High Performance Fiber Reinforced Concrete and its application in the Anchorage Zone of Post Tensioned Concrete Girders - A Review

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ABSTRACT: *Study of the advanced composites and the fundamental understanding of their behaviour has picked great momentum in the field of civil engineering in the past few decades. Use of High Performance Fiber Reinforced Concrete (HPFRCC) eliminates the transverse reinforcement with its higher energy dissipation, ductility, thermal resistance and slower stiffness degradation capabilities. The increasing development and availability of HPFRCC is providing enormous opportunities in structural applications particularly where improved damage tolerance is desirable. The stress distribution in the anchorage zone of a post tensioned beam is complicated and can depend on several factors such as the location of prestress force, the magnitude of prestress force, the transfer length, the quantity and arrangement of stirrups, presence of cracks and the size of the beam cross-section. Cracks developed in the anchorage zone pose severe strength and serviceability issues and their repair is costly, time consuming and few repair options exist. From an ownership and inspection standpoint, it is highly desirable to have minimal crack formation. A lot of research has been done on the application of HPFRCC in this zone. The paper provides a comprehensive review of the developments in the field of HPFRCC and its application in the anchorage zone of post-tensioned concrete girders.*

Key Words: *HPFRCC; Anchorage Zone; Post Tensioned.*

1.0 INTRODUCTION

Reinforced Cement Concrete is a widely used material for infrastructure development and especially in the transportation sector due to strength, stiffness, performance, efficiency and the economy that can be achieved with this material. Its use for construction of bridges reached its peak in the middle of 20th century and many notable bridges have been built using reinforced concrete given its wide civil and structural applications due the design flexibility it offers. Prestressed concrete overcomes the inherent property of concrete being weak in tension by introduction of predetermined engineered stresses which counteract the service stresses. Full prestressing allows complete elimination of tensile stresses while cracking may be allowed in partial prestressing at full service loads [1]. Longer spans and smaller sections can be achieved using prestressed concrete which made it a popular and economical technique for bridges apart from other applications like high rise buildings, slabs, prefabricated components like pipes, pressure vessels and offshore structures. Use of unbonded tendons even allows for maintenance and rehabilitation of such structures. In spite of many advantages, prestressed concrete presents many challenges. Application of prestressing force due to release of strands introduces high compressive and tensile local stresses making it susceptible to cracks and posing serviceability issues. This problem is more severe in post tensioned beams than in pre tensioned beams where the force is introduced gradually [2]. To counter these stresses, there is a lot of congestion of reinforcement in the end (anchorage) zones.

Since the early 1990's, possibilities are being explored by researchers for utilization of Fiber Reinforced Cementitious Composites (FRCC) in the anchorage zones of prestressed and post-tensioned bridge girders to reduce the amount of secondary reinforcement. FRCC consists of discontinuous discrete reinforcing fibers included as a part of concrete mix. Based on the fiber type, modulus, aspect ratio, strength, surface bonding characteristics, content and orientation, embedment; they can enhance the strength, crack resistance, impact resistance and shear capacity [3] of concrete. Since Biblical times, approximately 3500 years ago, brittle building materials, e.g. clay sin baked bricks, were reinforced with horse-hair, straw and other vegetable fibers [4].

Conventional concrete designed on the basis of compressive strength does not meet the functional requirements such as impermeability, resistance to frost and thermal cracking. To overcome these shortcomings, in mid 1980s, High Performance Cementitious Composites (HPCC) specially developed to suit a particular application and performance requirements, gave new direction to developments in this area. Based on their tensile performance, Naaman in late 80's proposed a new class of FRCC, referred to as High-Performance Fiber-Reinforced Cementitious Composites (HPFRCC).

This paper aims at describing the present state of knowledge and technology of HPFRCC and its application in the anchorage zone of post-tensioned girders.

2.0 POST-TENSIONED ANCHORAGE ZONES

Post-tensioning as a prestressing technique developed after 1923. Ulrich Finsterwalder invented the Dywidag post-tensioning system in 1940's after which it was widely used in bridges. VSL Post-tensioning systems have been used throughout the world after 1956. Anchorage Zone is the region where the prestressing force is transferred from prestressing steel to the concrete and then more widely to the member. Assessment of stresses in this zone is a problem generally encountered in design and has been of concern for over 70 years. The first publication related to the problem of anchorage zone was done in 1946 by Professor Mangel. The first Post Tensioning Manual came up in 1972. After the research done by Breen et al (1991) [5], AASHTO for the first time, included the post-tensioning anchorage design guidelines in its bridge specifications. IS 1343: 2012 [6], Canadian Highway Bridge Design Code, Australian Standard for Bridge Design also include similar guidelines.

High local stresses are developed in the vicinity of the anchor plate. In the zone immediately near the anchor plate, a tri-axial state of compressive stress (bearing stresses) is developed while the state of stress changes to vertical compression and biaxial tension little away from the anchor plate [7]. The state of stress induced in this zone is highly complex and three dimensional in nature [8]. Fig. 1 illustrates stress distribution in the anchorage zone. Along the axis of loading, transverse tensile stresses are developed. Such stresses were also found in studies conducted in 2013 [128]. The magnitude of the stress is sometimes higher than the permissible tensile stress in concrete at some location in the anchorage zone, leading to bursting of concrete in the zone. Transverse tensile stresses are also developed in the regions around the free corners of the beams designated as spalling stresses.

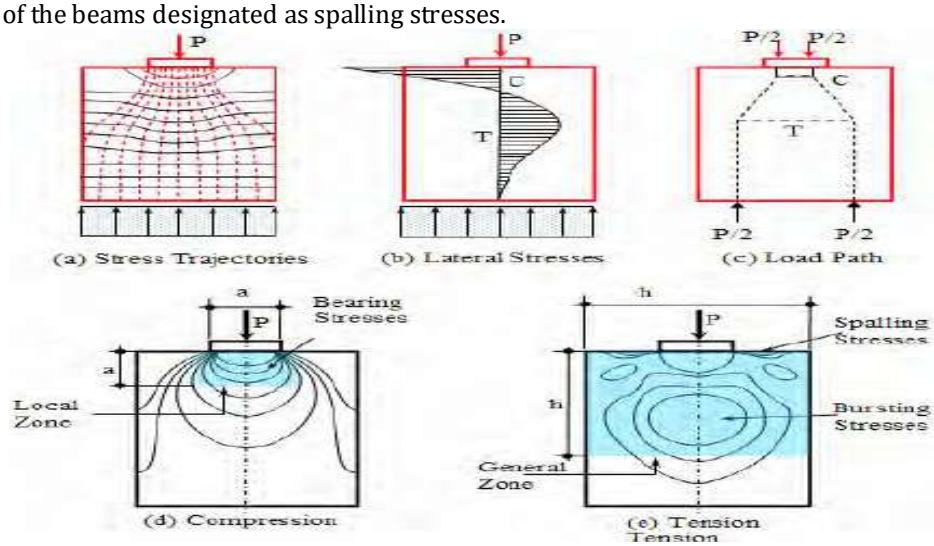

Fig. 1 Stress Distribution in the Anchorage Zone [9]

AASHTO 2014 LRFD Bridge Design Specifications specified anchorage zone to be comprised of two regions namely 'General Zone' and 'Local Zone'. Local Zone is considered to be in the immediate vicinity of anchorage plate whereas the General Zone including the local zone has transverse dimensions as the depth and width of the section but not larger than the longitudinal dimension of the component (or segment). The longitudinal dimension is between 1 to 1.5 times the larger lateral dimension [10]. The end anchorage zone also transfers shear force from girder to the bearing [11]. Interior anchorage also experience tie stress and tie-back stress [12]. Failure of anchorage zone would mean loss of prestressing force which is not easy to rectify. Most of these failures occur at construction stage and are repaired and not reported.

Different types of anti burst reinforcement such as spiral helices, rectangular helices and U-bars are used. There are no set standards as to which type of reinforcement is used as long as the required area of

reinforcement is provided in the entire zone [13]. Since, there is a lot of congestion of reinforcement in the post-tensioning anchorage zone (Fig 2); leading to poor concrete consolidation and hence failures in the zone. Construction in this part is also labor intensive and causes delays and hence adding to the construction cost in the form of claims. Use of high strength concrete can eliminate use of spiral reinforcement but lateral reinforcement is imperative in the anchorage zone to take care of the high stresses [124]. HPFRCC has been found to be a better option to replace skin and spiral reinforcement, thereby avoiding congestion of reinforcement in the regions.

Fig. 2 Steel Congestion in Post-Tensioned Anchorage Zone in a Segmental Bridge [9]

3.0 FIBER REINFORCED CEMENTITIOUS COMPOSITES

Concrete being a heterogeneous material can be regarded as a two-phased material consisting of aggregate dispersed in the cement mortar matrix, and heterogeneity can be taken into account by assigning separate modulus of elasticity for different ingredients. Prestressed concrete requires concrete to attain high compressive strength at an early age. High Strength Concrete (HSC) possesses high compressive strength, tensile strength and reduced shrinkage and creep strains as compared to Normal Strength Concrete (NSC). HSC has been found to be more brittle when compared to normal strength concrete and inclusion of fibers is one way to alleviate the problem of brittleness in High Strength Concrete.

The application of Fiber Reinforced Cementitious Composites (FRCC) to enhance performance of structural elements has been the subject of many researchers since 1960s, although the first patent was in 1874 [14,15]. Fiber Reinforced Concrete (FRC) consists of discontinuous discrete reinforcing fibers included as a part of concrete mix. Based on the fiber type, modulus, aspect ratio, strength, surface bonding characteristics, content and orientation, embedment; they can enhance the tensile strength, flexural strength, first crack strength, post crack resistance, fatigue strength, impact resistance, spall resistance and shear capacity [3] of concrete and even the development/splice strength of reinforcement [16]. Basic creep, shrinkage and total deformation of concrete are also reduced [17]. Such concretes find applications in industrial floors, heavy traffic concrete roads, military structures, seismic resistant strategic structures [14, 18], prefabricated elements and as retrofitting concrete [19]. Steel, nylon, synthetic, carbon, plastic, glass, natural materials, asbestos, vegetable such as sisal and jute fibers have been used for the purpose. Use of steel fibers in shotcrete, precast concrete, concrete slabs, concrete floors started as early as in 1960's [20].

3.1. MATRICES AND FIBERS FOR FIBER REINFORCED CONCRETE

The main components of the matrices for FRC are Portland cement, coarse and fine aggregates and other components like superplasticizers, admixtures and micro fillers. Proportion, origin and type of each of these components can be varied to get desirable properties of the matrix.

A variety of short discrete fibers have been used in construction mortar and concrete. Use of natural fibers such as straw, bamboo has popular since ancient times. The first possibility of usage of steel fibers was highlighted by Porter in 1910. The use of glass fibers goes back to late 1950s [21] and that of synthetic fibers to 1965 [22]. They can be characterized based on parameters like material, geometry and physiochemical and mechanical properties (Fig. 3).

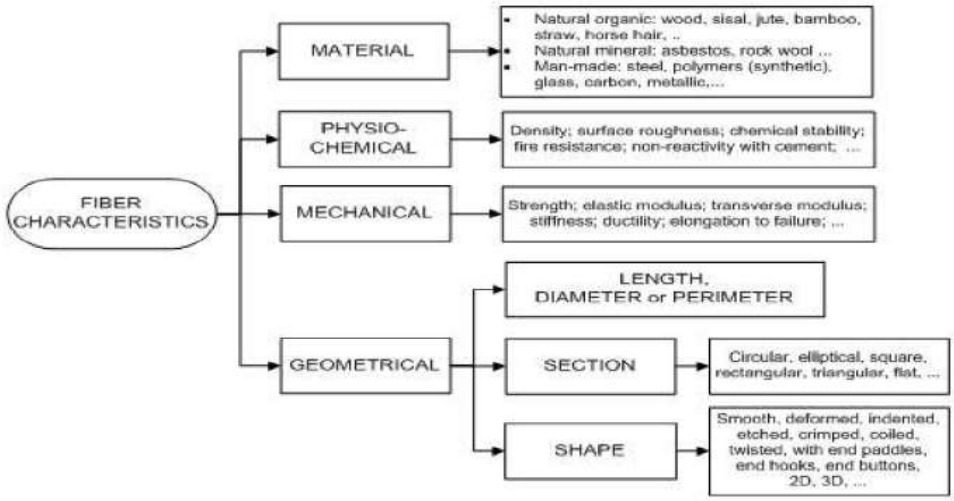

Fig. 3 Main fiber characteristics of interest in fiber reinforced cement composites [15]

Mixing of fibers with other constituents can be done using methods such as plant batching, ready-mixed concrete or hand mixing in laboratory. Ensuring uniform dispersion of fibers, preventing segregation or balling of fibers during mixing is important. Factors such as fiber aspect ratio, volume percentage of fiber, coarse aggregate size, gradation, quantity and water/ cementitious ratio and method of mixing. A maximum aspect ratio and steel fiber content in excess of 2 vol. % make it difficult to achieve a desirable mix [23].

Post-elastic property changes in the behavior of FRC depend on a number of factors like matrix strength, fiber type, fiber modulus, fiber aspect ratio, fiber strength, fiber surface bonding characteristics, fiber content, fiber orientation and aggregate size effects [24]. As per ACI 544.1R 1993 and 1996 guidelines, steel FRC may be used in supplementary role to inhibit cracking, improve resistance to dynamic loading; synthetic fibers (made with polypropylene, polyethylene and polyolefin, polyvinyl alcohol) for non-structural and non-primary load bearing applications and glass fiber for non-structural architectural cladding in mortar instead of concrete. Carbon, pitch and polyacrylonitrile fibers are another class of fibers [4] suitable for marine/strong winds environment on account of their durability. Natural vegetable fibers (cellulose pulp, sisal, bamboo, hemp, flax, jute, ramie fibers, etc) are not suitable for HPC but are applied in ordinary concrete in countries where they are easily available especially for the inexpensive buildings in the developing nations [108]. Polymeric fibers though strong and ductile, on the other hand have a modulus lower than concrete and do not enhance its properties much [9, 25] but are used to control the shrinkage cracking of young concrete which also has lower modulus at that time and also for fire resistance on account of their property to melt and relieve the pressure [26]. Metallic fibers exhibit ductile behavior and have high modulus and high strength. Fig. 4 shows few types of fibers.

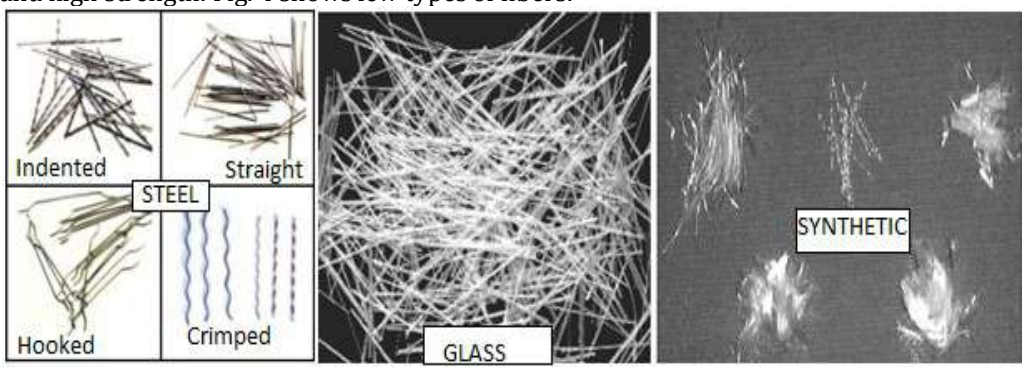

Fig. 4 Various types of Fibers

Fine fibers control opening and propagation of micro-cracks as they are densely dispersed in cement matrix and act as multi-directional concrete reinforcement. Longer fibers up to 50-80mm control larger cracks and contribute to increase in final strength of FRC [4]. With increase in aspect ratio of steel fibers, better strength is gained in FRC. The tensile behavior is dominated by the gradual growth and interconnection of the micro cracks and the ultimate is reached when they reach unstable situation. Fibers restrain them locally. The multiple cracking due to fibers increases the ductility of the composite. Fibers bridge across the

concrete matrix (Fig. 5) and help to control shrinkage cracking during the plastic stage and matrix micro cracks that occur as the concrete is loaded [24].

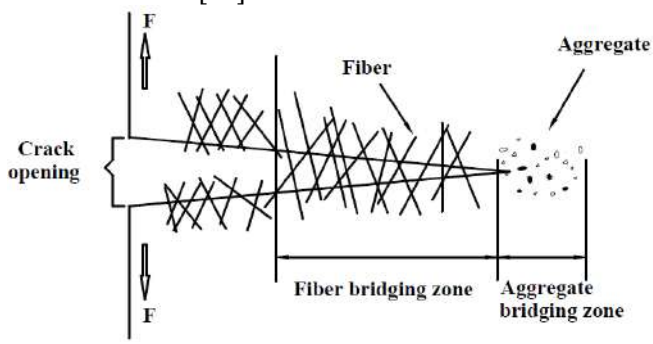

Fig. 5 Fibers Bridging across a Concrete Crack [27]

The critical length (length factor), l_c of a fiber above which the fiber fractures instead of pulling out when the crack intersects the fiber at its midpoint, can be approximated by Eq. 1 [28].

$$l_c = d_f / (2\, v_b)\, \sigma_f \quad (1)$$

d_f is the fiber diameter, v_b is the interfacial bond strength and σ_f is the fiber strength, ρ_f is the fiber percent by volume of the matrix, l is the length of fiber, d is the diameter of the fiber, V is the volume of one fiber element. Closer spacing of fibers increases the first cracking load (Fig. 5) of the matrix. Critical fiber spacing (space factor), s can be calculated using Eq. 2 [29], Eq. 3 or Eq. 4 [28].

$$s = 13.8\, d_f \sqrt{(1.0 / \rho_f)} \quad (2)$$

$$s = 3 \sqrt{(V / \rho_f)} \quad (3)$$

$$s = 13.8\, d_f \sqrt{l / \rho_f} \quad (4)$$

Fiber orientation (fiber efficiency factor) determines the efficiency with which the randomly oriented fibers resist the tensile forces in their directions synonymous to contribution of bent bars and vertical shear stirrups. The factor varies between 0.33 l to 0.65 l and the value is 0.41 l for perfect randomness [28].

Bayramov et al. [19] used Response Surface Method (RSM) optimization technique to optimize SFRC with special emphasis on ductility. With the consideration of mechanical properties and cost optimization, optimized fiber volume 0.56% and aspect ratio of 75.87 were proposed in this study. Another numerical study using time-efficient automated analysis was conducted by Pastorelli et. al. [30] to study the effect of orientation of fibers on performance of SFRC. Permeability due to cracking is also decreased since the micro cracks are prevented from becoming working cracks [20]. Research conducted by Swamy et.al. [31] on low carbon crimped steel fibers reinforced concrete beams showed their significant inelastic deformation and ductile behaviour. The fibers were also found to inhibit crack growth and their widening and were effective in resisting deformation at all stages. Similar results were found by Chaallal et al [32] in their study of SFRC concrete wall/coupling beam joints under cyclic loading. Use of SFRC in seismic regions to enhance structural integrity and to ease steel congestion in plastic hinge regions was recommended. Study done on seismic beam-column joints using steel fibers (2% by volume) by Bayasi, et al (2004) concluded that hoop spacing can be increased in the range of 1.5-2.0 times.

Fibers contribute to the enhanced performance of the composite by increasing its toughness by the energy absorption mechanism related to de-bonding and pull out processes of fiber bridging the cracks [33-35]. Use of higher volume fractions, centre point loading, small specimens or long fibers with significant fiber alignment in the longitudinal direction can produce improved flexural strengths up to 150% [36]. Vondran [20] reported that steel fibers can have up to twice the modulus of rupture, shear strength, torsional strength and fatigue endurance; up to 1.4 times the abrasion and erosion resistance and up to 5 times the impact energy of plain concrete. The effect of fibers on ultimate compressive strength is however slight (about 0-15% for 1.5 vol. % steel fibers) [36]. In direct tension, the improvement is in the order of 30-40%. Gustavo [14] in his overview of the applications of HPFRCCs using different fibers in earthquake resistant structures highlighted the outstanding damage tolerance and high drift capacities (larger than 2%) of such composites in low rise walls. He also discussed the effectiveness of these composites (Fig. 6) in beam column connections, coupling beams and flexural members subjected to large displacement reversals. Lesser steep slopes on the descending portion of the compressive stress strain curve indicate higher toughness.

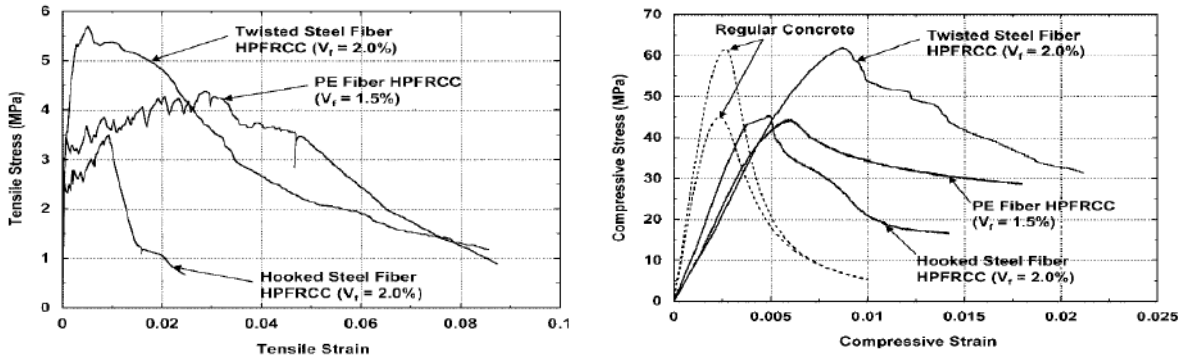

Fig. 6 Tensile & Compressive Stress-Strain Response of Steel and Polyethylene Fiber HPFRCCs [14]

The discrete fibers transfer the stresses and loads across the cracks thereby increasing the strength of the composite as well. Fibers act directly across diagonal cracks (in a manner similar to the stirrups), where the fibers would resist forces equal to those that cause pull-out or failure, depending on the type and volume of fibers used. Load is transferred through the matrix to the fiber by shear deformation at fiber-matrix interface [27]. But as deformation increases, the cracked FRC is unable to hold stress across the cracks. Hence, efficient location of fibers is vital [37]. In pull out tests conducted by Hamoush et al. [38] on four different type of fibers in Very High Strength Concrete (VHSC), the importance of frictional portion of the pullout work in the toughness and energy absorption capability of fiber reinforced VHSC composites was highlighted.

The addition of fibers to conventionally reinforced beams increases the fatigue life and decreases the crack width under fatigue loading. The role of fibers in reducing the shrinkage and creep effects of concrete has also been proved [24].

Fibers also contribute to lesser corrosion as compared to steel bars in concrete due to their short, discontinuous character which does not provide any continuous path for currents from electromotive potential between different areas of concrete. There is time saving due to elimination of rebar placing, bending and tying activity and the fiber reinforcement can be accomplished using ordinary mixing, placing and finishing methods. Corrosion is limited to the surface and only about 2.5 mm below it [39]. Cracked Steel FRC may lead to corrosion passing across the crack in chloride environment but the concern is more for cracks wider than 0.1 mm [36]. Long term durability of nylon, polypropylene and polyester fibers in concrete (0.5% by volume) were proven by Bohra and Belaguru (1991) in lime saturated water at 50°C in their research. In 1996, polypropylene fibers (2% by volume) were used in bridge deck overlays, bridge barriers, concrete paving and bridge deck replacement with good results by South Dakota Department of Transportation.

For 1 % volume of steel fibers, an increase of up to 170% in ultimate shear strength, reduction in spacing of cracks and change of failure mode to moment type from shear type was reported [40]. Contribution of fibers as an equivalent to a fraction of shear reinforcement was suggested by Junior et al [41] in their research on thin-walled I-beams with reduced shear reinforcement. First shear cracks result from prolongation of bending cracks. Moreover, numerous shear cracks in the extremities of the beam contributed to increased strength. They also concluded that fiber effectiveness is higher in beams with stirrups and also obtained higher ultimate shear force values as compared to theoretical values. Similar results were obtained by Ehsan et.al. [42] for one-way thick bridge slab. They additionally concluded that use of fibers would make the construction easier and economically, it is a viable option since additional cost of fibers is compensated by reduction in shear reinforcement.

3.2. HIGH PERFORMANCE FIBER REINFORCED CEMENTITIOUS COMPOSITES

High Performance Concrete (HPC) offers many desirable performance characteristics of concrete like ease of placement, long term mechanical properties, early-age strength, toughness, life in severe environments and volumetric stability [43]. These can be achieved by controlling material selection, mixing, placing and curing procedure. HPC may be defined as concrete having the highest durability for any given strength class, and comparison between concretes of different strength classes may not be appropriate. It may be noted that generally HPC has high strength, but High Strength Concrete (HSC) may not be HPC.

The low tensile strength of concrete is due to micro cracks at the aggregate-mortar interface which is the weakest link of the composite. Based on their tensile performance, Naaman in late 80's proposed a new class of FRCC, referred to as High-Performance Fiber-Reinforced Cementitious Composites (HPFRCC) [44]. The objective behind this classification was to distinguish between typical tensile performance obtained with

traditional FRCs, characterized by a softened response after first cracking and a tensile strain hardening response with multiple cracking exhibited by selected types of cement composites. Fig. 7 illustrates a qualitative comparison between typical stress strain curves corresponding to high performance and regular FRCC. As can be observed, HPFRCC exhibits substantially larger strain capacity and toughness compared to traditional FRCC which makes them ideal for its application in members subjected to large inelastic deformation demands.

Absence of coarse aggregates and use of high volume of fibers with proper dispersion provide strain hardening property to FRC overcoming its brittle properties such as spalling, crushing and bond splitting. Such class of concrete with improved matrix of post cracking behavior and interfacial bond between concrete and steel reinforcement are called HPFRCC. Such behaviour is achieved by use of high amount of Portland cement; very fine aggregate (maximum size 0.125-0.3 mm); superplasticizers and micro fillers such as metakaolin, silica fume, fly ash, ground quartz. Sometimes even different sizes of fibers are used to serve different purposes of micro crack control and strength and ductility enhancement.

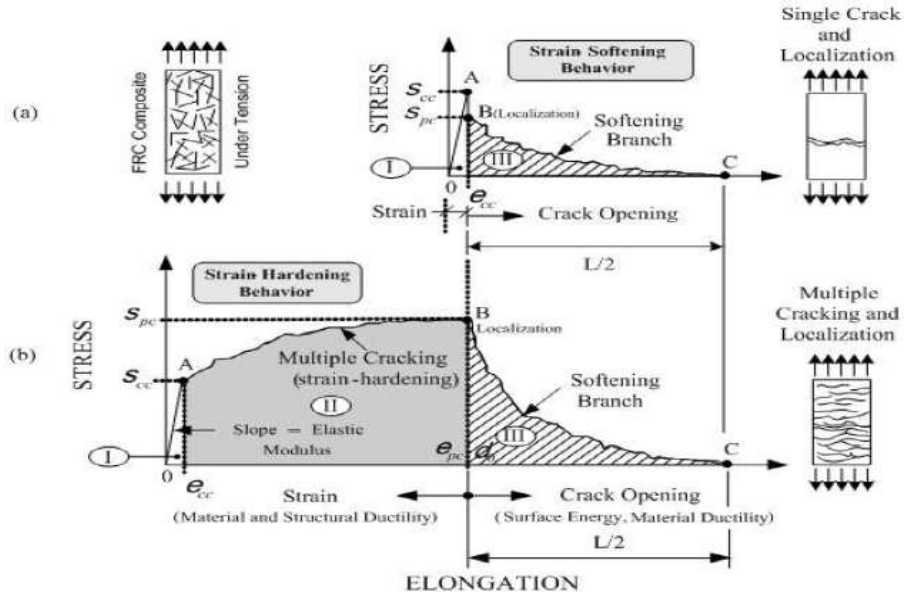

Fig. 7 Typical stress-elongation curves in tension in fiber reinforced cement composites: (a) Strain-softening behavior. (b) Strain-hardening behavior (HPFRCC) [15]

HPFRCC are currently defined as SIFCON (Slurry Infiltrated Fiber Concrete), SIMCON (Slurry Infiltrated Mat Concrete), DSP (Densified with Small Particle systems), ECC (Engineered Cementitious Composites), RPC (Reactive Powder Concrete) or BPR (Betons de Poudres Reactives), CRC (Compact Reinforced Concretes), SCC (Self Compacting Concrete), BSI® Special Industrial Concrete, MDF (Macro-Defect-Free) cements, BSI, Ultra-high-strength (UHS) concrete, DUCTAL®, etc. [5, 45-46]. Fig. 8 shows the main results obtained from the development of these materials in the optimum combination of strength and ductility/toughness, approaching the structural properties of steel and other common building materials like plastics, composites [46].

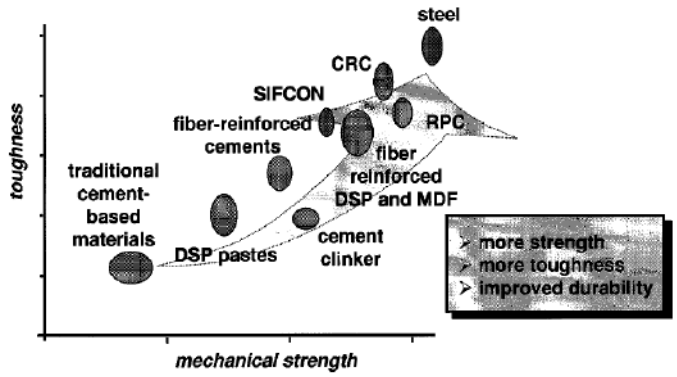

Fig. 8 Trends of Cement-based Materials [46]

In the past few decades, research has been done on HPFRCC for performance oriented structural applications. In the research done by Prof. Lankard in 1979, he illustrated that if the percentage of steel fibres in cement matrix could somehow be increased; one could get a material with very high properties and which finally resulted in production of SIFCON. SIFCON includes 5-30 percent steel fibre volume by placing the steel fibers into a formwork and then infiltrating fine aggregate and cement rich flowable slurry to coat the fibers. The matrix in SIFCON has no coarse aggregates and may contain fine or coarse sand and additives such as fly ash, micro silica and latex emulsions and high-range water-reducing plasticizers fly ash or silica fume [47]. The "Fiber Lock" (frictional and mechanical interlock) behavioural phenomenon of SIFCON due to its high fiber content is believed to be responsible for its outstanding stress-strain properties. The engineering properties of SIFCON were investigated by various researchers in early 90's [48-65, 129]. The peak compressive stress was observed to usually occur at a strain greater than 1.5 percent [53]. The toughness index of tension specimens was also found to be six to eight times greater than reference concrete. To predict shear strength of SIFCON, model proposed by Narayanan and Darwish [64] for evaluating ultimate shear strength was recommended [63]. The flexure response of reinforced concrete beams cast with SIFCON similarly, was investigated by Naaman et al on beams tested under three point loading with shear span ratio of four [55,58]. SIFCON beams were found to be 2.5 to 3.6 times more ductile and absorb 3.2 to 5.7 times more energy than plain concrete beams. The usefulness of SIFCON in avoiding a shear failure was also exhibited by Farnam et al. [66] in their comprehensive experimental program comparing stress-strain responses of HSC, HPFRC and SIFCON in which he went up to 10% fiber content in SIFCON. Increase in ultimate load carrying capacity, energy absorption and ductility factor and reduced stiffness degradation of RC beams using SIFCON has been demonstrated by researchers by experimental tests [130].

SIMCON is made by infiltrating continuous steel fiber-mats, with a specially designed cement based slurry. Continuous fiber-mats has the advantage of increased fiber length and aspect ratio, wherein tensile strength up to 17 MPa can be achieved at strains up to 1.5% with only 5.29% fiber volume fraction. The mat arrangement offers advantages such as better control over fiber distribution, orientation and convenient delivery in large rolls [67]. It is well suited for structural and durability retrofit as well as new construction of high performance structural elements.

In ECC, about 2-5 vol. % Poly-Vinyl Alcohol (PVA) and Poly-Ethylene (PE) fibers are used with cementitious materials and exhibit multiple cracking and strain hardening behavior with more than 1percent strain capacity in tension [68-71]. The large deflection response of ECC was established in numerous studies conducted [69-74]. Such behaviour is desirable for seismic response of beams [68]. Its use as jacketing in beam-column joints [75-76] also showed better ductile and damage tolerance behaviour. Higher stiffness retention and shear strength were observed in precast coupling beams using polyethylene and twisted steel fibers even without using additional transverse reinforcement [77]. Similar behaviour was observed in exterior beam-column joints without stirrups under reverse cyclic loading [78]. The tensile and post yield behavior of hybrid fibers such as Recron 3s fiber reinforced ECC was found to be better than that of steel fiber reinforced ECC [79-81]. Detailed hysteresis study has been conducted by Siva et al. [18] on exterior beam-column joints under cyclic loading using ECC, hybrid cementitious composites (hooked steel fiber reinforced ECC, brass coated steel fiber ECC). Lower damage index, higher ductility, uniform dissipation of energy with wide spread cracks, greater peak load were observed in this study for the HPFRCC specimens.

Ultra High Strength (UHS) concrete was developed in early 1990s in France. Ductal® and BSI® are few examples of this type that are used for thin precast elements due to elimination of conventional reinforcement and strength as high as 150 – 800 MPa [4]. Self Compacting Concrete (SCC) also called Self Levelling Concrete (SLC) can flow on its own without any vibration and is useful for industrial floors that require no additional work for leveling. Promising results have been obtained in the behaviour of high strength self-compacting concrete beams under combined bending and torsion (15-30% increase with use of 0.75-1.5 vol. % of steel fibers) [82]. DSP materials including fiber-reinforced DSP and CRC since the 80's have been more and more used in structural and non-structural applications [83-87]. RPC are very high-performance micro-mortars developed with reference to DSP cements [46, 88-89] which exploit a particularly dense microstructure obtained by thermal treatment. CRC slabs of load carrying drain covers made with fiber-reinforced DSP concrete (6 vol. % steel fibers) were used in the construction of the tunnel between Funen and Zealand instead of cast iron slabs and were designed for a 100-year lifetime [86]. Birchall and co-workers (Imperial Chemical Industries) developed MDF cements in the early 80's [90-91] which refers to absence of large voids (macro defects) that limit the tensile and flexural properties of cements. Such composites are based on use of adequate water-soluble polymers, high-shear mixing technologies such as two-roll mill compounding or extrusion and exploitation of the chemical interactions

between cement and polymer. CAC-MDF composites developed by CTG Italcementi Group Laboratories exhibit high toughness and a pseudo-ductile behaviour far exceeding the current limits of even light metals [46].

3.3. DESIGN OF FIBER REINFORCED CONCRETE

Several experimental methods have been proposed by researchers for the design of FRC elements and some approaches have been proposed in the past [92-94]. There is however, a lack of universally accepted approach for the calculation and strength verification of SFRC and availability of respective standards [4]. The mechanical properties of fiber-reinforced concrete is influenced by several factors such as fiber material and shape; fiber aspect ratio, volume percentage of fibers, fiber spacing, strength of concrete or mortar matrix and the size, shape and preparation of the specimen [23]. In order to get a good estimate of these properties, it is hence important to test specimens to failure in the form as of the design element.

The flexural design of an FRC element may be based on its behaviour as shown in Fig. 9. Two flexural strengths are commonly used. First – crack flexural strength corresponds to the point on the curve where it first becomes non-linear. Second is the Ultimate Flexural Strength which the greatest value achieved. First crack strength, R may be defined as (Eq. 5) [95].

$$R = P\,l / (bd^2) \quad (5)$$

Where, P is the first crack load, l is the span length, b is the average width of the specimen at fracture, d is the average depth of the specimen at the fracture .

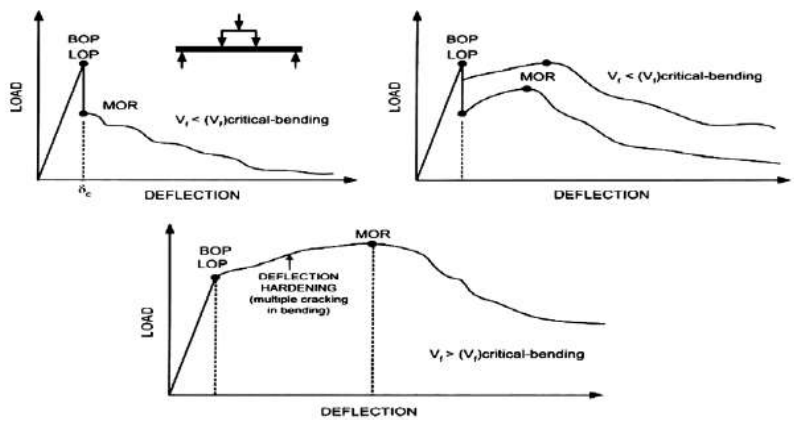

Fig. 9 Typical Load-Deflection response curves of Fiber Reinforced Cement Composites [36]

Another method to calculate the flexural strengths for beams with fiber reinforcement alone is defined in ACI Committee 544 (1993).

First crack composite flexural strength, psi (Eq. 6)

$$\sigma_f = 0.843\, f_r V_m + 425\, V_f\, l / d_f \quad (6)$$

Ultimate composite flexural strength, psi (Eq. 7)

$$\sigma_{cu} = 0.97\, f_r V_m + 494\, V_f\, l / d_f \quad (7)$$

For structural beams reinforced with both normal reinforcing bars and fibers added in the matrix, can be obtained as per expression (Eqs. 8-10) suggested by Henager et. al. [96] by accounting for the contribution of the concrete in the tensile zone (Fig. 10).

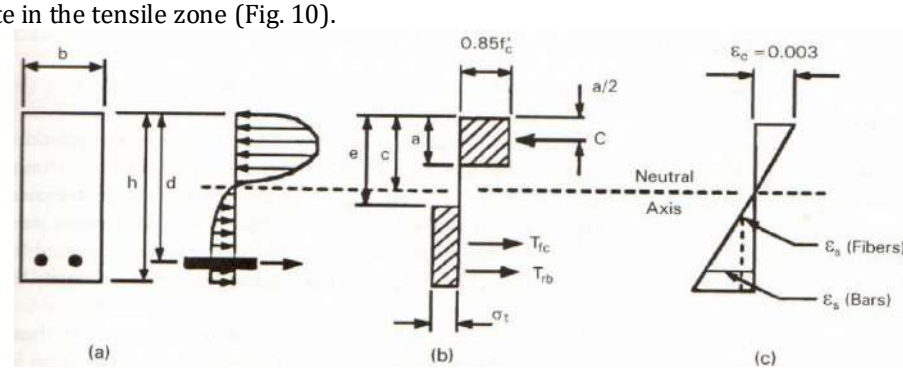

Fig. 10 Stress and strain distribution across depth of singly reinforced fibrous concrete beams [96] (a) Assumed stress distribution; (b) Equivalent stress block distribution; (c) Strain Distribution

$M_n = A_s f_y (d - a/2) + \sigma_t b (h - e) (h/2 + e/2 - a/2)$ (8)

$e = [\epsilon(\text{fibers}) + 0.003] c / 0.003$ (9)

$\sigma_t (\text{psi}) = 1.12 l / (d_f \rho_f F_{bc})$ (10a)

$\sigma_1 (\text{MPa}) = 0.00772 l / (d_f \rho_f F_{be})$ (10b)

where, F_{be} is bond efficiency of the steel fiber depending on its characteristics, varies from 1.0 to 1.2; a is depth of the equivalent rectangular block; b is width of beam; c = depth to the neutral axis; d is effective depth of the beam to the centre of the main tensile bar reinforcement; e is distance from extreme compression fibers to the top of the tensile stress block of the fibrous concrete; $\epsilon_s = f_y / E_s$ of the bar reinforcement; $\epsilon_f = \sigma_f/E_c$ of the fibers developed at pullout at a dynamic bond stress of 333 psi; σ_t is tensile yield stress in the fiber; $T_{fc} = \sigma_t b (h-e)$ is tensile yield of the fibrous concrete (Fig. 10); $T_{rb}=A_s f_y$ is the tensile yield force of the bar reinforcement (Fig. 10).

Flexural Toughness is traditionally estimated per ASTM C 1018 [95]. Indices I_5, I_{10}, I_{30} may be calculated from the load-deflection curve from a standard test on beam under bending (Fig. 11). ASTM C-1550 (2002) accepted by ACI Committee 544 measures flexural toughness based on bi-axial bending which is experienced typically by in-situ actual structures [36].

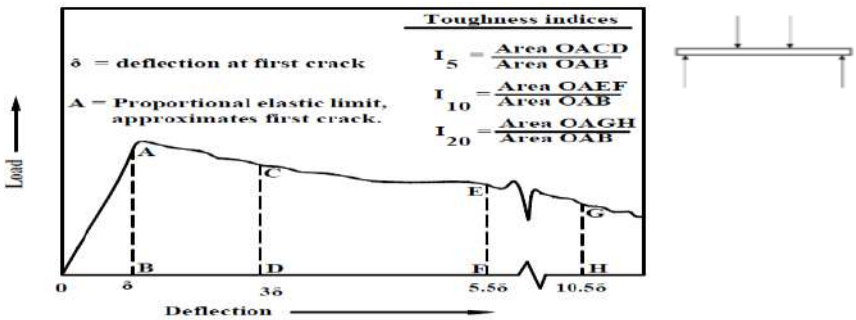

Fig. 11 Flexural Toughness Indices [95]

Residual strength factors (Eq. 11 & Eq. 12) represent the average level of strength retained after first crack as a percentage of the first crack strength for different deflection intervals [95]. Higher values indicate better performance.

$R_{5,10} = 20 (I_{10} - I_5)$ (11)

$R_{10,20} = 10 (I_{20} - I_{10})$ (12)

ASTM C-1339 (1998) test method measures the average residual strength of a beam.

The effect of the contribution of fibers to compressive strength is minor; however, the enhancement in ductility and toughness is significant. Toughness Index (TI) may be derived using Eq. 13 [97].

$TI = 1.421 RI + 1.035$ (13)

Where, RI = Reinforcing Index = $V_f (l / d_f)$; V_f is volume fraction of fibers; (l / d_f) is the fiber aspect ratio.

Equivalent tensile strength may be calculated from the bending test of the beam as per Eq. 14 [98]. Similar formulae are proposed in RILEM Recommendations [99].

$f_{eq} = T_b * L / (\delta_{L/150} b h)$ (14)

where T_b is work of bending calculated after area under load-deflection curve up to the deflection $\delta_{L/150}$ = L/150, b and h are width and depth of the beam, L is its span.

The shear behaviour of fiber reinforced concrete has been studied by many authors [40,100-107]. Mainly two methods have been are used for empirical determination of the same. One method is based on the truss analogy (accounting for concrete contribution) and the second takes into consideration the increased resistance equivalent to shear force decompression. Fiber act directly as shear reinforcement and also have indirect effect of alternative shear transfer mechanisms by concrete (dowel effect and crack friction) and contribution to the greater efficiency of stirrups by allowing delayed tensioning of stirrups. Larger number of inclined cracks prior to beam collapse is also achieved in fiber reinforced concrete. The ultimate shear capacity (V_U) of the concrete beams can be taken as the sum of the shear force carried by concrete (V_C), by stirrups (V_{ST}) and by steel fibers (V_{SF}) (Eqs. 15-17) [67].

$V_U = V_C + V_{ST} + V_{SF}$ (15)

Assuming the traditional 45° truss model, the contribution of vertical stirrups can be determined as in ACI Building Code 318-1992

$V_{ST} = \rho_y (f_{yv}) b_w d$ (16)

where ρ_y is the stirrup reinforcement ratio = A_v/b_wS; Av is the cross-sectional are of the vertical stirrups; S the spacing, f_{yv} the yield strength of the stirrups; b_w and d the width and depth of beam. Contribution of steel fiber;

$$V_{SF} = 0.6\, \sigma_{pc}\, b_w\, d \quad (17)$$

where σ_{pc} is the post cracking tensile strength of steel fiber concrete under uniaxial tension.
Another estimation of average shear stress, v_{cf} for beams reinforced with steel fibers (Eq. 18) is per ACI Committee 544 report (1993)

$$v_{cf} = 2/3\, f_t'\, (d/a_v) \wedge 0.25 \quad (18)$$

where f_t' is the tensile splitting strength; d is effective depth of beam; a_v is the shear span; equal to distance from the point of application of the load to the face of the support when concentrated loads are acting or equal to the clear beam span when distributed loads are acting

4.0 FIBER REINFORCEMENT IN PRESTRESSED CONCRETE

The complex nature of stresses in the post tensioned anchorage zone and the vital role played by the zone in the functioning of the prestressed concrete has instigated much research using various experimental, analytical and numerical techniques and to analyze existing structures. [1, 2, 11-13, 109-113, 125]. There has been substantial progress in modeling the behavior of fiber reinforced cement composites and also of the high performance composite [114-118]. Use of HPFRCC eliminates the transverse reinforcement with higher energy dissipation and slower stiffness degradation capability [72-76]. They find numerous applications as a stand-alone material in light structural elements like prefab elements, cement boards; as a hybrid material in combination with reinforced, prestressed or steel structures and even as a repair and rehabilitation material like column jacketing, etc. Their specific utility as a hybrid material in selected zones of structures requiring enhanced properties such as beam column joints in seismic frames, coupling beams, punching shear zone in RC slabs and anchorage zone in prestressed beams has been a major development in the past five decades.
Wafa et al [119] in their study established the utility of fibers (1% by volume) in increasing the ductility and torsional strength of prestressed beams. Haroon [120] subsequent to his study of using 0.5%, 0.75% and 1.0% of Xerox steel, Dramix ZP305 steel and Harbourite H-330 synthetic fibers in AASHTO Special Anchorage Device Acceptance Tests with cyclic loading; concluded steel fibers increased the compressive, tensile, flexural first crack strength and post-crack energy absorption capacity. He suggested that from reinforcement congestion perspective, elimination of spiral steel is more beneficial than the elimination/reduction of the skin reinforcement. In similar analytical and experimental study conducted by Johnson [3], the author additionally discussed the increase in dead load due to placement of fibers which cause an increase in stresses in all directions since the fibers are placed in all directions. But the loads are smaller as compared to the post-tensioning load.
Hung et al [121] in conducted experimental and analytical studies on anchor block using 0.75% steel fiber volume and found that with steel fibers 98% of design compressive strength was achieved in 7 days, thereby increasing its utility for early prestressing. Lesser cracks of smaller crack width were observed and they concluded that lesser local reinforcing bars could be provided. Setiawan et al [122] also explored the possibility of reducing the construction duration of cast in place segmental bridges and found with their analytical studies that jacking can be approved at one day of rapid hardening concrete age.
The ultimate load capacity of partially and fully prestressed steel fibrous concrete beams (Fig. 12) can be estimated using Eq. 19 proposed by Elsharkawy et al [25]. The authors used the analytical model proposed by Swamy et al [31] and the results obtained in the experimental studies validated this model. Apart from increase in tensile, flexural strength, peak load, ductility and energy absorption in the range of 1.2%-45.18%, it was found that fibers did not affect the pre-cracking behaviour and the failure mode of the beams. Polypropylene fibers showed lower efficiency as compared to steel fibers. Similar studies were conducted by Yoon et. al. [123] who obtained 16.4% larger flexural cracking moment over ordinary RC beam (0.5% fiber) and showed the effect of crack width control in SFRC in the displacement controlled cyclic tests performed in their studies. Ultimate flexural strength calculated with empirical formulae developed by Swamy and by Henager were both on conservative side when compared to these results.

$$\sigma_{cu} = \tau_o\, \tau_l\, \tau_b\, 2\, \tau\, l\, \rho_f / d_f \quad (19)$$

where τ_o is the orientation factor, τ_l is the length correction factor, τ_b is the bond efficiency factor, τ is the interfacial bond stress between the fibers and the matrix. The trapezoid of σ_m represents the contribution of fibers.

Tawfiq [9] conducted his research on post tensioned anchorage zone used Dramix ZP305 steel, Helix (twisted polygon shaped high tensile steel wires) and Novomesh 850 (combination of steel and polypropylene fiber blend) considering few box girder bridges already constructed in Florida using both analytical and experimental approach. He recommended 0.5% steel fiber by volume and concluded that higher volume of fibers led to formation of steel balls and probably contributed to lower compressive strength. He further found that even though addition of 0.5% fibers added 37% strength but steel spirals and steel ties are needed to prevent sudden failures due to punching shear and bursting tension. Based on finite element analysis, the author proposed a new equation (Eq. 20) for computing the tensile bursting force in anchorage zone of steel fiber reinforced concrete. The equation led to 16-18% less bursting reinforcement (tension ties) as compared to AASHTO requirements and hence reduction in retail costs.

$$T_{max} = 0.23\ P\ [1 - 1.11(b/h) - 0.15\ (F\%) + 0.15\ (b/h)\ (F\%)] \quad (20)$$

Where, T_{max} is tensile bursting force, P is the maximum factored tendon force, h is the transverse dimension of the anchor zone, b is the width of the anchorage plate, and F% is the percentage of steel fiber by volume.

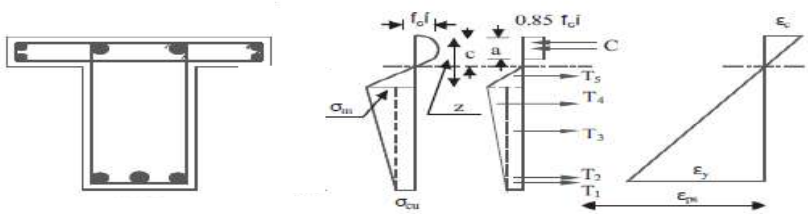

Fig. 12 Stress-Strain Diagram for Steel Fibrous Prestressed Concrete [22x]

Yazdani et. al. [24] used varying percentage of steel (ZP305 and XOREX) and synthetic (Harbourite H-330) fibers to develop FRC and based on promising results obtained for steel fibers used it for AASHTO Special Anchorage Device Acceptance Tests and finite element modeling. With varying concrete strength (34-45 MPa) and fiber volume(0.75% & 1%) and type, they were able to achieve substantial reduction (23-65%) in secondary reinforcement and about 50% in spiral reinforcement. In some cases they were able to completely eliminate both types of reinforcement as well. Jonhnson [3] conducted FEM on a segmental bridge section using 0.5,0.75 and 1.0% Dramix ZP305 fibers to investigate the stresses and failure load in the anchorage general zone. 65% reduction in mild steel reinforcement was seen with 0.5% fibers. No significant improvement was seen by increasing the fiber content beyond 0.5%. The author also used Strut-and-Tie Model for validation of the finite element results. Vitek. et al. [127] used fiber reinforced ultra high performance concrete and also stirrup reinforced only UHPC in anchorage zone and observed the first crack at about 1.3-1.9 the characteristic prestressing force and suggested the elimination of all types of reinforcement with use UHPC in anchorage zone with the results obtained.

Use of Ductal® in precast deck slabs as well as girders has been successfully accomplished to replace the mild reinforcement in the prestressed girders in Bourg-les-Valence bridge in France with the use of 3 vol.% dispersed microfibers [4]. Ultimate resisting capacity of post tensioned anchorage zones in Ultra High Performance Concrete beams has been validated as given in the NCHRP Report 356 as a modified equation (Eq. 21) [126].

$$F_u = F_{cc} + F_{sp} = 0.8\ (A/A_g)0.5\ A_b f'_c + K(n)\ f_{lat}\ A_{core} \quad (21)$$

where $n = f'_c/35$ MPa, and n = 1 when f'_c is less than or equal to 35 MPa and K(n)=0.695n+3.305, A_g is the gross area of the bearing plate i.e. $(\pi/4)D_a^2$,A_b is effective net area of the bearing plate $(\pi/4)(D_a^2 - D_{duct}^2)$; $f_{lat}=2f_yA_s/D_{sp}p_{sp}$, A_s and f_y are the section area and yield strength of spiral reinforcement. $A_{core}= \pi(D_{sp}^2 - p_{sp}^2)/4 - A_{duct}$, D_{sp} is the diameter of the spirals section, p_{sp} is the pitch of the spiral, and A_{duct} is the area of the duct zone.

5.0 CONCLUSION

Fiber reinforced cement based composites have made striking advances and gained substantial momentum in the last five decades due to advances in the understanding of the components, production process and fundamental mechanisms of behavior. There are limitations of high material cost, lack of design rules and standards limiting its current applications in special market niches. Such composites have been successfully used in the anchorage zone of post-tensioned prestressed girders to replace the conventional local reinforcement without decreasing the capacity of the member. There is a huge scope for use of HPFRCC in the anchorage zone of post tensioned prestressed girders for replacement of the conventional skin and

spiral reinforcement for reducing the reinforcement congestion in the zone. Other applications with prestressed concrete include the improvement in seismic performance and reduction of transfer length of pre-tensioned strands. Such applications are desirable from the point of view of the strength and serviceability performance of such girders.

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