Steel Fibre Reinforced Concrete (SFRC): Areas of Application

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The use of steel fibres in grade slabs such as industrial floors, warehouses, ports and highway pavements has been prevalent in many countries for over 4 decades. They are known to have been widely used in Hydro sector, particularly tunnel linings and slope stabilization. In India, thanks to the improvements in steel fibre technology and more user experiences in terms of economy and durability, the use of Steel Fibre Reinforced Concrete (SFRC) is gaining traction. Advancements in admixture technologies over the last few decades coupled with developments in fibre manufacturing technology (e.g. collated/glued fibres) have enabled easier mixing, batching and improved workability of SFRC. There is an increased understanding in the industry that each fibre type behaves differently and this fact must be considered while specifying steel fibres and designing SFRC elements in various projects. However, it is also true that absence of appropriate material specifications for SFRC and lack of Indian standards for testing and design has led to a rather slow acceptance of the concept.

Behaviour and Characterization of SFRC

SFRC is a concrete that has a homogenous distribution of randomly oriented discontinuous and discrete steel fibres. Steel fibres are introduced in the concrete matrix during the mixing of its constituent ingredients. Upon hardening, these fibres improve the properties of concrete such as ductility, fracture toughness, energy dissipation, impact resistance, fatigue resistance and limiting of crack propagation. Under tension, as cracks start propagating inside concrete, steel fibres present in the matrix bridge the cracks and transfer the tension across them during this process. Thus, SFRC actually causes no considerable increase in the flexural strength (modulus of rupture) of the concrete yet contributes in improving the load carrying capacity of a structural system on account of increased toughness and rotation capacity.

The behaviour of plain concrete and SFRC is made clear with the help of a four point beam bending test as illustrated in Figure 1. It is observed that for plain concrete, a sudden and brittle mode of failure occurs after the peak load is reached which then is used to calculate the flexural strength of the concrete. When sufficient ductility is ensured in the beam with the addition of steel fibres in concrete, a strain softening phenomenon is observed after the load at first crack or peak load in the beam. Thus, with this kind of toughening behaviour in the beam, post-crack flexural strength of SFRC is guaranteed.

Adding steel fibres purely on a volume fraction basis has its disadvantages in that it fails to differentiate between various kinds of steel fibres and considers the volume of steel added as the only criterion. This is obviously not true because for a given volume of fibres, smaller diameter fibres are more in number than the larger ones. This consequently results in a larger network of fibres within the concrete matrix which would definitely alter the performance of the concrete due to higher confinement. Similarly, aspect ratio (length/diameter) of the fibre has a greater bearing in the performance of SFRC in that higher aspect ratios yield better performance due to longer anchorage lengths and fibre network. Apart from the differences in sizes and aspect ratios, steel fibres may come to differ in shape (straight/hooked end/ undulated), form (fibres glued together with water soluble glue/ loose), tensile strength (high/medium/low) and materials (mild steel/ galvanized/stainless). Thus, all fibres are not alike (Figure 2) and must be selected based on the requirements of the user and applications they will be put to use.

SFRC Applications

One of the major goals of design of structures is to provide for predictable ductile failure modes and avoid brittle unpredicted modes. In other words, the first crack in the structural system must never be the last crack and there should be multiple load paths to have some redundancy. In all systems where this holds (meaning statically indeterminate structures), steel fibres come across as excellent substitutes to conventional...
concrete. Moreover, the fibres contribute to the bending stress block by allowing the tension side of concrete to be used in the moment resistance calculations as shown in Figure 3. The following paragraphs list appropriate applications for SFRC use in both ULS:

Grade Slabs

One of the major application areas of SFRC happens to be “slab-on-grade” (industrial flooring, concrete pavements, ground slabs etc.) where it has been a well-established building material and a meaningful alternative to plain or reinforced concrete. Slab-on-grade can be defined as a slab that can be fully supported by a sufficiently compacted sub-base (see Figure 4). The general loading cases in such a structure include stationary loads due to racks, pallets, containers etc. and moving loads like trucks, stackers and fork-lifts.

As a design basis, bending moments are calculated according to the appropriate ground support and loading conditions. Depending on whether the slab is plain concrete or SFRC, appropriate design approaches have to be used. Conventional plain concrete slabs work only up to a point where the stresses in the slab lie within the elastic range of the material. As soon as the stresses in the slab exceed the elastic threshold range, the plain concrete cracks in a brittle manner, losing its capability to carry any further substantial loads. Such a scenario in slabs leads to large cracks which require costly repairs. SFRC slabs on the other hand work on the principle of load redistribution which allows the use of a plastic design approach where the stresses in the slab are not just limited to an elastic threshold value, but are allowed to go beyond by the sheer capability of this transformed material. The plastic design approach allows for the full properties of SFRC to be put to use.

Real scale lab tests performed to characterize the behaviour of plain concrete vis-à-vis SFRC reveal a lot of differences. Results show distinct and large cracks appearing in plain concrete slabs that run through the section, dividing the slab into various pieces as soon as the moment capacity is reached while SFRC on the contrary allows for yielding of the slab by progressively smearing the excess moments, leading to finer cracks as illustrated (Figure 5).

Shotcrete Tunnel Linings

Construction of tunnel linings forms an integral part of any tunnel drilling activity. After the drill and blast operation inside a tunnel, the surrounding rock mass requires some kind
of a temporary support which is typically provided by thin shotcrete linings. The role of such a shotcrete lining is not to try and support the original ground pressures but to stabilise the deformations required to mobilise the inherent ground strength. Consider an illustration (Figure 6) which details the Ground-Lining interaction inside a tunnel. As excavation proceeds, ground moves into the tunnel and radial pressure required for equilibrium reduces as the ground strength is mobilized. Following completion of lining at B, load from the ground causes inward movement of lining until a point C of equilibrium at which radial pressure required for equilibrium is provided by the lining.

Rock supports in tunnels involve a constant risk of unexpected loads and deformations. In such a case, the best safety is achieved by having a shotcrete layer support that allows for the highest possible fracture energy i.e. toughness or ductility.

**Segmental Linings**

Segmental linings are the support system for shield Tunnel Boring Machine (TBM) excavated tunnels. Precast concrete segments are assembled inside the shield to form a series of rings (Figure 7) that become the support structure of the tunnel. Such tunnels are mainly used for Water Transportation and Metro Rail Projects. It is possible to partially or fully replace conventional steel bar reinforcement with steel fibres in recast segments based on the loads acting in the ring section. Steel Fibres in precast segments help in decongesting steel reinforcement cages and are greatly reduce the chipping and spalling of concrete in segments during handling, stacking and installation (Figure 8). Unreinforced concrete cover areas even in heavy conventional rebar reinforced segments are often prone to damage. Steel Fibres provide a 3 dimensional reinforcement in the entire section of the segments greatly reducing the extent of such damages.

**Structural Elements**

Steel Fibres have been used in structural elements world over to achieve a variety of objectives best suited and justified on a case-to-case basis. For example, the world famous Oceanographic Park at Valencia, Spain (Figure 9) had steel fibres shotcreted in conjunction with steel mesh to allow for an easy installation due to the curvature of the structure and accommodate the limited design shell thickness (6 cm to 12 cm). Similarly, fibres have been known to reduce congestion of reinforcements in link beams and beam column junctions in tall buildings.

Rafts and Foundation Slabs of Buildings have also been getting equal attention in extreme cases where the regular reinforcements are too congested and the bar diameters are already too high (≥ 32 mm) to allow for further increase. In such cases, steel fibres become most suited as they contribute substantially to the moment capacity of the sections.

**Fibres working in Serviceability Limit State (SLS)**

Apart from bending, fibres work in containing cracks in axial direction as well. Steel fibres lead to formation of controlled crack patterns with reduced crack widths, and thus appropriate for crack width design. Consequently, in cases where clients impose stringent limits on crack-widths and liquid tightness, less rebar reinforcements are required (smaller diameter, larger distances) and the durability and serviceability of the structural elements is greatly improved.
Liquid Tight Floors

Some industrial/warehouse floors need to be designed in such a manner that they have to act as a secondary barrier against hazardous goods that may leak from the storage containers. Usually a very stringent crack-width limit of 0.1 mm is imposed on the floor in such industries (Figure 11). Such projects are almost certainly required to be combined reinforcement (Mesh + Fibres) to fully leverage the benefits of the composite system in an optimal manner.

Water Tight Raft Foundations

Similar in concept to the liquid tight floors, the primary concern for rafts is the seepage due to uplift forces of water from beneath which can lead to certain crack-width requirements for the structure. For example, the project illustrated in Figure 12 involved the use of combined steel fibres + rebar reinforcement to reinforce the load bearing foundation slab. Calculated crack width was 0.2 mm. The 60 cm thick slab had an uneven bottom and was founded on rock, crushed rock and piles which increased the possibility of restraint cracks. A combined fibres + rebar solution got rid of the problem and led to major savings for the contractor due to reduction in construction time because of simplification of the slab reinforcing scheme.

Conclusion

We have seen until now as to how steel fibres have certain technical advantages that make them suitable and preferable for the applications listed. However, one must also not forget that using fibres to replace steel reinforcements in part or whole make sense practically on site as well in terms of saving man-hours (with the reduction/elimination of bar bending activities) and construction time (no rebars to be laid). With increased understanding of properties of SFRC, coupled with standardization and further improvements in fibre manufacturing, one is bound to see an increase in the use of Steel Fibres in Construction in the coming years.