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Fracture Mechanics of Fiber Reinforced Concrete: An Overview

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Abstract **– It is known that cracking is a characteristic feature of brittle materials like concrete. A growing crack in plain concrete can very soon lead to failure. Reinforcing concrete with randomly distributed short fibers may improve the toughness of cementitious matrices by preventing or controlling the initiation, propagation, or coalescence of cracks. The service performance, operational life and the fracture behaviour of the structure depend on the applied stress level, the initial size of the flaw, material properties and the mechanisms by which the cracks propagate leading to fracture. One of the developments in modern engineering design is to adopt Fracture Mechanics (FM) based design. Although tensile toughness is an essential property for concrete, it has never been explicitly taken into account in design. This is due to the fact that its importance has not been understood and methods of taking it into account have been lacking. Today FM takes into account the influence of toughness on the tensile fracture behaviour. And also, the number of structural applications of Fiber Reinforced Concrete (FRC) has been limited. In order for FRC to be a viable material, it must be able to compete economically with existing reinforcing systems. Continued studies on this subject are necessary in order to increase the usage of FRC.**

Keywords **– Fiber Reinforced Concrete, Fracture Mechanics, Crack, Toughness, Stress Intensity Factor, Mode, Fracture Energy, Pull Out, Crack Bridging, Fracture Process Zone.**

I. INTRODUCTION

Conventional concrete is used extensively in civil engineering practice because of its low production cost, formability, and favourable behaviour under compression [1]. The main disadvantages are weak tensile strength and limited deformation capacity in the presence of cracking. With increasingly available synthetic fiber additives or fiber-reinforced composites, new ways are being invented to tackle the limitations of concrete while alleviating the dependence on metallic reinforcement, which renders concrete susceptible to the deleterious influences of corrosion. Tensile strength and deformability as well as improved crack distribution are achieved by addition of fibers directly to the concrete mix or by reinforcing concrete with various forms and shapes of fiber-reinforced polymers.

As cracks cannot be avoided in concrete, hence to study the behaviour of concrete in presence of cracks, use of concepts of “Fracture Mechanics” (FM) is a must. When structures are made from softening materials like concrete, crack formation often governs the structural behaviour. But when a crack is formed in Fiber Reinforced Concrete (FRC), the fibers will typically stay unbroken [2]. The fibers crossing a crack will resist further crack opening and impose what is called crack closing or crack bridging effect on the crack surfaces. Different failure modes can result, depending on the effectiveness of the fibers in providing crack bridging. Hence FM of FRC has become popular with researchers.

II. FIBER REINFORCED CONCRETE

Concrete either Normal Strength Concrete (NSC) or High Strength Concrete (HSC), being a brittle material, has low tensile strength and ductility. It is a complex material with multiphase [3]. The phases include large amount of C-S-H gel in micron-scale size, sands in millimeter-scale size and coarse aggregate in centimeter-scale size. Thus, properties of concrete will be improved to a large extent, if reinforced with fibers. Fiber reinforced concrete, having uniformly distributed fibers, has better resistance against cracking, improved strength in shear, tension, flexure and compression and better toughness and ductility as compared to plain concrete. Adding fibers to concrete makes it a homogenous and isotropic material (fibers randomly distributed through out volume of concrete at relatively small spacings and thus provide equal resistance to stresses in all directions) and converts its brittle characteristics to a ductile one [4].

The addition of randomly distributed fibers improves many properties of concrete, such as fracture strength, toughness, impact resistance, flexural strength and resistance to fatigue. Improved fatigue performance is one of the primary reasons for the extensive use of SFRC in pavements, bridge decks, offshore structures and machine foundations, where the composite is subjected to cyclically varying loads during its life time. When concrete cracks, the randomly oriented fibers function to arrest micro cracking, thus very much useful to resist shear forces due to earthquake and wind loading [5]. Secondly, fibers increase the concrete’s resistance to crack formation and propagation. The resulting reduction in crack size and beam deflection under service load conditions may be critical to the success of using HS reinforcing steel and ultimate limit state design without being restricted by service load performance.

Also, the increased resistance of concrete cover to spalling and cracking helps to protect steel from corrosion in adverse environments, and hence, improve structural durability. Thirdly, since conventional stirrups used in beams require relatively high labour input to bend and fix in place, fiber reinforcement may significantly reduce construction time and costs [5]. Fiber concrete can also be easily placed in thin or irregularly shaped sections such as architectural panels where it may be very difficult to place stirrups. Adding fibers influences the ascending portion of the stress-strain curve only slightly but leads to a noticeable increase in peak strain and a significant increase in ductility, as described by the area under the descending portion curve.

Consider a matrix reinforced with an identical volume fraction of long fibers and short fibers [6]. For the volume of fibers normally used in cementitious composites, when relatively long fibers are used as reinforcement, only a small improvement in strength is observed. The probable reason for this is that matrix cracking first occurs at the micro level. If fibers are far apart, they have no ability to arrest micro cracks. However, once the macro cracks coalesce into macro cracks, the long fibers can arrest propagation of macro cracks and substantially improve the toughness of the composite. It the short fibers are used, they can bridge micro cracks, since for a given volume these fibers are larger in number and, therefore, much closer together. Short fibers can thus significantly enhance the strength of the composite. However, short fibers may be pulled out after macro cracks are formed, thus providing little improvement in post peak toughness. By combining fibers of varying sizes (mixed aspect ratio) into matrix, improvement in both the peak stress and post peak toughness can be expected. Thus short fibers are more effective in serving as crack arrestors in the finite volume enclosed by the longer fibers, where as the latter contribute to the overall ductility and toughness through the phenomenon of debonding and fiber pullout. It has been shown recently that by using the concept of hybridization with two different fibers incorporated in a common cement matrix, the hybrid composites can offer more attractive engineering properties because the presence of one fiber enables the more efficient utilization of the potential properties of the other fiber.

III. FRACTURE MECHANICS

Fracture mechanics deals with the behaviour of materials in the presence of cracks and crack like defects and offers convenient means to measure the fracture strength or toughness of the material [7]. Fracture mechanics relates the fracture strength of material or structure under a given applied stress to the critical flaw size in the material. Hence FM is concerned with the problem of cracks propagating through a material and the mechanism of fracture in the presence of these cracks. When structures are made from softening materials, crack formation often governs the structural behaviour.

It is well established that two basic criteria govern the fracture of materials: these are the stress and energy criteria [8]. The stress criterion is based on the fact that the local tensile stress developed around a flaw must be large enough to overcome the cohesive strength of the material. The energy criterion is that the incremental extension of a crack requires a certain amount of energy; thus the overall reduction in the energy in the structure caused by the crack extension must equal or exceed the energy demand for that extension. Both criteria must be satisfied for a crack to extend; the second criterion to be met is the one that governs fracture. Although these two conditions can explain the fracture behaviour of any material in any stress state, the difficulty is in determining accurately how much energy is consumed in the fracture process under specific boundary conditions.

IV. FRACTURE MECHANICS OF CONCRETE

Three different types of structural materials can be identified: brittle materials (ex: glass); quasi brittle material (ex: concrete); and ductile elastic plastic materials (ex: steel). The difference between these materials lie in the shape and dimensions of the Fracture Process Zone (FPZ) that is formed ahead of the crack tip prior to fracture, and the mechanism of energy consumption.

In brittle materials, elastic energies are consumed in the form of surface energy with no FPZ [9]. In ductile materials, the FPZ is the plastic zone that can consume a considerable amount of energy – much more than surface energy [10, 11]. For quasi brittle materials, a large FPZ is usually formed that consumes large amounts of energy prior to failure. This provides concrete with its post peak nonlinear (softening) response. The FPZ is also one source of the size effect phenomena observed in concrete testing [12]. A large zone of micro cracking in concrete blunts the fracture front. This causes size effect in concrete.

Hence the conventional FM are not suited for application to concrete structures. This is mainly due to one or more of the following reasons: (1) The fracture process zone is assumed to be small compared to the size of the structure. This is not the case in concrete, where this zone may be more than 100mm long at maximum load. (2) The stresses within the fracture process zone are assumed to increases or to remain constant as the load increases. This is not true for concrete, where the stresses within this zone decrease as the load increase. (3) Conventional FM only deals with what happens to an already existing crack. For the practical application to concrete, it is essential that the formation of a crack can also be analyzed. These circumstances make conventional FM unsuitable for the analysis of the influence of fracture toughness on the behaviour of concrete structures. It was suggested that a NLFM criterion would be more suitable for determining the fracture process in concrete.

Studies of concrete crack growth have proved the existence of FPZ [13]. The difficulties encountered in the application of FM to concrete comes from the different toughening mechanisms taking place in FPZ of concrete as compared to the plastic zone of ductile materials. These toughening mechanisms include “micro cracking”, “crack branching”, “crack deflection”, “crack bridging”, “crack-face friction” and “crack tip blunting” [14].

V. FRACTURE MECHANICS OF FRC

Additional toughening mechanisms arising from the presence of fibers include fiber bending and the internal work of fiber fracture [15]. Developing other energy consuming mechanisms in concrete will further increase its fracture toughness. This is because fiber can consume a large amount of energy through fiber crack bridging, fiber pull out and or fiber debonding [16,17].

The presence of chopped fibers in concrete results in a minimal increase in stiffness prior to cracking and holds the matrix together after cracking. During the early stages of loading, the interaction between the fibers and concrete matrix is elastic, with stress transfer occurring through shear at the fiber concrete interface [18]. As the load increases, shear may cause the matrix to fracture or the fiber to debond. Fiber debonding activates a combination of elastic and frictional stress transfer mechanisms [19].

The first analytical model of stress transfer to and from fibers embedded in an elastic matrix was developed by Cox (1952). The analysis assumes that the matrix and the fibers are linear elastic materials perfectly bonded together. The fibers are assumed to be arranged in a regular, repeated array with no stresses transmitted through their ends. The requirement of strain compatibility requires the tensile strain in the matrix at a radial distance R from the fiber to be equal to average tensile strain of composite.

As FRC being a quasi brittle material, the stress transfer is different than that described by Cox model; the maximum interfacial shear stress will occur at the fiber end. In the cracked concrete, however, the maximum shear will occur at the point at which full bond between fiber and matrix still exists. When debonding takes place either prior to cracking or in the cracked zone, shear transfer will be a combination of frictional shear adjacent to the crack and decreasing elastic shear stresses away from it. On the other hand, if there is debonding, the shear stress distribution at the fiber–crack intersection will initially be elastic following Cox's model.

Bartos examined the effect of fiber length on the fracture mode of FRC [20]. Three different cases of stress transfer were considered for the cracked state; elastic shear stress transfer where no debonding could occur; frictional stress transfer without any elastic stress transfer and combined elastic and frictional stress transfer. The shear force per unit length of fiber (shear flow) rather than the average shear stress was used in the analysis. Fiber shapes that provide mechanical anchorage are known to be more effective (for example, hooked end fibers or fiber nets).

Stenberg and Mukhi proposed an analytical solution of the classical pull out problem in which they equated the presence of the fiber with a distribution of disk loads in the matrix [21]. Ramualdi & Batgon assumed that in the absence of a crack, the strain in the concrete due to remote tension is equal to the strain in the wires, thereby implying a perfect bond between wires and the surrounding concrete. Aveston et al. assumed a frictional shear bond with no debonding [22]. Kar & Pal assumed a linear shear stress distribution along the fiber, with a maximum at a point where a crack intersects the fiber [23]. Rajagopalan & Parmeswaran suggested that there is no strain compatibility between matrix and reinforcement once debonding occurs [24]. Gopalarathnam and & Shah attempted to apply shear lag theory to the problem of fiber pullout [25].

Nammur & Naaman derived analytical bond-slip relationship of FRC composites [26]. In the model, a constant value for the normal strain in the cross section of material and a linear relationship between slip and shear stress were assumed. Hamoush & Salami found out that the interfacial slip of fibers out the concrete is a function of the bond shear modulus at the interface [27]. Hamoush et al. developed a model for determining the interfacial bond shear modulus of steel FRC based on the axi-symmetric modeling of the pulled out steel fibers in which elastic behaviour of both concrete and steel fibers was assumed i.e. a linear relationship between bond shear stress and interfacial slippage of the steel fibers [28].

Experimental investigations using fiber pullout tests have revealed a linear load-slip relation of FRC up to a peak value, followed by a nonlinear descending part. These experiments showed the governing factors for pullout strength to be the interface shear strength and fiber dowel action. Dowel action, however, seems to damage the matrix at the crack surface making multiple fibers less effective [29]. Many models have been developed that successfully predict pullout strength of fibers in a cement matrix, the major difference between all these models is their definition of the elastic shear stress transfer parameters [30].

It has been shown that pore water affects adversely the mechanical strength of concrete because of the disjoining pressure it exerts on the gel structure (Rehbinder et al. 1948; Mill 1966; Robertson and Mills 1985; Imran and Pantazopoulou 1996). The same was also observed for FRC by Pantazopoulou and Zanganeh [1]. The sensitivity of FRC's mechanical response to the load path is due to different rates of damage buildup (volume expansion) under different load and boundary conditions. To evaluate the degree of effectiveness upon damage of fiber in partially restraining volumetric expansion of concrete and the resulting influence on the mode of failure strength and deformability, two different loading procedures were considered in subjecting the specimens to triaxial stress states. Triaxial stresses were applied either by hydraulic pressure or by means of passive confinement by means of carbon fiber reinforced polymer jackets wrapped to a fixed number of layers. Passive jacketing with FRP wraps proved to be a far more effective means of concrete confinement than active hydraulic pressure.

Fibers influence the fracture process in composites ahead of the crack tip in the FPZ and behind the crack tip in the crack bridging wake. The mechanics of fiber bridging in the crack wake are well understood [5]; however, the reinforcing effect of fibers in the FPZ of cementitious composites has not been researched as extensively.

VI. FIBER WORK OF FRACTURE

Fibers are used in concrete to provide high fracture toughness through the addition of extra toughening mechanisms in the FPZ of concrete. The role of toughening mechanisms is to consume energy, thus increasing the total energy required for fracture. Fiber pullout and fiber debonding are two possible toughening mechanisms provided by fibers in concrete. Pullout work is defined as the work done against sliding friction as fibers are extracted from a broken matrix, while fiber debonding is defined as the work done in destroying the bond strength between the fiber and matrix [19]. Fiber pullout follows fiber debonding and is preferred to fiber debonding alone as the former consumes much more energy and does not result in a catastrophic failure.

Beaumont (1974) showed how both fiber pullout and fiber debonding can contribute to increasing the energy consumption in the FPZ. Mindess reported that fiber pullout and /or debonding could consume more than 95% of the total fracture energy [17]. Li et al. suggested that fibers suppress crack growth through fiber bridging, interfacial debonding and frictional sliding, arguing that the last two mechanisms absorb a considerable amount of fracture energy [16].

Piggott proposed a method for estimating the fracture surface energy of a fiber reinforced material wherein the surface energy increases with increasing fiber content, strength and diameter, and decreases with increasing fiber modulus and matrix shear strength [31]. Bartos proved that the maximum energy demand for fracture can be achieved by limiting the fiber length to a maximum value of critical length including fiber pullout rather than fiber rupture [20]. Taha & Nigel also found the same behaviour with carbon fibers also [32]. Fracture toughness of concrete increases by 45 – 60 times depending upon number and orientation of fibers at the fracture plane for a given fiber content [7].

Yao, Li & Wu showed that the best composite properties are possible from the hybrid containing carbon and steel fibers which had the greatest strength and flexural toughness [3]. They found that the main advantage of carbon fiber addition is the resulting high compressive and splitting tensile strengths, while the main advantage of steel fiber addition is the resulting high modulus of rupture and flexural toughness.

Gopalaratnam and Shah discussed several types of failure mechanisms and fracture of fiber reinforced concrete composites [33]. These include, multiple fracture of the matrix prior to composites fracture; catastrophic failure of the composite immediately following matrix cracking due to inadequate reinforcing, fiber pull-out following matrix cracking leading to significant energy absorption; and fracture of short fibers bridging the matrix cracks without multiple fracture of the matrix. Aspects relating to the modeling of the two major causes of non-linearity associated with fiber concrete composites, namely, interfacial bond-slip, and matrix softening were also discussed.

VII. FRACTURE PARAMETERS OF FRC

In the recent years, attempts have been made to determine the fracture parameters, which characterized the fracture behaviour of FRC. Several experimental and theoretical studies have been conducted to apply the concept of LEFM and NLFM to determine the fracture parameters.

Swamy studied the influence of slow crack growth on the apparent fracture toughness of fiber concrete from four point bending test [34]. Because of the presence of fibers at the crack tip, the value obtained from the fracture toughness tests was referred to as the apparent fracture toughness. He concluded that the apparent fracture toughness increased slowly at first, almost linearly with early crack growth and then more rapidly with increasing crack propagation.

Since FRC is a material with highly nonlinear stress-Strain relationship, it was suggested and also applied (NLFM criterion) methods such as COD, J-integral and R-Curve analysis to plain concrete and FRC.

Halverson described the use of the J-integral to measure toughness of SFRC. A simple maximum failure load criterion was used to determine the critical value of the J-integral. The parameters studied were type of fiber, fiber content, fiber length and aspect ratio. It was concluded that the toughness of SFRC, as defined by J-integral, increases with fiber content, fiber length, aspect ratio and end anchorage. But the large scatter of results may limit applicability of this procedure. Brandt reported test on notched SFRC beams under four-point bending. The critical stress intensity factor, critical fracture energy, the surface energy and J-integral were evaluated. It was concluded that the J-integral approach seems to give logical results concerning the appearance of the first crack [35].

Naaman et.al developed a statistical model to predict the tensile properties of FRC. The model uses the approach of extreme value statistics for the tensile strength based on the hypothesis of weakest chain link. The fracture behaviour of these composites varies from ductile to brittle mainly depending on the fiber length and volume fraction. The model was divided into two major parts. The first one, simulating ductile failure, was based on the mechanics and statistics of composite materials. The second, covering brittle failure incorporates a fracture mechanics criterion in the analysis. Each formulation leads essentially to the assessment of the composite characteristics, tensile strength and its distributive functions [35].

Hillerborg et al. applied the fictitious crack model to analyze fracture in FRC and determined the fracture energy [36]. The FPZ was modeled as a fictitious crack, the stress-displacement responses were obtained for the bulk material as well as the fracture zone. Hillerborg suggested that the action of fibers modifies the crack opening behaviour, and thus controls the stress-displacement response in the fracture zone [37]. He also suggested that the type of fiber and the fiber material have an influence on the bond-slip properties of the composite, which in turn controls the crack opening behaviour. Hillerborg proposed the use of fracture energy G_F as a material property instead of G_C, the critical energy release rate, since G_F is based on energy absorption and crack formation in the same plane.

Javan and Dury measured fracture parameters of FRC by testing a circumferentially notched round bar under bending for carbon steel fiber and polypropylene fibers. They concluded that the improvement in fracture toughness due to the addition of fibers, broadly agrees with the increase in flexural strength and energy absorption capacity reported by earlier researchers [35].

The load relaxation method was used to determine the relationship between crack velocity and stress intensity for DT specimens by Mindess and Anthony [38]. It was concluded that the fracture properties of the specimens are much affected by the degree of compaction and the type of fiber does not significantly affect the fracture toughness.

Barr and Liu carried out tests on the fracture performance of glass fiber reinforced concrete using CT specimen. They proposed the fracture toughness index based on the load-deflection curve. The only requirement during the test was that the deflection has to be continuous up to twice the deflection at which the first crack occurred. The main advantage of the toughness index is that it is not limited by any restrictions regarding defined deflection and type of geometry. It was shown that the fracture toughness values are independent of the notch-depth/specimen width ratio. Consistent results were obtained for a notch-depth/specimen width ratio in the range of 0.4 to 0.5[35].

Visalvanich and Naaman used the term ‘pseudo-plastic zone’ to describe the zone where fibers provide bridging across cracks [39]. The model proposed assumes that the main portion of energy required during the fracture comes from the fiber pull out in the pseudo-plastic zone. The entire R-curve of the composite was generated using the stress-displacement law and the crack shape during fracture. For fiber reinforced concrete, the stress-displacement law was calculated from small-scale tensile tests. The use of entire crack growth resistance energy was proposed, rather than the fracture toughness or fracture energy, in order to describe crack initiation in addition to stable crack growth and fracture.

Wecharatana and Shah proposed a theoretical model in which a crack in the matrix was divided into three zones namely, a traction free zone, fiber bridging zone and the matrix process zone [40]. It was assumed that the closing pressure in the matrix process zone is considerably smaller than that in the fiber bridging zone and can be ignored. The fiber bridging pressure depends on the crack opening displacement, which in turn depends on the geometry of the specimen, external loading and the closing pressure. An iterative procedure was used to calculate the matrix process zone.

Jenq and Shah proposed a two parameter model to study the fracture behaviour of plain concrete, which accounts for the nonlinear slow crack growth [41]. The two parameters are critical stress intensity factor (K_{IC}) and critical crack tip opening displacement ($CTOD_C$). At the critical point, the CTOD and K_I reach their critical values. Depending upon the geometry of the specimen, the rate and the method of loading, further crack growth may occur at a steady state value of K_{IC}. Significant inelastic displacement and slow crack growth occur during nonlinear range and these aspects were used in calculating effective crack length. The K_{IC} can be derived from the measured peak load and form the knowledge of the effective crack length. Based on tests on notched beams, it was concluded that these two parameters are six independent. Jenq and Shah extended the two parameter model to predict the crack propagation resistance of FRC [42]. The crack propagation in FRC matrix was assumed to be governed by the same criteria as those for the unreinforced matrix. However, the fiber bridging effect must be included in calculating the imposed stress intensity factor. The load for FRC does not necessarily attains its maximum when K_I just reaches critical value. Depending upon the volume fraction of fiber, the maximum load for FRC occurs for a crack length larger than that corresponding to the peak load of the unreinforced matrix.

Chang et al. carried out fracture tests to investigate the fracture behaviour of SFRC structures. Parameters investigated were, notch depth, fiber volume fractions and aspect ratios. Based on the experimental results, regression analysis was performed to predict the fracture energy [35].

Hamoush et al. developed a fracture model to predict the stress intensity factor of FRC composites [43]. The model accounts for the fiber bridging over the crack faces in the crack-tip zone. The model was based on the superposition technique in conjunction with fracture mechanics. Two basic steps were used in the solution procedure. The first step ignores the contribution of the fiber and finds the crack-flange displacement at the location of the fibers. The second step finds the crack-flange displacement due to a unit force at each fiber location. The compatibility condition was employed to find the final pullout force in each fiber.

Rossi proposed a new Probabilistic Discrete Cracking model for steel fiber reinforced concrete (SFRC) in which cracking was modeled through contact elements which will have perfect elastic-plastic behaviour with brittle fracture [44]. The plastic step as well as the postcracking energy was uncorrelated random variables.

Tamrakar proposed a toughness parameter for fiber reinforced concrete based on the energy approach which gives idea of the toughness of matrix as well as the toughness contribution by fibers [7]. He concluded that fracture toughness of concrete increases by 45-60 times depending upon the number and orientation of fibers at the fracture plane for a given fiber content.

Ganesan et al. studied the characteristics of latex modified SFRC using three point bending tests [45]. Form the test results they concluded that the fracture toughness computed using the method proposed by Karihaloo and Nallathambi and apparent J-integral approach were useful criteria for latex modified SFRC.

Sabir investigated the toughness and tortuosity of polypropylene FRC using notched specimens [46]. He observed significant increase in the fracture toughness when the cement was replaced by 15% silica fume. The fracture toughness was found to be largely unaffected by the polypropylene fibers. The tortuosity was found to decrease with increase in the silica fume content. He also found that the tortuosity decreased with increase in notch size. However, significant increase in toughness indices was observed by addition of small amount of fibers.

Nelson et al. investigated the reinforcing behaviour of microdiameter fibers in the FPZ of cement composites [47]. They found that the polyvinyl alcohol fibers and refined cellulose fibers were able to effectively postpone microcrack formation, thereby delaying the localization of the failure crack, where as the polypropylene fibers were not able to provide the same level of reinforcement. They used an optical microscope to monitor the progression of damage and acoustic emission technique to confirm the accuracy of the fracture toughness values.

High performances FRC with high fiber volume fractions were tried by Balaguru et al. and were successful [48]. Their test results showed HPFRC with 3.75% steel fiber volume fraction is attainable and can be successfully applied in the field.

VIII. FRC UNDER MODE II

Many researchers had attempted to study pure mode II fracture also. Cracking of Structures due to in-plane shear, known as mode II fracture, is of considerable importance in concrete structures. Shear failure in concrete is known to be brittle and catastrophic. Several previous studies have demonstrated the effectiveness of fiber reinforcement in improving the shear performance of structural concrete. Swamy and Bahia found that the presence of steel fibers reduced shear deformations at all stages of loading [49]. Fibers were very effective to increase fracture processes of cementitious materials are complex and fracture studies in mode II are important as these materials are very weak in shear. Efforts have been made to develop suitable test specimen geometries for investigating mode II fracture of concrete and FRC.

Since Iosipescu's shear testing specimen was proposed, a superimposed mode I component cannot be avoided in the specimen configurations used in their experiments [50]. In order to perform mode II fracture experiments without a superimposed mode I component, a double-edge notched specimen has been proposed and has been applied to wood by Xu et al.(1996). Measuring K_{IIc} and G_{IIF} in the direction perpendicular to the grain is possible for wood due to its highly orthotropic properties. Later this kind of geometry was extended to normal strength concrete. This specimen geometry was numerically and experimentally studied by some researchers (Reinhardt et al. – 1997; Reindhardt and Xu – 1998; Cedolin et al. – 1997; Prisco and Ferrara – 1998)[51]. Later, a practical testing approach to determine mode II fracture energy for concrete was proposed by Reinhardt and Shilang Xu [51].

A number of specimen geometries such as compact shear specimen, compact cube and cylindrical specimens, four-point and punch-through shear specimens have been investigated in the recent years. In the case of compact shear specimen, a compact cylindrical shear specimen and compact cube and cylindrical specimens, casting and testing is easy. However, tensile stresses are also induced in addition to shear stresses either at crack tip or in the middle zone and a pure shear zone of cracking is not achieved. In case of four-point specimens, the failure is due to mixed mode fracture. For punch through shear specimen geometries, crack initiation is in mode I and subsequent failures is in mode II. Prakash Desayi et al. conducted experiments on specimens with four geometries namely 'double central notched' geometry, 'double edge notched' geometry, 'notched column footing' geometry and 'modified double edge notched' geometry and concluded that 'double central notched' (DCN) geometry is better suited for studies of mode II fracture and shear strength studies [52].

Bazant and Pfeiffer conducted tests on symmetrically notched beam specimens of concrete loaded near the notches by concentrated forces that produce a concentrated shear force zone [53]. They observed the failure was due essentially to shear fracture (mode II) (the cracks did not propagate from the notch in the direction normal to the maximum principal stress but in a direction in which shear stresses dominate). They also concluded that the shear (mode II) fracture follows the size effect law of blunt fracture. This implies that a large FPZ must exist at the fracture front, and that nonlinear fracture mechanics should be used, expect possibly for extremely large structures.

Naryanan and Darwish tested FRC beams with crimped steel fibers and concluded that at least 1% fiber by volume is needed to avoid shear failure and to change the mode of failure from shear to flexure [54]. There is no standardized test method in the ASTM or CSA standards to measure the material properties of FRC in shear such as shear strength or shear toughness. In the context of material properties, there have been some attempts to use the Z-type push-off specimen to measure the shear strength and shear toughness of traditionally reinforced and FRC. Using such specimens, Valle and Buyukozturk investigated polypropylene and steel fibers and reported significant increases in ultimate load carrying capacity and ductility [55]. Similar to Naryanan and Darwish, they also found fibers to be more effective in high strength concrete than in NSC. Similar tests were carried out by Karihaloo and Nakseok, who tested hooked-end steel fibers of varying lengths and concurred with both Narayanan & Darwish and Valle & Buyukozturk that concrete of higher strength benefited more in shear from fiber reinforcement [56]. In their studies, plain concrete failed in a very brittle manner with limited warning before collapse, but fibers provided a gradual softening in shear.

Although the Z-type push-off specimen allows one to measure the properties of FRC in direct shear, the stress field in the specimen beyond cracking is highly complex, and stress conditions deviated significantly from being in pure shear. More recently, the Japan Society of Civil

Engineering (JSCE) has proposed a standard test method SF-6, which is an improvement over the Z-type specimens in that during the test, the stress field remains substantially that of pure shear, and hence a more reproducible shear response is obtained. No significant attempt has yet been made to measure the shear properties of FRC using the JSCE–SF6 method. Recently, Amir et al. studied the behaviour of FRC by adopting JSCE-SF6 method and found that the failure was due to pure shear [57]. They also found that the plain concrete failed at a low equivalent shear strain of 0.4%, FRC supported as high as 10% strain in shear.

More recently, Sreenivasa Rao et al. investigated the mechanical and fracture properties of SFRC under Mode II loading using a new specimen geometry and JSCE SF-6 test method of loading [58,59]. They demonstrated that the failure of the specimens exhibited pure Mode II failure along the predetermined plane coinciding with the pre-notches.

IX. CONCLUSION

1. FRC is definitely a better material than plain concrete.
2. FM based analysis is the better method of analysis as it considers the fracture properties of the material.
3. Behaviour of FRC under mode I, III and mixed mode loading was extensively studied by several researchers and its fracture properties were found out.
4. There have only been limited numbers of studies in the past aimed at measuring properties of FRC under mode II loading.

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