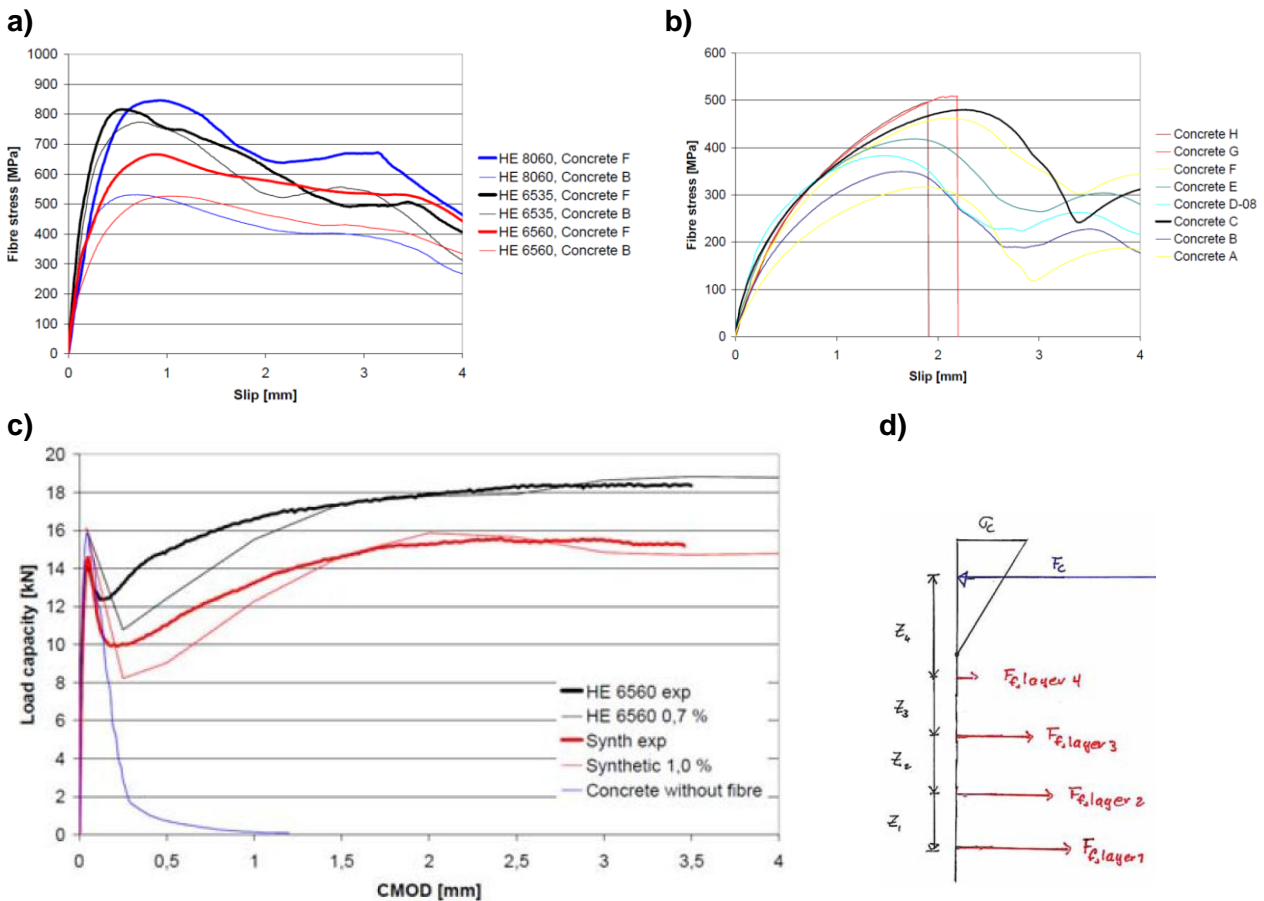


Figure 1. Results from pullout tests of single fibres. 1a: Steel fibres, L=35 or 60mm, concrete with 38 or 68 MPa compressive strength. 1 b synthetic fibres, L=48mm, concrete with strength between 24 and 125MPa. 1c: Results from beam tests, and 1d stress distribution in accordance with the calculation model) [1].

Synergies between fibre reinforcement and self compacting concrete (SCC) related to residual tensile strength were clearly demonstrated several years ago in both beams, slabs and walls, see e.g. Døssland [2]. Additional synergies between SCC and fibres related to production aspects are also relevant, and therefore mainly flowable concretes are targeted in the present project.

Figure 2a and 2b presents results from medium scale beams (150/250/3000mm) exposed to bending and it is seen that the additional capacity resulting from the fibres for self compacting concrete is more than two times the corresponding contribution from the ordinary vibrated fibre concrete. The reasons for this are partly due to higher strength and more fines in the SCC, but the major reasons are due to the effects of flow on fibre orientation and a certain segregation in the SCC beams. This is verified by fibre counting on sawn cross sections close to the failure zones [2].

In Figure 2c results from standard beams (150/150/600mm) sawn out from horizontal slabs are shown. In this case both concretes had compressive strength around 60MPa, and it is seen that the SCC slab showed considerably better performance regarding both statistical scatter and strength. A similar investigation was also made for vertical walls, but these results are harder to evaluate, and the conclusions are not as straightforward as for the slabs due to more complicated concrete flow in the walls, Døssland, [2].

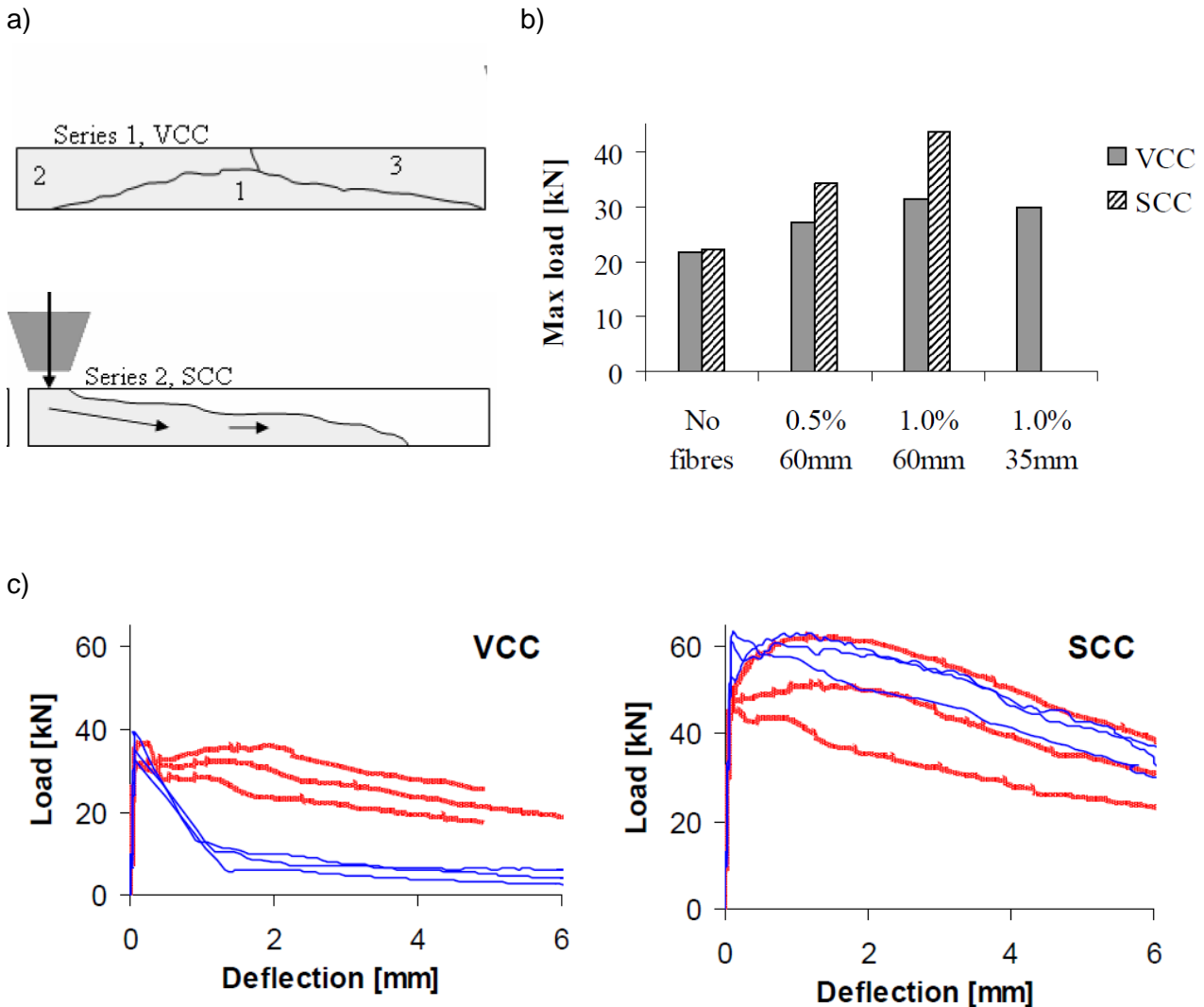


Figure 2 a) Ultimate load (moment capacity) of beams made of ordinary vibrated (VCC) or selfcompacting (SCC) steel fibre reinforced concrete,  $b/h/L=150/250/3000\text{mm}$ , Døssland, [2].

## 2.2 Ongoing research

So far focus has been towards concrete for ordinary construction projects, which means that advanced materials such as UHPC not have been prioritized. Despite for this, materials with residual bending strengths as large as 17 MPa has been made using ordinary constituent materials and steel fibre content in the range 2-3 volume % ( $160\text{-}240\text{ kg/m}^3$ ). Of this material even a 3 meter long model of the famous Leonardo da Vinci Bridge has been built.

To develop suitable fibre reinforced concretes for use in load carrying structures three criterions have been defined [1]:

1. Strength criterion, i.e. post cracking strength > cracking strength
2. Ductility criterion, i.e. relatively large crack openings (e.g. 2,5mm) at maximum load,
3. The practical criterion, i.e. the concretes should be applicable at construction sites.

To achieve this for different strength ranges, the following parameters have been varied: Cement content, w/b-ratio, filler type and content, maximum aggregate size, amount and type of fibres. For further details, fresh concrete properties, and general experience, see Vikan et.al. [3]

or Sandbakk [1]. Here, it shall only be noted that  $d_{max}=8\text{mm}$  is chosen because reduced  $d_{max}$  makes the concrete more flowable with large fibre volumes, and because it makes monotonic strain hardening behaviour easier to achieve. Furthermore limestone filler was used for sustainability reasons, and also because replacement of cement by limestone filler reduces the cracking strength to a larger extent than the residual strength, and therefore makes it simpler to fulfil the strength criterion referred above [2,3].

Figure 3 shows residual bending strength versus crack-width (CMOD) determined by three-point bending tests (NS-EN 14651 [4]) of concretes with various fibre types and fibre content. Using the results for beams with 1 volume% 60mm end hooked steel fibres in Figure 3a as basis, it can be seen that replacement of 0.5% of these fibres by 0.5% of the shorter 35mm long similar steel fibres clearly increased the residual strength at small crack-widths, while it was correspondingly decreased for larger crack-widths. If the target is ductile concretes the long fibres should be chosen, but if focus is directed towards crack width limitations in the service limit states long and short fibres might be combined. In the same figure, still keeping the beams with 1% long steel fibres as reference, it is shown that replacement of 0.5% by 48mm synthetic fibres resulted in a weaker, but more distinct strain hardening material, which is what the present project is aiming at. Consequently, the combination of 60 mm end hooked steel fibres and synthetic fibres was further investigated. The combination of 0.5% synthetic and 0.5% steel fibres resulted in a residual bending strength at 2,5 mm crack-width quite close to the concrete with 1.0% steel fibres only. In Figure 3b) some selected concretes with large tensile ductility are included, the concrete with the lowest strength is of quality about B25 with 0.5% of the two fibre types considered above, while the second lowest one is a B45 with 1% steel fibres and 1% synthetic fibres. Number two from the top is a B75 with 1.0% steel fibres only. These concretes have also been used in full-scale structural elements briefly presented in the last chapter, where special weight is laid on investigations of fibre distribution, orientation, and the relation between residual strength of small standard beams and fullscale structural elements.

### 3. GUIDELINES FOR DESIGN, EXECUTION AND CONTROL

#### 3.1 General

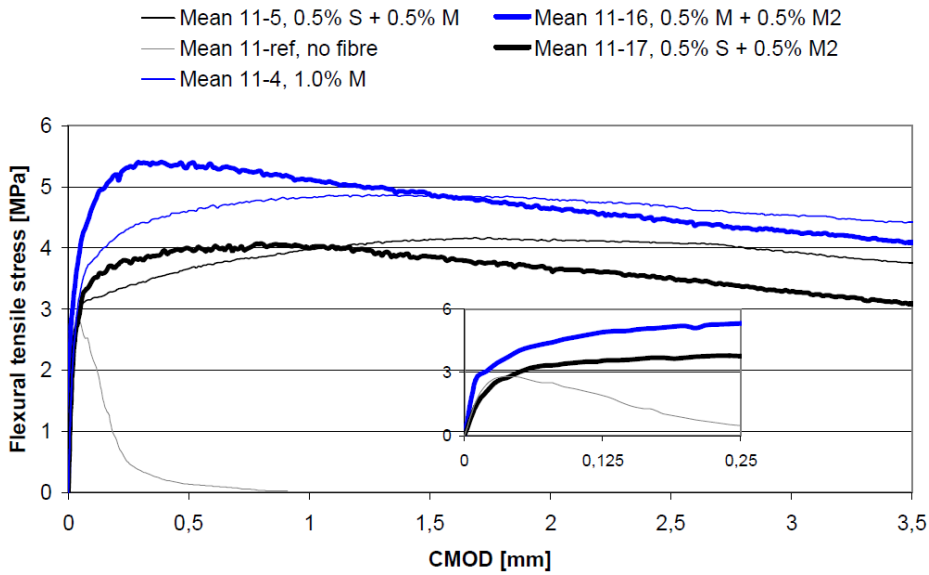
The guideline proposal is mainly meant for load carrying structures, and it is quite closely related to the relevant chapters in *fib's* new Model Code [5]. It is mainly written for flowable concrete, and there are no strict limits for the strength range and fibre content, Kanstad et.al, [6]. It is made for fibres in general, and is based on the performance of the fibres in the three-point bending test described in EN 14651 [4]. It holds for hardening behaviour on the structural level, and it is stated that this can be achieved by fibre reinforcement alone, combined use of reinforcing bars and fibres, or by structural redundancy. The following notations are introduced:

Fibre reinforced concrete: Concrete reinforced with fibres only

Reinforced fibre concrete: Concrete reinforced with fibres and ordinary bars

For reliability and safety reasons it is particularly stated that fibre reinforced concrete only can be used for load carrying structures in reliability class I (defined in EN 1990). When reinforced fibre concrete is used in reliability classes 2, 3 and 4, an additional requirement is that moments and axial forces shall be carried without the fibre contribution using load and material factors equal to 1.0.

a)



b)

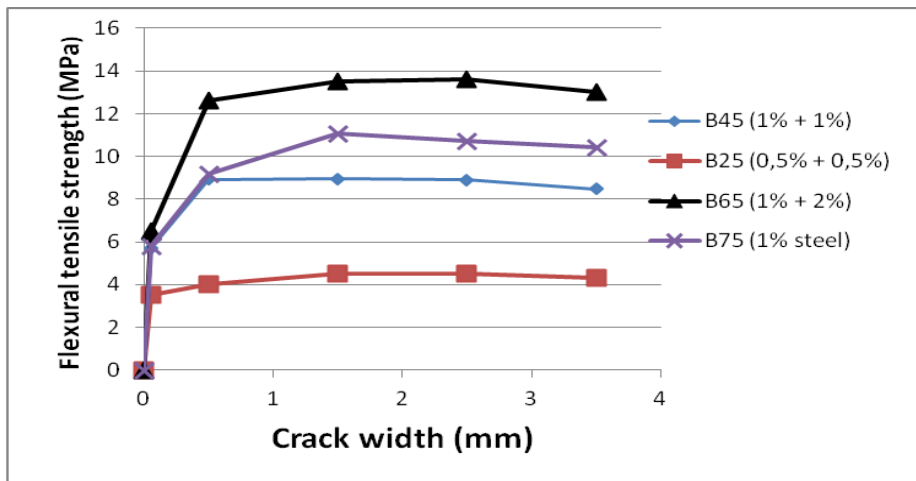


Figure 3 Residual bending strength vs Crack mouth opening displacement for different concretes, a) Different fibre types; S=48mm synthetic, M= 60mm steel, M2=35mm steel. b) Different concrete strength and varying fibre volumes (48mm synthetic and 60mm steel) [1,3].

### 3.2 Execution and Control

The guideline proposal is published as a project-report [6], and contains the following parts: Material related topics for concrete and fibres, test methods, verification and execution, and finally design methods and reinforcing rules. Ongoing activities are related to test methods for characterization of fresh concrete properties, the coupling between these properties and the three decisive characteristics; fibre distribution, fibre orientation and mechanical strength in standard test specimens and in full-scale structural elements.

The fresh concrete properties are rather important for the structural properties (i.e. post-cracking tensile strength), and relevant test methods and corresponding material requirements should therefore be included. However, the research on fresh concrete has not yet concluded, and presently experience is gained with the traditional spread measure, the LCPC-box [7], and the 4C Rheometer [8]. Furthermore are procedures for control of fibre content at the building sites, and corresponding requirements described

The basic design material property is the residual tensile strength determined from the three-point bending test EN14651 [4]. Alternative methods might be used if the relation to the EN14651 test has been established. A test regime for the concrete producer's verification of residual strength class is specified. The rules are prepared for consideration of different fibre orientation in the standard test method specimens and the real concrete structures as explained in the next section.

### 3.3 Design Methods

Compared to the fibre concrete chapters in *fib* Model Code [5], the present approach is simpler. Design both in SLS and ULS are based on the residual strength at 2,5mm crack width (CMOD) only ( $f_{R3}$ ). Explicit expressions for moment capacity (Figure 4), shear capacity, minimum reinforcement and crack-width rules are included. In general the procedures seem to be quite robust compared to experimental behaviour.

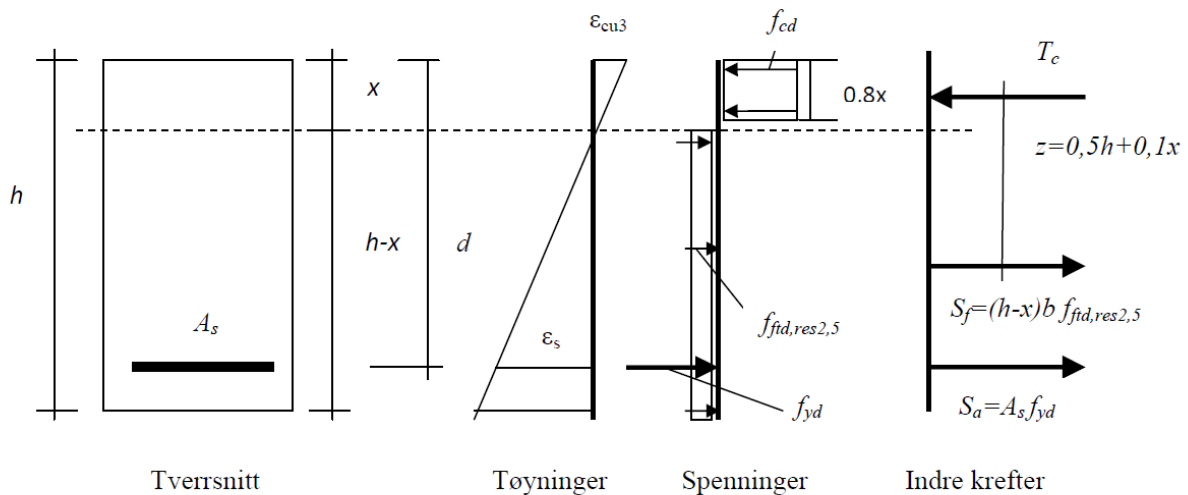


Figure 4 Stress- and strain distribution for a rectangular cross section of reinforced fibre concrete exposed to pure bending [6].

#### Adjustments for the effect of flow on fibre orientation

If the fibre orientation and the local amount of fibres in the standard beam test not is representative for the concrete and the casting conditions in the actual structure, the residual strength can be normalized to a generally valid value as follows:

$$f_{ftk,res,2,5,norm} = f_{ftk,res,2,5} v_{f,nom} / (v_f(4\alpha - 1))$$

Where:

$v_f$  = measured volume ratio of fibres

$v_{f,nom}$  = nominal fibre content according to recipe

$\alpha$  = fibre orientation factor calculated with measured number of fibres and volume ratio,  $\alpha=0,5$  corresponds to isotropic fibre distribution.

$f_{ftk,res,2,5}$  = Characteristic residual tensile strength determined experimentally.

$f_{ftk,res,2,5,norm}$  = Normalized characteristic residual tensile strength

Correspondingly can the residual tensile strength which shall be used for the structures be corrected from the normalized value if another orientation factor than the isotropic one is documented.

$$f_{ftk,res,2,5,struct} = f_{ftk,res,2,5norm} (4\alpha_{struct}-1) V_{f,struct} / V_{fnorm}$$

Where:

$V_{f,struct}$  = volume ratio of fibres in the current structural element

$\alpha_{struct}$  = fibre orientation factor documented for the structure

$f_{ftk,res,2,5struct}$  = Characteristic residual tensile strength in the structure

## 4. FIELD - AND FULL SCALE LABORATORY TESTING

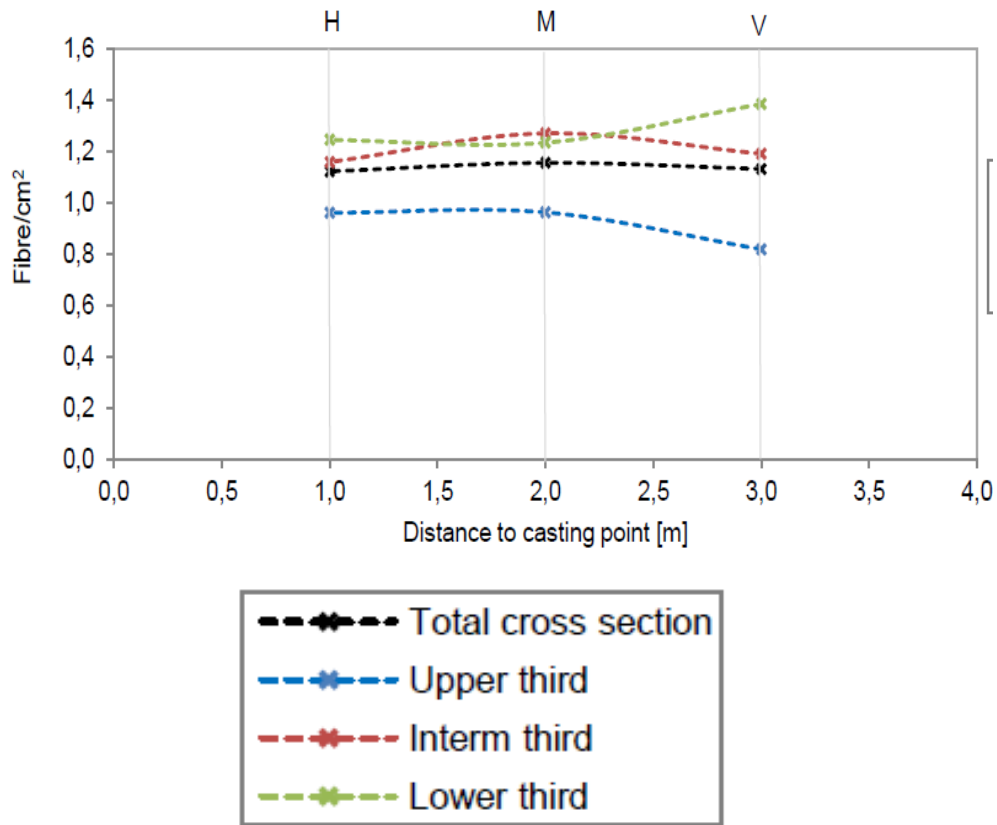
### 4.1 Mechanical properties in real structures versus small standard beams – effect of flow

This sub project includes a series of full scale post-tensioned and fibre reinforced flat slabs, walls and slabs cast on construction sites, several series of slab and beam elements cast in the laboratory, and precast beam elements made of both lightweight and normal density concrete. As part of the result evaluation, control of the fibre content in the critical sections have been carried out in many cases, and one major observation is that while the fibre content usually seems to have rather small variations in the structures, the variations in fibre orientation within the structures may be rather large, and probably the main explanation of the large scatter we often observe in test results for fibre reinforced concrete structural elements. This is also the reason why the present guideline proposal is prepared for taking fibre orientation deviating from isotropic conditions into account as explained in the previous section. Furthermore is close cooperation established with the Civil Engineering Department at the Technical University of Denmark (DTU) where simulations of fibre reinforced concrete flow are carried out, see f Svec et.al. [10,11]. The results so far seem to predict very well the influence of the flow and the fibre orientation and contribute to a solid basis for utilization of the positive effects of the fibre orientation which have been observed in many structural elements [1,2,12].

Figure 5 presents results from full-scale beam tests [1,12]. Figure 5a concerns beams with  $b/h/L=200/300/4000$ mm, longitudinal tensile reinforcement, and B25 with 0.5% 60mm steel fibres and 0.5% 48 mm synthetic, previously shown in Figure 3. The major findings are that the number of fibres per area is largest in the lower parts as illustrated in Figure 5a, a situation which can be explained by more longitudinally oriented fibres close to the bottom surface, and a certain extent of fibre segregation, Sarmiento et.al [12]. Furthermore does inverse analysis of the load deflection relations show that the residual strengths of the FRC in the full-scale beams are considerably larger than in the related standard beams (EN14651), in fact the strength increase is larger than 100%. From the moment-curvature relation in Figure 5a it is seen that the fibre contribution does not decrease with deformations beyond the yield limit of the reinforcing steel, as observed in beam tests carried out previously [2]. Consequently the fibre concrete optimization towards increased ductility as described in Chapter 2.2 has worked. The results are presently being verified by flow simulations and further beam testing.



a)



b)

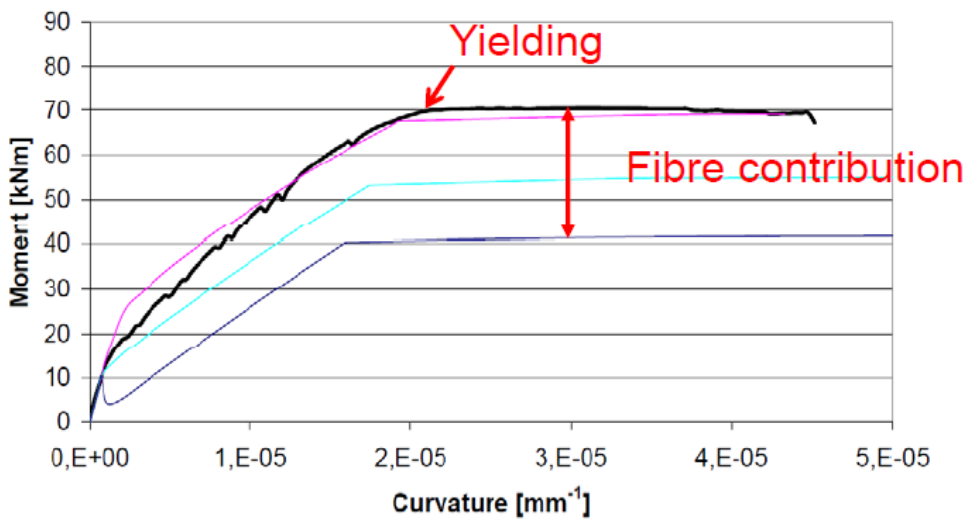


Figure 5: Results from full-scale beam element tests,  $b/h/L=200/300/4000$ . (a) Fibre areas along the beams determined by fibre counting through photographs and image analysis. (b) Moment-curvature relations [12].

## 4.2 Performance of Structures

As one more example on structural behaviour, Figure 6 presents results from a test series of beams with corbel ends, where parts of the ordinary reinforcement have been replaced by steel fibres. The elements are as a starting point quite heavily reinforced, and the testing was planned for a typical shear failure close to the support. The fibre concrete denoted B75 with 1.0% steel fibres in Figure 3b has been used in several of the beams, and one major conclusion is that, in this structural element type, most of the traditionally used beam end reinforcement can be omitted and replaced by fibres without considerable loss of capacity and ductility. Considering the results it is seen that the traditional solution still clearly has the best ductility. Further it is seen that the strength of the pure fibre reinforced solution and the alternative with vertical reinforcing bars and no fibres have similar capacity, although the ductility of the first is quite low compared to the bar reinforced solution. In addition, it is seen that the combination with vertical shear reinforcement only plus fibres (simplified solution) achieves about the same capacity as the traditionally reinforced solution. Finally comparing the results it can be concluded that the capacity of the solutions with combined reinforcement, i.e. fibres and bars, can be found by superposition of the capacity of the fibres and the bars at corresponding deflections. The presented experiments are a part of ongoing research on application of fibre reinforcement in D-regions, and establishment of strut & tie models for fibre reinforced concrete. In an experimental series, which currently is being carried out, one of the objectives is to optimize the casting procedure towards optimum fibre orientation in the critical sections.

## **5. SUMMARY AND PLANS FOR FURTHER WORK**

The paper presents an overview over the activities in the fibre concrete project of the Norwegian research umbrella COIN. The major activities, materials development, design guidelines and fullscale element testing, are briefly described. The work confirms the large potential of FRC to replace ordinary reinforcing bars, even in load carrying structural parts.

Based on existing knowledge and previous experience, the main future focus is on utilising flowable concretes to achieve favourable fibre distribution and orientation (to reduce the amount of fibres needed), as well as to improve the placement of FRC with relatively high amounts of fibres.

The important topic about fibre orientation is addressed both from the experimental and theoretical side, and is evidently a complex relation between concrete rheology, fibre types and amount, casting technique, and geometry of the part to be concreted. A crucial point is how to verify that the fibre distribution and orientation is as presupposed in the structural design.

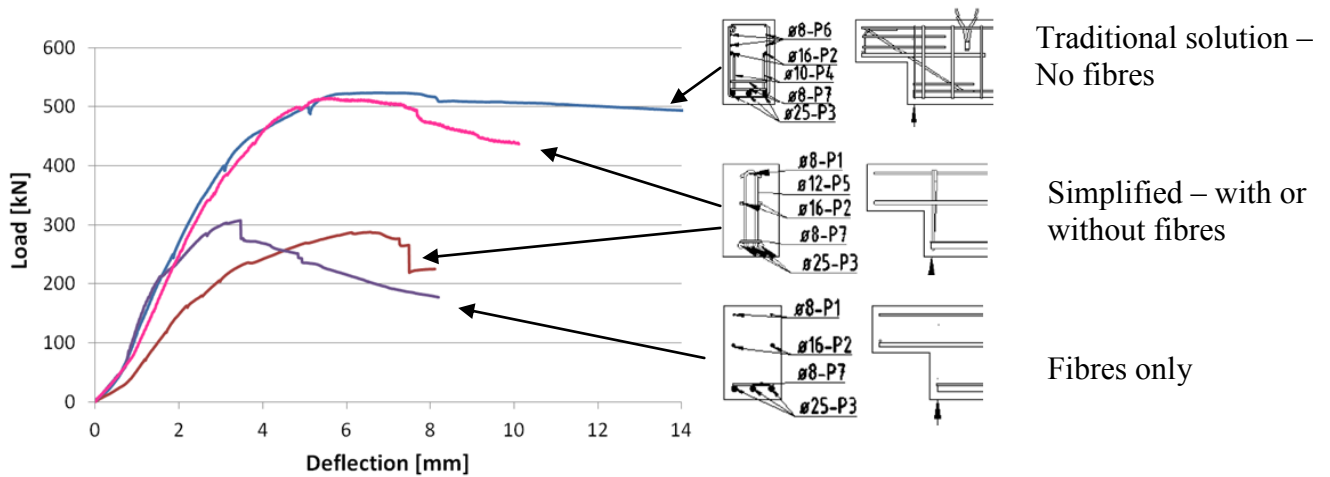
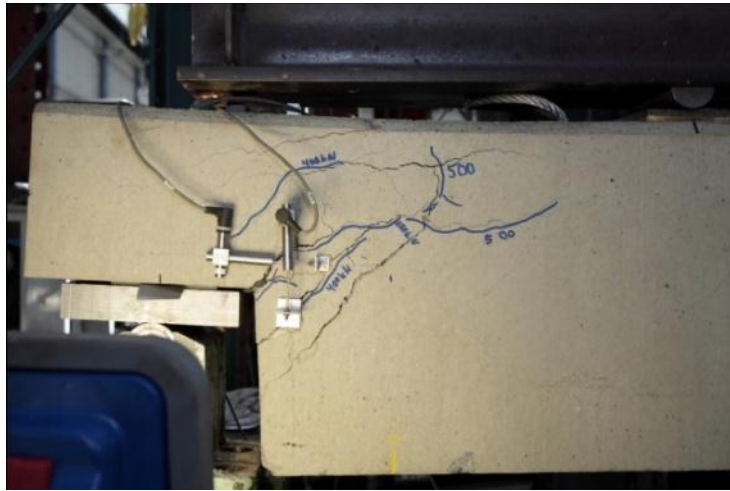


Figure 6: Results from full-scale beam element tests. (b) Beams with corbel ends, investigation of reinforcement solutions. Load deflection relations.

### ACKNOWLEDGEMENTS

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