Steel fibre reinforced concrete combined with conventional reinforcing – Joint Free pavements

Alan Ross CPEng IntPE, NZ Manager, BOSFA

Synopsis

Steel fibres and conventional reinforcing mesh/bar are both used to effectively reinforce concrete due to their ability to provide an effective restraining tensile force across any cracks that open. In Australia and New Zealand this has typically resulted in steel fibres being substituted for mesh in the main applications of slab on grade, shotcrete for ground support and precast concrete elements, as well as a number of other more specific applications. In Western Europe it is becoming more and more common to also use combined reinforcement solutions, which consist of both steel fibres and conventional steel reinforcement. The synergies that result from combining these two types of reinforcement make it possible to achieve commercially competitive solutions when designing to reach a desired level of ultimate load carrying capacity or serviceability. This innovation has been driven by the incorporation of the combined reinforcement option into various technical approvals and design guidelines currently available in Europe.

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

1. 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 the cracked section is 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, 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 restraint, temp, (and deformation) to 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 designs rules that make it possible to use steel fibre reinforced concrete (SFRC) in combination with conventional reinforcing. The combination of using SFRC and conventional reinforcing can significantly reduce the expected crack width and has a strong effect on the amount of bar or mesh required when designing for the SLS. The following paper provides a short introduction to the design of combined reinforcement.


2. The Importance of Crack Widths

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 \textsuperscript{14} 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 \textsuperscript{7(9)} and DIN \textsuperscript{8} 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 \textsuperscript{16}, where typically 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. BOSFA has just such a spreadsheet for combined reinforcement.
3. 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 or raft, the cracked section is the weakest section and it is impossible to determine 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, and they do effectively reduce the tendency of these cracks to propagate, but it is not possible to effectively quantify their performance in this regard, making it necessary to rely on experience when nominating joint centers, fibre dosages and the preparation of any supporting surfaces.

4. 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 certainly 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 as follows:

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.

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.

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 i.e.

\[
w_k = \text{function}[f_{ct} - f_{ct, SFRC}].
\]

A number of related test programs have been carried out and a number of design methods have been proposed (10)(11)(12)(13). 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 minor, but in some cases significant, contributions to the load bearing capacity are possible.

5. Effect of Combined Reinforcement on Quality and Speed

The influence on quality may be seen from different perspectives. As a rule of thumb, the required amount of reinforcement can be reduced by up to 50% when using high performing steel wire fibres. This allows for larger distances between reinforcing bars and/or smaller diameters while keeping crack widths at the same level. As a consequence the reinforcement placing process will typically become less complicated, more accurate and faster. Placing and compacting concrete also becomes easier with better results being likely. In many cases, reinforcing bars can be replaced by welded mesh so that even more time is saved and other building methods can be applied. Examples will be given in the following chapter.

Another option may be to keep the original reinforcement details the same, but significantly improve the quality in terms of cracking, by simply adding steel fibres in addition to the foreseen reinforcement.

In any case, steel fibres even reinforce the concrete cover - which is definitely not the case for reinforced concrete alone. Furthermore, the whole section benefits from steel fibres, even outside the zone within which the conventional reinforcing steel is effective.

Very often short construction time and high quality conflict on a construction site. In the case of combined reinforcement, durability, serviceability and construction time may be improved in one pass. Significant savings of maintenance costs may therefore also be achieved. Hence it makes good sense to evaluate the costs, and also the savings, over the full live time of structures with combined reinforcement.

7. Practical Experiences

A variety of projects have been built with 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.

7.1 E17 motorway

The E17, a major Belgian highway was constructed with a lane using Dramix® 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 CombiSlab enabled a reduction in calculated crack width, allowed a reduction in longitudinal reinforcing and improved the risk associated with punch out failure.
7.2 NZ, Raupuha Road tunnel

The Raupuha Road tunnel located on a back road deep in Taranaki, was required to be designed with no joints along the length of the tunnel. This meant there is 110m between joints and the CombiSlab jointless panel has a remarkable length to breadth ratio greater than 30:1. Dramix® SFRC was used in combination with one layer of mesh (A = 314mm²/m). Being able to use one layer of mesh instead of potentially two layers or reinforcing bars, simplified construction, improved crack control and reduced cost.

7.3 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 Dramix® SFRC with one layer of mesh (As = 400mm²/m) 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.
7.4 NZ, Dangerous goods store, joint free liquid tight

Dangerous goods stores require concrete slabs to act as liquid tight membranes. The separate areas have irregular length to breadth ratios (two rooms of 31m x 10m and 85m x 21m) that would typically require jointing. The design crack width was 0.1mm would have required heavy bar reinforcing (10mm bars at 110mm centres each way and top and bottom) in a conventional design. Combining Dramix® SFRC with one layer of mesh, 7.5mm wires at 100mm in one direction and 150mm in the other, resulted in a more cost effective solution that simpler to construct.

7.5 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 Dramix® SFRC with one layer of mesh (As = 500mm²/m) enabled the design of a water tight layer and construction of the bund without any joints. 120mm thick, design crack width 0.2mm.
7.6 NZ, Victoria Park Tunnel, primary shotcrete lining, watertight layer

The primary shotcrete lining was sprayed over secant piles and watertightness in this environment is of paramount importance. Dramix® SFRC was used in combination with traditional reinforcing in the watertight shotcrete layer; significantly reducing crack width and or the required amount of reinforcement.

7.5 NZ, Slab track construction

The original slab track design included heavy top and bottom reinforcing which would have required surveying the location of every track bolt when the reinforcing cage was installed and after the slab was poured. The areas where more than one track joined on a bend would have made it a difficult task to locate the bolt in a position to avoid the top reinforcing. By using Dramix® SFRC it was possible to remove the top layer of reinforcing; simplifying construction; improving crack control and reducing cost. The expected multiple fine cracks were also expected to provide the concrete with a longer life and low maintenance.
The industrial floor of a handling facility for metal scrap (metal recycling facility, St. Gallen, Switzerland) was foreseen as a jointless slab with dimensions of 100m x 40m. Loads originate from metal scrap and the steel structure of the building. Heavy impact loads from scrap handling also needed to be considered. Retaining walls, clamped to the slab, allowed heaping up scrap to a height of more than 5m.

As the slab was cast under exterior conditions before the actual building was finished, restraint deformations due to temperature were likely to occur. The slab was fully restrained by connecting it to the strip foundations of the exterior walls. Therefore crack inducing deformations were expected to occur even after years. For durability reasons, a calculated crack width of 0.2mm was required.

Looking at the total costs of ownership, the investor preferred combined reinforcement to reinforced concrete. Finally a 25cm slab was cast with a concrete C30/37 containing Dramix® SFRC reinforced with two layers rebar Ø12-15cm.

The foundation slab and also the cellar walls of an office building (local tax authorities, Hersbruck, Germany) had to be designed for a calculated crack width of 0.1mm. This severe requirement is due to ground water pressure. A concrete C25/30 was used containing Dramix® SFRC.

The 60cm slab, ~43m long and ~11m wide, had to be reinforced with Ø14mm at an alternating bar distance of 35mm and 100mm respectively to allow for sufficient workspace. For the 25cm walls, a mesh Ø10-15cm plus additional rebar Ø10-20cm at the in- and outside was sufficient.

The amount of reinforcement needed was still high. But compared to reinforced concrete, smaller diameter bars were able to be used, at a distance which still enabled the workers to place and compact the concrete in a proper way. This, of course, is almost as important as a sufficient amount of reinforcement if a crack requirement of 0.1mm is to be met in practice.
7.8 Raft in SLS and ULS

At a court house (Södertörns Tingsrätt, Flemningsberg, Sweden) combined reinforcement was used to reinforce the load bearing foundation slab.

The 60cm slab with an uneven soffit was founded on rock, crushed rock and piles. Water pressure of 15kN/m² had to be compensated for by the dead weight of the slab in order to avoid floating. Required crack control was provided by a top layer reinforcement of rebar Ø10mm at 100mm spacing and Dramix® SFRC.

As the effect of fibres was also taken into account for ultimate limit state, additional reinforcement only had to be placed locally, especially at the bottom and basically where load bearing columns of the building were located. Slab dimensions were ~ 32m x 30m. Pumping and placing the concrete did not cause any problems, due to the provision of a suitably designed concrete mix. Reducing and simplifying the reinforcement and thus reducing construction time led to major savings for the contractor.

Calculated crack width was 0.2mm. Despite the slab having maximum dimensions of 32m and being connected to the ground, no visible cracks could be found even half a year after execution.

7.9 Shotcrete Shell

Combined reinforcement was used for a thin shell structure (Oceanographic Park, Valencia, Spain). Due to the curvature and the very limited shell thickness of 6cm to 12cm it would have been very difficult to install a complicated traditional arrangement of reinforcement in an accurate and safe way. A maximum diameter of 8mm rebar was preferred due to required concrete cover and the need to curve the reinforcement. As the reinforcement had to be placed close to or even at the neutral axis of the section, post crack strength was also taken into account for the ultimate limit state design.\(^{(15)}\)

Dramix® RC-80/35-BN and a single layer Ø8-15cm were applied, providing durability, serviceability and strength.
8. Conclusions

Combining reinforced concrete with steel fibres offers new possibilities to improve the building process on the one hand, and serviceability and durability of concrete structures on the other hand. A number of design methods are available and may be used for designing combined reinforcement. Very positive practical experiences have confirmed the concept from both a design and practicality view point as well as identifying the economic benefits offered. There appear to be few, if any, reasons for engineers and builders not to consider this option on many more projects going forward and for it to become a standard construction practice over time.

9. References

1. DIBt, Deutsches Institut für Bautechnik: Z-71.3-18 - allgemeine bauaufsichtliche Zulassung für Fundamentplatten aus Stahlfaserbeton für den Wohnungsbau (DIBt, German institute for construction technology, Z-71.3-18 - general approval for steel fibre reinforced load-bearing foundation slabs in housing applications), Germany 2000.
2. DIBt, Deutsches Institut für Bautechnik: Z-71.3-36 - allgemeine bauaufsichtliche Zulassung für Fundamentplatten aus Stahlfaserbeton (DIBt, German institute for construction technology, Z-71.3-36 - general approval for steel fibre reinforced load-bearing foundation slabs), Germany 2009
5. NZS 3101:2006 Concrete Structures Standard
7. DAfStb, Deutscher Ausschuß für Stahlbeton: Richtlinie für Betonbau beim Umgang mit wassergefährdenden Stoffen (DAfStb, German Committee for Structural Concrete: technical rule on concrete structures for hazardous substances), Germany 1996 - 2011
8. DIN 1045-1:2008 Concrete, reinforced and prestressed concrete structures — Parts 1-3
9. DAfStb, Deutscher Ausschuß für Stahlbeton: Richtlinie Stahlfaserbeton (DAfStb, German Committee for Structural Concrete: technical rule on steel fibre concrete), Germany 2010
11. P. Niemann: Gebrauchsverhalten von Bodenplatten aus Beton unter Einwirkung infolge Last und Zwang, Heft 165 der Schriftenreihe des iBMB, Eigenverlag TU Braunschweig (P. Niemann, Serviceability of ground supported concrete slabs subject to load and restraint deformation, publication No. 165 of iBMB at TU Braunschweig, Germany)
15. A. Domingo, P. Serna, C. Lazaro: Estudio del comportamiento del hormigon con fibras de acero en elementos laminares de pequeño espesor y su comportamiento post-fisuracion, Hormigon y Acero, n° 233,3 Trimestre 2004