Joint Free Restrained Slabs – SFRC combined with mesh

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Abstract: Controlling cracking to acceptable levels in concrete structures requires accurate detailing and good construction practices. This is more prevalent in ground supported slabs that are typically detailed to avoid cracks occurring under service stresses. Detailing the slab to avoid these cracks puts a number of limitations on the floor design and construction. There is an upper limit on panel size and shape, restraint should be limited as much as possible and of course joints are required, which can be expensive and may require on-going maintenance. And even with all this effort, cracks can still occur, and when they do they tend to be large and can have an adverse effect on the serviceability of the floor. Recent Standards from Europe[5,6,7] enable the engineer to design using steel fibre reinforced concrete (SFRC) combined with conventional reinforcing. For floor slabs this means any panel size or shape can be considered, even when the floor is fully restrained, and importantly these solutions can be joint free. Using combined reinforcing also enables the design of economical liquid retaining structures, such as containment bunds, dangerous goods store floors, tank base slabs, watertight basement slabs.

This paper discusses the theory behind this design approach and provides a number of local and overseas project examples.

Keywords: CombiSlab, combined reinforcement, crack width calculation, SFRC, steel fibres, serviceability design

Introduction

Concrete is a brittle material and cracking is normal. In fact, in order to take account of the reinforcing effect of bar or mesh, cracked section material properties and design capacities are used in the design of concrete structures. If these cracks are controlled within specified levels they are not detrimental to the integrity of the structure and do not affect its serviceability. This control is generally met by providing a minimum percentage of steel reinforcing and/or appropriate joint detailing.

With this in mind, a major design consideration for any concrete structure is the location and detailing of joints. This can become paramount for concrete pavements or slabs where joints have traditionally been the Achilles' heel of this form of construction. Being able to minimise or eliminate joints is an attractive proposition in terms of on-going maintenance costs.

This is one of the main reasons continuously reinforced concrete (CRCP) pavements, which are designed to eliminate the need for joints, are often preferred over jointed pavements with large numbers of closely centred crack control joints. CRCP are designed with enough steel reinforcing to keep the inevitable cracking within acceptable limits - by typically utilising 16mm or 20mm reinforcing bars at close (< 200mm) centres, the requirement for crack control jointing, such as saw cuts, is removed.

On the other hand, jointed pavements/slabs are detailed and designed in such a way as to limit the stresses in the slab due to restrained, temperature and shrinkage deformations to be less than the tensile capacity of the concrete, i.e. the design is based on the slab remaining uncracked in its serviceability limit state (SLS).

Innovation in this field of concrete design has led to the development of design rules that enable the use of steel fibre reinforced concrete (SFRC) in combination with conventional reinforcing. This makes it possible to design economic solutions for controlled cracking under service stresses. For floor slabs this means any panel size or shape can be considered, even when the floor is fully restrained, and importantly these solutions can be joint free.

Say NO to Joints

Designing for controlled cracking in concrete elements is common practice, to suggest that this is a good idea for a ground supported slab requires quite a shift in thinking. A warehouse slab or external pavement is arguably the most important part of the tenanted space; it has to remain operational and serviceable with preferably as little maintenance as possible; and this maintenance typically involves joints.

There are flooring solutions that can reduce the number of joints, but as mentioned earlier, these put a number of limitations on design and construction. Particularly post tensioned slabs where wall block outs and pour strips may be required, joints over large distances open significantly and it's common for the slab to curl at joints and free edges. To avoid cracking a slab is normally tensioned incrementally as the concrete gains strength; this can put it on the critical path for construction. Importantly, limiting restraint is of paramount importance and the construction and design/detailing of these floors types is a specialist field.

Joints can work well, if detailed and constructed properly, but almost always require maintenance, as shown in figure 1. This dowelled movement joint will require a maintenance programme to reseal it possibly many times over the life of the floor. They can also perform poorly, as shown in figures 2 and 3. This costs the building owner and has a detrimental effect on the serviceability of the floor.

Figure 1

Figure 2

Figure 3

The photographs in figures 4 and 5 show controlled fine cracking in a slab containing steel fibres and mesh. Figure 4, a close up and figure 5 showing two controlled cracks running parallel to each other, taken from head height, they are quite difficult to see.

Figure 4

Figure 5

So, instead of trying to detail and construct the slab with joints to avoid cracking under service stresses, another approach is to assume the slab will crack under services stresses but to design with enough tensile capacity at the cracked section to ensure any cracks are controlled and hence small enough not to affect the serviceability of the floor. To do this efficiently and economically you can use a 'CombiSlab' solution; steel fibres combined with mesh or bar.

This approach is particularly beneficial where there is unavoidable restraint in the floor. Rather than trying to detail round this restraint, by the judicious design and construction of a suitable arrangement of joints, the approach entails designing a suitable combination of mesh and steel fibre reinforcement to ensure an acceptable level of crack width whilst eliminating or minimising the need for either movement (dowel) or crack control (saw cut) joints.. Restraint may result from precast concrete panels being tied into the slab, pads or plinths that are poured integrally with the slab, or non-symmetrical shapes to the floor etc. etc.

It is worth noting, that in floors where restraint can be limited, joints are acceptable, the serviceability demands on the floor are small and there is no requirement for a crack width calculation, steel fibre only solutions can still be the most economically attractive option.

Quantifying Concrete Reinforced by Steel Fibre

Most current standards for design of SFRC provide guidance on how to quantify the reinforcing properties based on the measured post crack tensile strength of SFRC. The universally adopted approach is to measure the post crack performance in a flexural beam test, performed in the laboratory (Fig 5) and by means of suitable conversion factors, convert the laboratory measured flexural performance in terms of a load versus deflection or crack width curve into a tensile stress/crack width as shown in Figure 6 and hence into a stress/strain relationship that can then be used for design as shown in Figure 7.

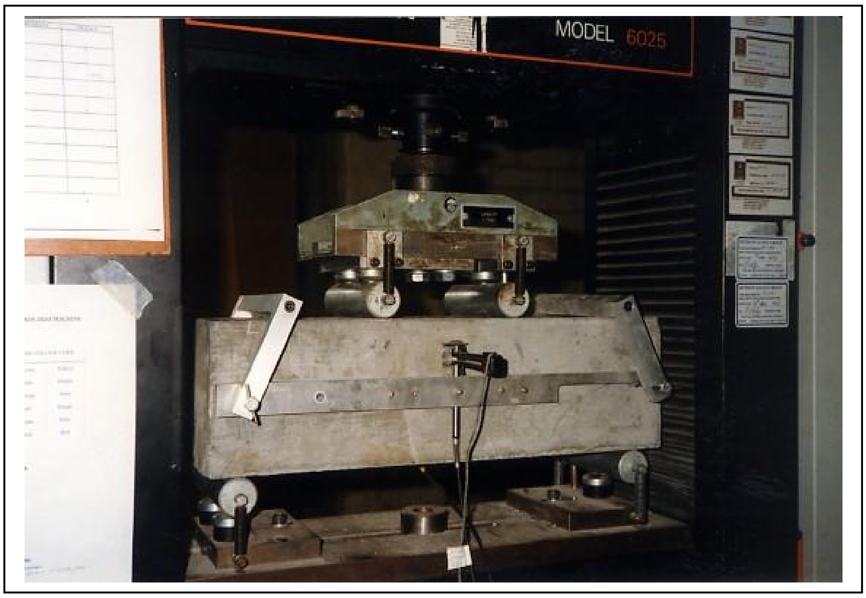

Figure 5 Typical Beam test setup in the laboratory

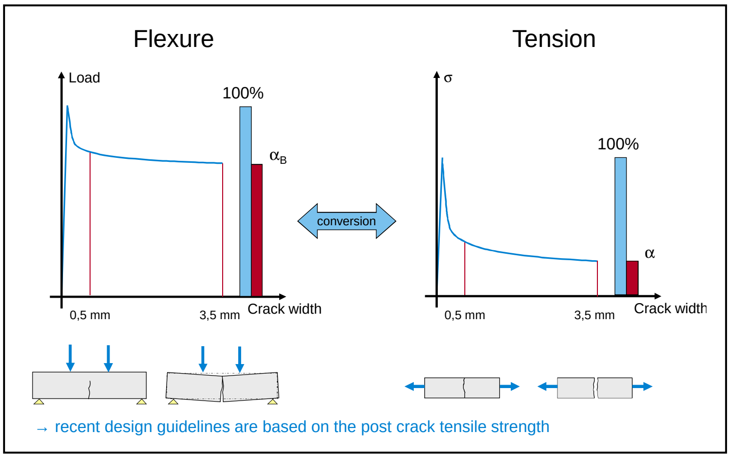

Figure 6 Converting Test results for SFRC

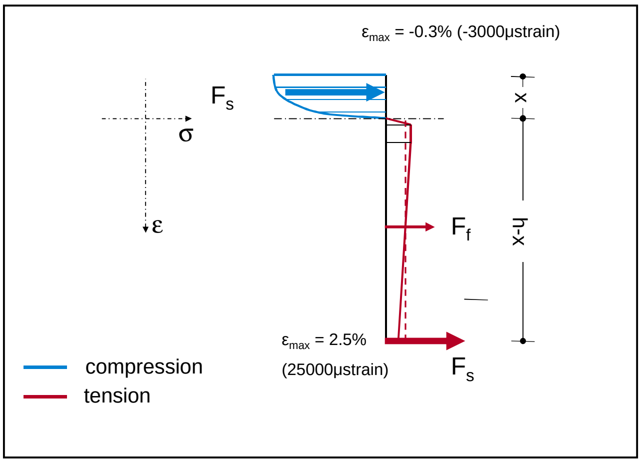

Figure 7 Stress/Strain for RC

There are a number of important points to be noticed about Figure 7 as follows:-

1. The stress strain diagram is exactly what is expected for conventionally reinforced concrete with the addition of a tensile stress block (dashed red line in figure 7) to model the effect of individual

fibres crossing the crack that develops below a sections neutral axis. For more accurate modeling a refined stress-strain diagram should be applied (continuous red line in figure 7).

2. The strain nominated at the main reinforcing bar or wire can be chosen such that the steel will have yielded, as shown, or not. The nominated stress strain diagram is therefore suitable for determining either a sections Ultimate Moment Capacity or the tensile stresses that will exist in the section under working or service loads.
3. The compressive stress in the concrete and the tensile stress in the cracked fibre reinforced concrete (c.f. Figure 6) will in reality be curvilinear in shape. However, for simplicity it is acceptable to assume a stress block for both.
4. The value used for the magnitude of the steel fibre stress block varies with the section capacity that is to be determined. For the ultimate limit state moment capacity the tensile stress value used is the residual stress value shown in Figure 6 for a crack width of 3.5mm. For the serviceability limit state (e.g. for a crack width calculation) the tensile stress value used is the residual stress value shown in Figure 6 for a crack width of 0.5mm

Point 4 above brings into play an important concept for fibre reinforced concrete, namely the interplay between the stress in the reinforcement and the width of cracks. For conventionally reinforced concrete the lower the stress and hence strain in the steel the smaller will be the crack width. Conversely, for SFRC exhibiting strain softening behavior as shown in Figure 6, the lower the crack width the higher will be the residual stress value provided by the steel fibres. For this reason, to incorporate the effects of steel fibres in a combined reinforcement solution, it is critical that the stress values used in design for both the fibres and conventional reinforcement are those that will occur for the same, or at least consistent, values of strain.

As strain is a nebulous concept for SFRC, the fibres are actually pulled out rather than being strained over some imaginary fixed length that varies with a fibres orientation in 3-dimensions, it is more practical to fall back on crack widths. The difficulty of effectively and consistently relating crack widths to strain has been addressed in the DAfStb(4) guideline on SFRC, where crack width is defined as:

w = ε_{ct} x 140mm, where ε_{ct} is the concrete strain in the tensile zone.

The fixed value of 140mm is due to defining a crack opening of 3.5mm as being equivalent to a strain of 2.5% or 25000µstrain.

This fixed relationship between strain and crack opening means that the defined stress/strain relationship applies to any depth of section, even when the material properties are derived from different sized beam tests; the same strain always gives the same crack width irrespective of the size of an actual element. This means the strain, crack width and design strength are the same irrespective of how deep your section is. RILEM (and NZS3101) on the other hand links design strength to section thickness, which means that they require a size factor to compensate. This latter approach is not being used in the recent design rules from Fib and DafStb; they have used the constant relationship between strain and crack width.

With the stress strain properties of SFRC, as well as concrete reinforced with combined reinforcement effectively defined, it is possible to determine, the tensile and ultimate moment capacity of a section reinforced with SFRC and/or SFRC combined with conventional reinforcing.

The Importance of Crack Control

A crack width calculation is based on empirical guidelines and requires an understanding of the strains and stresses in the concrete section prior to cracking as well as a number of other assumptions in regards to the strength the concrete will be when cracking actually occurs. It is therefore not an easy calculation to perform and thus not often carried out in engineering design offices. The ability to avoid performing crack width calculations is typically addressed in Concrete Standards by the provision of guideline criteria that will indirectly provide a suitable level of serviceability/durability as well as strength in the finished structure, usually built around the service stress in reinforcing steel as well as the quality and amount of concrete cover in different environments.

As concrete standards are being revised and rewritten, both in Australasia and overseas, durability and serviceability of concrete structures is becoming more and more important. Typically this is done by means of additional requirements on material properties, detailing and minimum reinforcement. In fact what these concrete standards are typically achieving with their recommendations on durability and serviceability is to impose limits on crack widths i.e. higher durability and serviceability can very often be interpreted to mean the use of more reinforcement to effectively control crack widths.

Concrete Standards typically do a good job with these guidelines when it comes to cracking caused under load. However, when it comes to cracking caused by the restraint of shrinkage and thermal movements these recommendations become much less tangible. For instance in AS3600(1) there are two recommendations for the minimum secondary reinforcement required in restrained slabs based on the degree of control over cracking that is required and a third level is added for slabs fully enclosed in a building. It is up to the engineer to decide what level of restraint is present.

The important parameters to judge if a crack is still acceptable or not will vary with the type of element, how the element is used and to what environment it is exposed. The owner of a concrete element or structure is really only interested in whether or not the element “works” and how long it lasts. It is therefore necessary that “works” is translated into an acceptable design crack width, which is the role of the designing engineer with guidance from suitable standards and technical recommendations.

An indicative example related to acceptable crack widths in reinforced concrete slabs on grade comes from DafStb(4,6) and DIN(5) as follows:

- Dry environment 0.5mm
- Soil or moisture 0.3mm
- Chlorides 0.1 – 0.3mm (+possibly coated)
- Coated 0.2mm
- Water tight 0.1 – 0.2mm (+ possibly coated)
- Environmental 0.1 – 0.2mm (+ possibly coated)
- Chemical 0.1 – 0.2mm (+ possibly coated)
- Heavily trafficked 0.2 – 0.3mm

A local example for designing concrete pavements can be taken from Austroads(2), where continuously reinforced pavements are designed for a nominal crack width of 0.3mm.

It is obvious that the usefulness of such recommendations makes it essential that a crack width calculation be performed. Fortunately spread sheets can be developed that not only perform these calculations quickly and easily but can be used to investigate the sensitivity of the assumptions an engineer needs to make when using them. As an example, BOSFA can provide Dramix 4D CombiSlab designs to engineers, contractors and the like using a design tool based on relevant European Standards.

SFRC with No Conventional Reinforcement

The strain softening behavior of SFRC is problematic in terms of calculating crack widths. Although it is theoretically possible to calculate a crack width in a section that has a permanent compression zone, the fact is that the tensile strength of the **uncracked** fibre reinforced concrete is higher than the tensile strength of the **cracked** fibre reinforced concrete. This means that for a concrete element where the full section is in tension, for example due to restraint of shrinkage and temperature stresses in a ground slab, the cracked section is the weakest section and it’s not possible to determine accurately if and where the concrete section will crack again i.e. it is impossible to determine a theoretical spacing between cracks and without a crack spacing it is also impossible to determine a crack width using current crack width calculation theory. The determination of crack spacing and hence crack widths is discussed more in the next section.

This situation can be likened to the determination of crack widths for conventional reinforcement where the tensile capacity of the reinforcement is less than that of the concrete. At a cracked section that is under reinforced it is possible for the steel to yield giving the possibility of uncontrolled and hence very large localized crack widths.

It should not be forgotten that steel fibres are effective in “locking off” or arresting the development of cracks at their earliest stage of development i.e. micro cracking. They effectively reduce the tendency of these cracks to propagate and as such fibre only saw cut free slabs on grade and rafts have been constructed successfully for many years. But it’s not possible to effectively calculate a precise crack width, making it necessary to rely on experience when nominating joint centers, fibre type and dosage.

Combined Reinforcement, the synergies

When conventional and steel fibre reinforcement are combined the strain softening behavior of SFRC does not change. However, the post cracking tensile capacity of the SFRC can be taken into account when calculating crack widths for the conventional reinforcement.

In conventionally reinforced concrete the width of a crack is a function of the distance between cracks and the distance between cracks is determined by the bond length of the reinforcing bars, this is shown graphically in figure 8 and explained below:

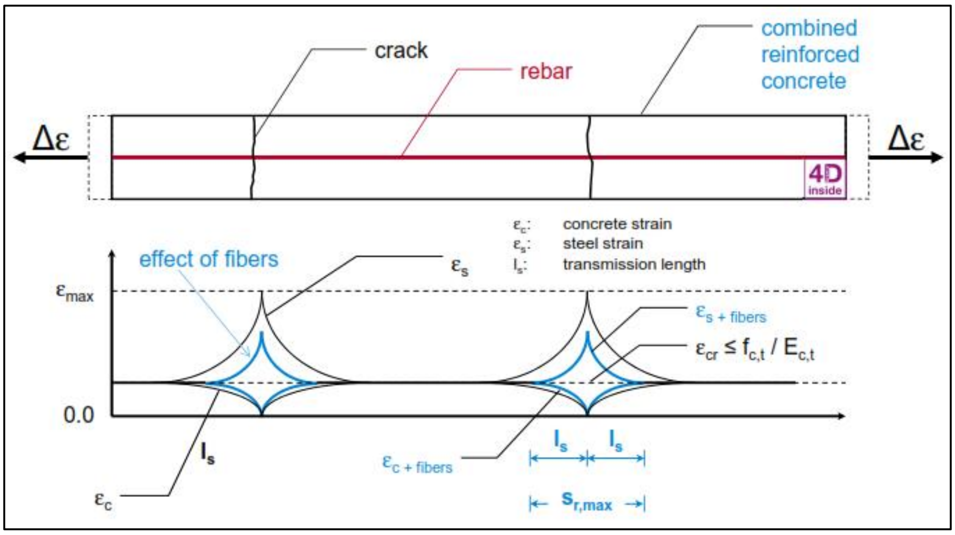

Figure 8. Initial state of cracking

At a crack the tensile force in the concrete is zero with all the tensile force being carried by the reinforcing steel. Away from the crack the reinforcing bars, being effectively bonded into the concrete matrix, transfer this tensile force into the concrete, with all the force being transferred into the concrete a distance from the crack equal to the reinforcing bars development length. This means that the minimum spacing between cracks is one development length and the maximum spacing is two development lengths. The maximum crack width will therefore result when the cracks are spaced at the maximum spacing of two development lengths. In practice, it may be somewhere in-between.
The effect of steel fibres is to increase the tensile force in the concrete at a crack from zero to the tensile capacity of the cracked SFRC. The result of this is that the tensile force in the conventional reinforcement at the crack is reduced and the development length of the steel is consequently reduced. The same holds for the strain in the steel. Reducing the development length and the strain of the reinforcement reduces the maximum distance between cracks and thus results in more but narrower cracks. This has a significant effect on the amount of bars or mesh required for a particular crack width design, using a SFRC with a residual tensile strength > 1.0 N/mm^2 can reduce the conventional reinforcing by about 50% for the same level of crack control.
As a simplification of this concept the crack width w_k may be seen as a function of the concrete tensile strength f_{ct} in the case of reinforced concrete and a function of the concrete tensile strength minus the cracked tensile strength of SFRC $f_{ct,SFRC}$ in the case of combined reinforcement, this is shown in equation (1):

$$w_k = \text{function } [f_{ct} - f_{ct,SFRC}] \qquad (1)$$

A number of related test programs [3,8,10,12] have been carried out and a number of design methods have been proposed. These approaches differ in some points but more or less follow the same principle, namely the reduction of the concrete tensile strength by the post crack tensile strength of SFRC.

Apart from serviceability and the determination of crack widths, the post crack strength of SFRC may also be taken into account for the ultimate limit state, where significant contributions to the load bearing capacity are possible. In joint free slabs there is also no requirement to model the floor loads on a joint, this leads to more efficient use of concrete – thinner slabs.

Practical Experiences

Over 1m m^2 projects have been constructed utilising combined reinforcement in countries all over the world. A few examples are given to explain why combined reinforcement was used and what benefits were achieved.

NZ, Container handling pavement

Pavements designed for the handling and storage of containers need to accommodate high loads and constant wear and tear which invariably damages joints, resulting in expensive maintenance programs. Reducing or eliminating these joints is an attractive proposition to the asset owner. This project is about 13,000m^2, the pavement winds its way round corners and up slopes, has been designed to accommodate stacked containers and is completely joint free. The SFRC was used in the ULS design, resulting in a thinner slab compared to PT and conventional reinforcing, AND it was used for SLS crack control in combination with one layer of mesh. Design crack width 0.25mm.

Belgium, E17 motorway

The E17, a major Belgian highway was constructed with a lane using SFRC in combination with 20mm reinforcing bars. Crack width is an important parameter for the long term performance of CRCP, particularly the development of punch outs (pavement failure). Using a CombiSlab enabled a reduction in calculated crack width, allowed a reduction in longitudinal reinforcing and improved the risk associated with punch out failure.

NZ, Commercial building, restrained joint free floor

The building is 95m x 45m and has full restraint along one 95m length from tied in precast panel walls. Using conventional methods of construction, this level of restraint would have required jointing in the floor. Taking this restraint into account in the design through combining SFRC with one layer of 441 mesh (7.5mm wires at 100c/c) enabled the construction of the floor without any joints. Eliminating construction, and importantly, maintenance costs associated with saw cuts and movement joints. The increase in load carrying capacity provided by the SFRC resulted in a slab thickness of 130mm. Design crack width of 0.25mm.

NZ, Containment bund, joint free water tight

Leakage of containment bunds can be an issue and costly to put right. Typical design and construction has sealed joints and expensive water stops. However, if the bund cracks outside these control points then there commonly isn't enough reinforcing to control them to acceptable levels. Combining SFRC with one layer of mesh enabled the design of a water tight layer and construction of the bund without any joints. 120mm thick, design crack width 0.2mm.

NZ, Bulk Storage facility, restrained joint free floor

This building is approximately 10,000m2, split into four rooms. The precast panel walls required large foundations due to the storage of bulk materials, and these were cast monolithically with the slab, fully restraining the floor. The whole building was constructed completely joint free using SFRC plus one layer of mesh. Design crack width 0.3mm.

Australia, 15,000m^2 seamless floor

The main challenge with this project was being able to accommodate 25t post loads, re-entrant corners, the slab being tied into the perimeter and tight time constraints. All this was taken into account in the design and a completely joint free floor was constructed using SFRC plus one layer of mesh. Design crack width 0.25mm.

NZ, external saw cut free yard slabs

Sealing of external saw cuts is time consuming, expensive and requires maintenance. Saw cut free panels approximately 30 x 30m, constructed using SFRC plus one layer of light mesh. Design crack width 0.25mm.

Australia, dam spillway

This joint free watertight spillway is approximately 700m long. The conventional design used 2 layers of bars plus mesh and very expensive jointing. The SFRC option was used in combination with one layer of heavy mesh. This resulted in a solution that was cost effective, joint free, more durable and quicker and easier to build, Design crack width 0.2mm.

Conclusions

Combining SFRC with mesh or bar provides the engineer and contractor greater flexibly in slab construction; restraint, panel size and shape, as well as joint location are no longer a constraint on design. Importantly, designing for controlled cracking under service stresses and the elimination of joints will result in a floor that is more durable, serviceable and maintenance free, a very attractive proposition for the building owner. The CombiSlab solution also provides an economic option for liquid retaining structures such as containment bunds, dangerous goods store floors, tank base slabs and watertight basement rafts/slabs.

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