Steel fibre reinforced concrete (SFRC) – Quality, performance and specification

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Synopsis

Steel fibre reinforcement is widely used as the main and unique reinforcing for industrial concrete floor slabs, shotcrete and prefabricated concrete products. It is also considered for structural purposes in the reinforcement of slabs on piles, tunnel segments, concrete cellars, foundation slabs and shear reinforcement in prestressed elements. Ensuring the quality and performance of the steel fibres and ultimately the SFRC is critical and the challenge faced by engineers involved in designing these projects is to unambiguously specify the performance required by the SFRC so as to achieve in the finished structure the performance that was assumed in design.

Since 2006, design methods for SFRC have been available in NZS 3101:2006 Concrete Structures[1]. The documented test and design methods describe not only how the material properties are determined but provide guidance on the design of SFRC used in structural applications, in the ultimate and serviceability limit state, for different Performance Classes (SFRC grades). An identical approach to the use of strength grades for the specification of both steel and concrete.

The documented test method describes one form of beam test that can be used to determine the properties of SFRC. Internationally there are a number of slight variations to this test, but all fundamentally measure the same thing, the post crack strength provided by the steel fibres in terms of flexure. Direct tension and shear capacities can also be interpreted from the results of these flexural beam tests.

This paper discusses the Performance Class concept and the progress being made in Europe with quality control measures for SFRC being adopted by the ready mix industry. It also discusses the importance of specifying steel fibres that can guarantee a minimum level of quality and performance, as well as the inherent variability of beam tests that make them unsuitable as a means to confirm or determine material properties of SFRC through limited or isolated testing.

Background

The New Zealand building industry has had access to a range of different fibre types used to reinforce concrete for over 10 years and in recent years the choice of proprietary products available has increased significantly. Steel fibres, macro synthetic fibres, micro synthetic fibres, cellulous fibres are widespread within construction today. It is a common misconception that all fibre types reinforce concrete in the same way and that substitution between fibres is possible. Different combinations of fibre raw materials, dosage and geometry will all produce a fibre reinforced concrete element with quite different material properties. This will influence the performance and dictate their suitability in certain applications. Steel fibre reinforced concrete (SFRC) is the most common in NZ and is included within NZS3101:2006, encouraging engineers to consider its use under the framework of the Building Code.

History of SFRC

Steel fibre reinforced concrete (SFRC) was introduced commercially into the European market in the second half of the 1970's. No standards or recommendations were available at that time which was a major obstacle for the acceptance of this new technology. Initially steel fibres were mostly used as a substitute for secondary reinforcement or for crack control in less critical parts of the construction. Today steel fibres are widely used as the main and unique reinforcing for industrial floor slabs, shotcrete and prefabricated concrete products. They are also considered for structural purposes in reinforcement of slabs on piles, full replacement of the standard reinforcing cage for tunnel segments, concrete cellars, foundation slabs and shear reinforcement in prestressed elements.

Performance Classes

This evolution into structural applications was mainly the result of the progress made in SFRC technology, a steady build up of knowledge and understanding of its use into a wide range of applications as well as the research carried out at different universities and technical institutes in order to understand and quantify the material properties; a time line is shown in Figure 1. Generic design guides or standards could only be developed with this understanding of material properties of SFRC independent of fibre type.

In the early nineties, recommendations for design rules for steel fibre reinforced concrete started to be developed and since October 2003, RILEM TC 162-TDF [2] recommendations for design rules have been available. These form the basis of the design methods provided for SFRC in NZS 3101:2006 Concrete Structures Standard.

The documented test and design methods describe not only how the material properties are determined but provide guidance for the design of SFRC used in structural applications in the ultimate and serviceability limit state for different Performance Classes (SFRC grades), an identical approach to the use of strength grades for the specification of both steel and concrete. A performance class is used to classify the post crack strength for SFRC. There are a wide range of steel fibres available in the market and the performance class concept enables any fibre to be used in order to achieve the desired strength or grade. It allows the engineer to carry out a design using this material without worrying about fibre type and dosage.

A particular performance level can be achieved in different ways; fibre type, dosage, concrete strength and is based on standardised beam or
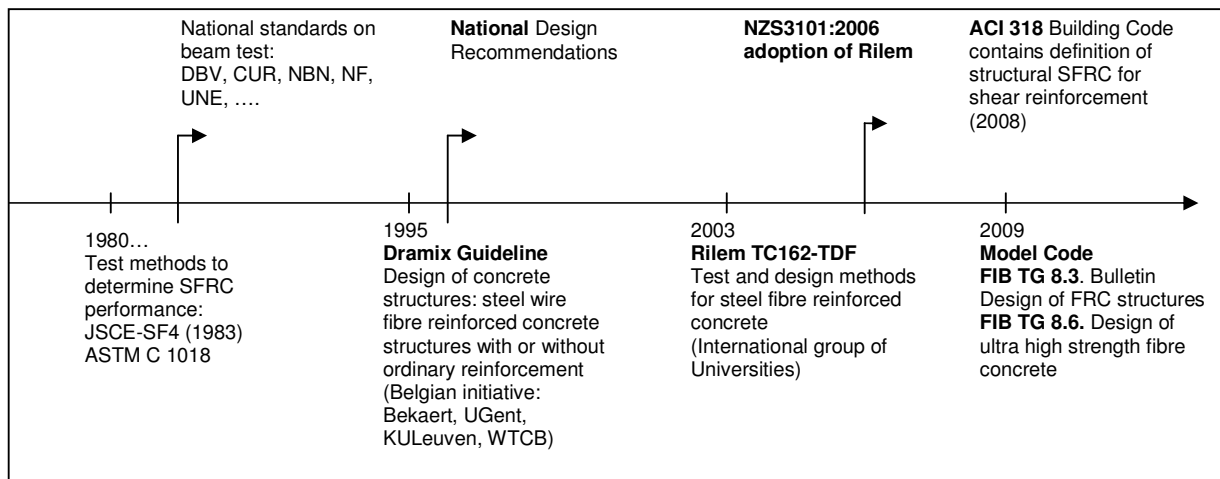

Figure 1: time line of SFRC test and design methods

panel tests. In a similar fashion to how the material properties of other engineered products are determined though laboratory based testing. The test method in NZS3101 describes one form of beam test that can be used to determine the properties of SFRC, there are a number of slight variations to this test that all fundamentally measure the same thing, the post crack strength provided by the steel fibres in terms of flexure. Direct tension or shear capacities can also be determined with the recommendations provided in NZS 3101.

At this stage New Zealand has no commercial testing facility with equipment and experience suitable for testing SFRC; this is something that needs to be addressed.

In Australasia these capacities are typically provided by the steel fibre manufacturer, however as the performance class concept evolves ready mix companies may supply certified SFRC grades as part of their product offering to the market and as engineers use these design values in structural applications they will require confidence that the properties assumed in design are what's supplied to site.

Test variability

Because of the inherent variability of beam tests they are unsuitable as the only means to confirm or determine material properties of SFRC through limited or isolated testing. There are a number of different factors that can influence the variability of results, namely:

- Fibre type and dosage
- Ratio of fibre length to max aggregate size
- Batching and mixing
- Casting of test piece
- Size of test piece
- Number of test pieces in a sample
- Laboratory equipment and experience

Most of the above can be controlled either by QC or laboratory experience, however the size of the test piece relates to the area of concrete in tension and this is where the fibres are providing capacity. Assuming all other things remain equal (concrete strength, fibre type, dosage, batching and mixing etc) it has been shown [3] that the coefficient of variation for results in a particular test method is directly related to the cracked area of concrete. This is illustrated in Table 1 where the beam test is compared to the Round Determinate Panel test (one test method currently used for shotcrete) and a crushing test used on sewerage pipes.

	Beam	RDP [4]	Sewerage pipes [5]
Cracked area	$0.02m^2$	$0.1m^2$	$0.4m^2$ to $0.8m^2$
Average COV	20%	10%	3.5%

Table 1: Average coefficient of variation of different test methods for SFRC

As a consequence of this a test with high variability will result in lower design values, because the coefficient of variation is a function of the characteristic design strength.

$$F_{fctk,L} = F_{fctm,L} - k_x * s_p$$

Where: [6]
$F_{fctk,L}$ = characteristic design strength
$F_{fctm,L}$ = mean strength
k_x = factor dependant on number of specimens
s_p = standard deviation
$COV = s_p$ / mean

Test variability should also be a consideration where mean values (not characteristic) are used in design or are used to verify a performance level. The mean value obtained from a test sample is only an estimation of the true mean and is dependant on the test variability and the number of tests carried out. Statistically 15 beams are required to generate a mean value that will be within ± 10pc of the true mean, based on an upper limit of 30pc COV. [3]

In real structures however this coefficient of variation will depend on the size of the cracked area of the actual concrete element, which in turn is based on the concrete volume and redundancy of the system (load redistribution and multiple cracking).

Understanding this is an important step towards developing 'upgrade' factors that could be used by designers when post crack strengths are based on a beam test with a small cracked area and subsequently a high variability and the real structure has a cracked concrete section larger than $0.02m^2$. This is currently under development in Europe and has led some countries to implement this philosophy into their design guides for SFRC[7]. Another option is to base design values on a test with good repeatability and reliability and to use safety factors in design where the cracked area in the real structure is less than the test.

Limited testing

In Australia for large infrastructure projects it is common practice for ready mix companies at tendering stage to carry out limited testing (2 or 3 RDP panels, or 3 beams) to confirm a fibre type and dosage to satisfy the design properties. With this limited number of tests the results are statistically irrelevant and it is entirely possible that two very different materials could show the same post crack strengths, as shown in Figure 2.
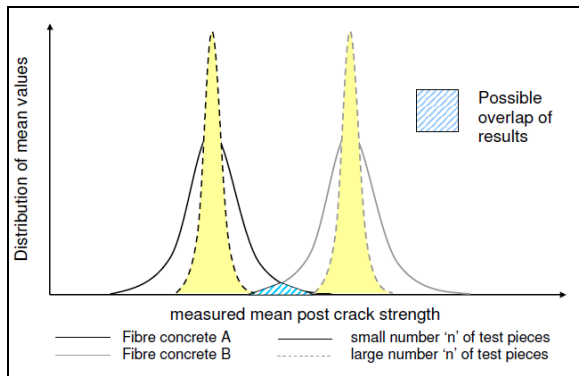

Figure 2: Normal distribution of mean post crack strengths for two different SFRC's and two different sample sizes

By increasing the number of test pieces in a sample the variation decreases and the results become more realistic and reliable. This demonstrates that comparing the individual values of two different SFRC is meaningless and the practice of confirming a fibre dosage based limited testing at tender stage can lead to an increase in fibre dosage during the course of the project as the test data builds.

It is crucial that the correct material properties or design strengths are used in the first place and one very important aspect to this is that the typical average COV's for the adopted test method shown in Table 1 do not take account of variations in the quality of either the concrete or the fibres used to produce the SFRC. Large variations in the quality, and hence performance, of the concrete and/or fibres will result in a broadening of the distribution plots shown in Figure 2 with a consequential increase in the overlap area shown. Quality control in the manufacture of SFRC is essential; this has lead to the development of a performance based manufacturing standard for steel fibres[8] which is used as part of the quality control measures being implemented at the ready mix plant.

Quality control – steel fibres

EN 14889-1 fibres for concrete, part 1, steel fibres

EN 14889-1 is the European and currently the only quality control performance based manufacturing standard for steel fibres. Similar in concept to other manufacturing standards for engineered products such as concrete, steel, LVL etc. It is mandatory in EU member states for steel fibres used in construction to be manufactured in accordance with this standard. It ensures a minimum level of quality and performance and because a minimum fibre dosage has to be declared to achieve a required post crack flexural strength in a reference concrete it enables complete transparency when comparing the performance of different fibre types.

Firstly the manufactures class their fibre in accordance with the base material; cold drawn wire, cut sheet, melt extract, shaved cold drawn wire or milled from blocks and then declare the shape; straight or deformed. This allows any steel fibre to be manufactured in accordance with this standard, provided it can be produced within the control and tolerances set to guarantee quality and consistency.

Manufacturers must declare values for each individual fibre characteristics that influences performance; such as length, diameter & aspect ratio, fibre tensile strength etc. These values must not deviate by more than the tolerances outlined in Table 2.

PROPERTY	SYMBOL	DEVIATION OF INDIVIDUAL VALUE FROM DECLAIRED VALUE	DEVIATION OF AVERAGE VALUE FROM DECLAIRED VALUE
Length >30mm ≤30mm	l, ld	± 10%	± 5% ± 1.5mm
diameter >0.30mm ≤0.30mm	d	± 10%	± 5% ± 0.015mm
Aspect ratio (length / diameter)	λ	± 10%	± 7.5%
Tensile strength	Rm	± 15%	± 7.5%

Table 2: Tolerances on fibre geometry and tensile strength

The standard details the minimum sample size and frequency of testing for each property being monitored and initially sets these quite high until there is enough data to demonstrate that the manufacturing process is in control and results are representative of the full production. Six months of production data is the minimum period set before a reduction of sample size can be considered.

There are two types of Classification for the steel fibres that can be achieved; Class 1 and Class 3. Class 1 steel fibres are submitted to more scrutiny during manufacture (more intensive sampling and testing) and production is monitored by an external third party. They can be used in applications where the fibres contribute to the load carrying capacity of the concrete element. A summary of the differences can be seen in Table 3.

Class 1	Class 3
Field of use	
• Structural use	• Non structural use
"structural use of fibres is where the addition of fibres is designed to contribute to the load bearing capacity of a concrete element"	
Quality control	
• Initial type testing (ITT) under the responsibility of the Notified certification Body	• Initial type testing by a notified laboratory
• Initial and **annual** Factory Production Control (FPC) assessment by **Notified Body**	• Factory Production Control under responsibility of the **manufacturer**
• **Certificate of Conformity** issued by 3rd party	• The manufacturer creates and signs a '**Declaration of Conformity**'

Table 3: Differences between class 1 and class 3

Effect on strength of concrete

'The behaviour of the steel fibre reinforced concrete element is more critical than the properties of the steel fibres themselves'

This is why as part of the certification to EN 14889-1 manufacturers must declare a minimum dosage required to meet prescribed residual flexural strength values. This enables the engineer, concrete company, contractor to legitimately compare the expected performance of different fibre types on offer. This information along with the fibre description, tensile strength and manufacturing facility is included on a CE label attached to the product. A typical example is shown in Figure 3.
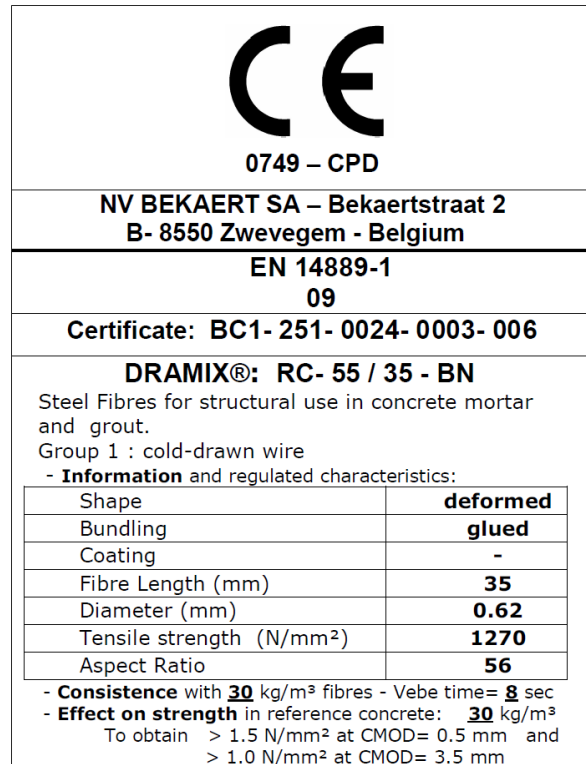

Figure 3: CE label

The concrete company can use this information to record that the correct fibre type has been used in the supply of their SFRC.

Quality control – Ready Mix

It has been shown that the type of test method, sample size and a number of other factors can greatly influence the results achieved in testing the properties of steel fibre reinforced concrete. For this reason tests on their own shouldn't be used as a quality control measure in the production of SFRC, but rather a manufacturing process should be established that in itself is under control, with consideration to the following.

• Fibre type with guaranteed quality and performance (through EN 14889-1 or similar)
• Fibre dosage
• Homogeneous distribution throughout the concrete matrix

Fibre type with guaranteed quality and performance

Steel fibres manufactured to EN 14889-1 provide the concrete company with a product of known and consistent quality and the CE labelling system enables them to easily record and check the correct fibre type has been used in the supply of their SFRC.

Correct dosage, batching of fibres

Automatic dosing equipment is becoming more widespread in Europe and in Australasia for tunnelling projects. The equipment can be linked to the central batching system which allows accurate dosing and provides a record for QC documentation.

Figure 4 shows two incite dosing machines that hold approximately 1500kg of fibre, the fibres are added in 1000kg bags. The one on the left has steel fibres and the one the right has micro synthetic fibres, both of which discharge the exact dose of fibres onto a conveyor belt leading to the hopper. These were used in the manufacture of segmental tunnel linings.

Figure 4: Incite dosing equipment

Figure 5 shows 'Booster' dosing equipment where the steel fibres are packaged in 250g dissolvable bags and are either fed onto a magnetic or standard conveyor belt. The magnetic belts can be used to access batching areas at the top of tower plants where the belt can run vertically up the wall.

Figure 5: Dramix Booster

Fibre distribution and dosage

A visual inspection is common practice to determine whether random distribution and the separation of collated fibres has been achieved. Various methods to determine fibre quantity in fresh or hardened concrete are well documented in several European standards[9] or guides[10], the most common of which relate to sprayed concrete but the same approach could be used for conventionally cast concrete. One example to determine fibre content from CUR Recommendations[11] suggests the following:

"Two samples of at least 8 litres shall be taken from each mixer truck to be checked; at least three mixer trucks shall be checked, and the quantity of the fibres shall be measured by washing out. The mean fibre dosage, measured over at least six samples, shall not be lower than the intended value minus 10% and shall not be lower than the intended value minus 4kg/m3. No individual results shall be lower than the intended value minus 20%, nor lower than the target value minus 9kg/m3"

There are also fibre counters available that will automatically separate the steel fibres from the fresh concrete, shown in Figure 6.

Figure 6: Fibre counter

Currently in Australasia steel fibre reinforced concrete is viewed as two products; concrete + steel fibres. A change in this mindset may help towards concrete companies setting up quality control measures at the batching plant to monitor and assess the product which is being supplied to market; steel fibre reinforced concrete.

Conclusion

New Zealand currently has design recommendations through the provisions in NZS3101:2006, but is lacking the minimum quality and performance requirements for steel fibres. There is an opportunity here to take advantage of the progress made in Europe and to create an environment in NZ where engineers have the confidence to consider the benefits of SFRC as a material in their designs and to have a regulated market where quality and performance of the material are guaranteed.

Determining or confirming design properties for SFRC should be carried out with an understanding of test variability and its causes and care should be taken when assessing post crack strengths on limited test data particularly when comparing two different steel fibre reinforced concretes. Also, such tests should not be used as a measure of quality control in their own right but rather should form part of a quality controlled process at the batching plant.

The natural progression for SFRC in New Zealand would be to include EN14889-1 as a requirement for steel fibres into NZS3101, just as there is a requirement for all structural steel to conform to quality based manufacturing Standard AS/NZS

4671. This controls one important variable and will allow the concrete company to focus on other aspects of quality control in the manufacture of SFRC with perhaps in the future certified performance classes for SFRC being offered just as NZ delivers plain concrete grades under a quality controlled certification scheme.

[1] NZS3101:2006, Concrete Structures Standard, New Zealand
[2] RILEM TC 162-TDF, Test and design methods for steel fibre reinforced concrete, σ-ε-design method, Published in Materials and structures, Materiaux Et Constructions, Vol. 36 – No. 262, October 2003
[3] Lambrechts Ann, NV Bekaert, Performance Classes for steel fibre reinforced concrete: Be Critical
[4] ASTM C-1018, Standard Test Method for Flexural Toughness and First-Crack Strength of Fibre-Reinforced Concrete
[5] EN 1916:2002, Concrete pipes and fittings, unreinforced, steel fibre and reinforced
[6] NZS3101:2006, Concrete Structures Standard, Part 2, Clause C5.A
[7] CNR-DT 204/2006, Guide for the design and construction of fibre-reinforced concrete structures
[8] EN 14889-1, Fibres for concrete – part 1 Steel Fibres, Definitions, specifications and conformity
[9] EN 14488, Testing sprayed concrete, Part 1, Sampling fresh and hardened concrete
[10] EFNARC, European specification for sprayed concrete
[11] CUR, Steel fibre reinforced concrete industrial floors on piles – dimensional analysis and performance