Torsional Behavior of Steel Fiber Reinforced Concrete: A Review

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Abstract. Steel fiber improves the strength, ductility (post-peak ductility), and energy absorption capacity of concrete. Despite of its numerous advantages, application of steel fiber in structural members like beam, column and elevated slabs is still in its early stage. In a structural member where complexity of loading is prevailed due to many reasons, torsional or twisting load avail itself either with other loads like shear and flexure or dominantly by itself called pure torsion. Failure of torsion of concrete on the post cracking stage can be predicted by the skew bending or space truss analogy and it is reliant on the tensile strength of the concrete and its ductility which in turn concrete is lack of. Therefore, with the advancement of technology addition of fiber (i.e. that is well known by its crack arresting behavior) in concrete gives an advantage on concretes inability. The improvement degree of steel fiber in concrete is also affected by concrete strength, fiber type, volumetric ratio, and fiber aspect ratio. Thus, this paper provides a summary of the properties of steel fiber reinforced concrete subjected to a twisting loading and gives a recommendation on areas that yet need further investigation.

Keywords: Torsion · Steel fiber · Matrix strength · Aspect ratio · Volumetric ratio · Reinforcement · Failure

1 Introduction

Torsion or twisting or torque is a moment acting about the longitudinal axis of a member caused predominantly by eccentric loading (i.e. equilibrium torsion or statically determinate torsion) and deformation compatibility due to continuity (i.e. compatibility torsion or statically indeterminate torsion) in a structural member like beams Wight and MacGregor [1].

Torsional load does not attract the consideration of most designers like its associated axial, shear, and flexural properties unless this particular property comes up with dominant effect. Eventually in the current design codes of concrete structures a strict consideration of torsion effect is followed [2]. The main reason for that is probably its

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complex nature that the effect it could make when it combines with axial, shear and flexure effect and also the arrangement of structural system.

Torsional load seldom act alone (i.e. pure torsion) and are almost always simultaneous with bending moments, transverse shear [1] and sometimes with axial force in column even if the pure torsion effect that is categorized under equilibrium torsion is the apprehension of this review. Twisting moment can occur in curved bridge girder, spandrel beams, spiral stairways, balcony girders, asymmetrical structure subjected to earthquakes and shells.

1.1 Material and Its Effect on Concrete Structures

From the point that concretes wide applicability in the construction industry, researchers devote to avoid its salient weakness (i.e. tensile strength and ductility). With this objective in mind utilization of fibers in general was seen as one alternative. By far steel fiber is the most widely used type in the fiber application and in research areas that devoted for triggering fibers in the structural application [1, 3, 4]. The reason for that is probably its recognized compatibility with the concrete matrix and its attributed intrinsic properties that support its reinforcing effectiveness such as tensile strength, durability, and elongation [5] other than the opposing fiber types (synthetic, natural and glass fibers).

Steel fibers in the current construction industry are performance oriented than that of its late 1970s uniform and straight steel fiber type that is produced mainly by cutting a wire or by cutting thin low strength sheet materials. The current steel fibers produced from either wire, sheet, or bulk raw materials incorporating surface deformation like surface roughening, surface indentation and crimping other than straight fiber profile to improve pullout resistance, and enhanced anchorage effect by hook or enlargement of fiber ends [5].

Bentur and Mindess [6] stipulate due to the fact fibers are short, discontinuous, and randomly distributed through the matrix, they are not sufficient to endure the tensile stress alone. However, their closeness in distribution over the concrete matrix than the conventional reinforced bars make them better at arresting cracking which is mainly by transmitting force between cracks. Accordingly, the conventional reinforcement bar is thus used for the improvement of the load-bearing capacity of the concrete section while the fibers are more effective at controlling crack.

Though, in the case of High-performance fiber reinforced concrete (HPFRC) having a strain hardening behavior owing to the high percentage of fiber volume, fibers may reasonably improve ductility, energy absorption, impact resistance, fatigue and abrasion resistance with a significant additional enhancement in strength. In HPFRC, the cracking strength of the composites and the post cracking strength are a key parameter that determines its hardening behavior. Whereas the cracking strength is mostly dependent on the strength of the matrix, the post cracking strength is reliant on the fiber reinforcement and the fiber to matrix interaction or interface bond [7].

Conventional FRC provides post cracking ductility, they are a strain-softening material with a significant improvement in tensile strength of plain concrete matrix that is dependent on matrix strength, volume fraction, aspect ratio, the tensile strength of fiber, fiber modulus, fiber surface bonding and aggregate size [8].

Fiber dosage and length or aspect ratio in general in a particular mix is dependent on fiber type and target performance. However, practical consideration aimed at the application of steel fibers for satisfactory workability intended for consolidation, effortlessness of placement and finishing without much effort providing uniform distribution of fiber (avoiding balling or bundling effect) without segregation and bleeding limit the range of volume of fraction of steel fiber in structural application to be 1.5% [1, 8]. The usual diameter and length range of steel fiber is 0.25 to 1 mm and 12 mm to 70 mm respectively (see ACI Committee 544 [8]).

Despite of the fact that fibers are not introduced in national building standard codes, their application in the construction industry mostly with the conventional concrete reinforcement (reinforcing bars and prestressing tendons) mainly in Europe and United States of America is promising. Because of their flexibility in the method of fabrication, economy, random distribution over the mix, discreteness or smallness in size and their improved strength character, makes them viable for any application. For example, in slabs on grade, mining, tunneling, and excavation support applications, steel and synthetic fiber reinforced concrete and shotcrete are the lists of application [8].

1.2 Research Significance

Steel fiber addition in a concrete matrix improves the mechanical behavior of the member including principal enrichment in ductility, durability, improved energy absorption and reduction of crack width. In addition, the steel fibers delay the formation of crack by controlling the crack opening process in which that leads to a distributed crack pattern that is characterized by a closely spaced crack. The literature reviewed in this study expected to add insight about the increase of resistance of concrete to torsional stress with the addition of different percentages of steel fibers. Consequently, the significance, besides moves further to the practical world (working sites) by revealing the main behavior of the addition of steel fiber for torsion prone member (beams, helical stair, spandrel, slabs, and shell) in the structural application.

2 Failure and Analysis Highlight

To idealize failure pattern and or for designing of concrete member under torsion the “skew bending theory” and the “thin-walled tube or plastic space truss model” approaches are widely known in most design codes. However, the latter that is easy for visualization and simpler in calculation procedure than the skew bending theory is used in the current European design code (EC-2) and American concrete design code (ACI-318) [1, 9].

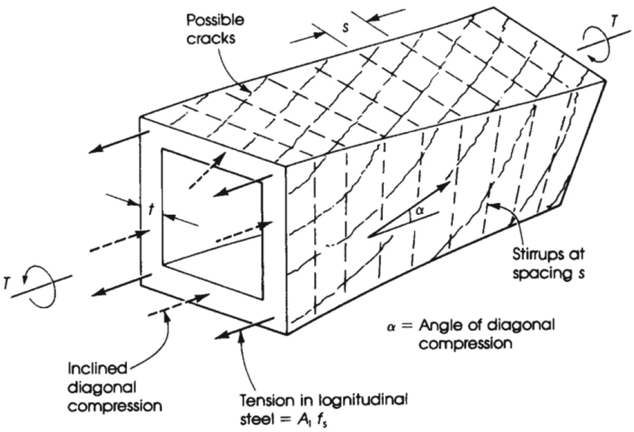

Fig. 1. Failure in space truss analogy [10].

The space truss model analysis is based on an equivalent tubular member, since test data confirms after the torsional crack occurs in a member, the central cross-sectional region of a member has no significant effect on torsional strength [1]. Thus, shear stressed (i.e. shear flow) in this case is assumed to be constant over a tubular thickness and resist the applied torsion. The analysis procedure is clearly depicted in Wight and MacGregor [1], McCormac and Brown [2], Hassoun and Al-Manaseer [10] and others (see Fig. 1).

The approach of the skew bending theory is that failure of member assumed to by bending accompanied with torsion on a skew surface (plane) that is 45° inclined and crack spiral around the sides of the member (see Fig. 2) [1, 10]. Failure or angle of failure for steel fiber is confirmed similar to that of the concrete as explained herein in a skew axis parallel to the long face of beam [11] except the modified skew bending analysis proposed in Mansur and Paramasivam [4] work overestimate the torsional capacity. The failure modes in this case are [9];

- The mode I (dominant positive flexural moment) failure; has a compression zone at the top face and failure is case by yielding of bottom longitudinal reinforcement and transverse reinforcement along the three remaining faces.
- The mode II (dominant torsional shear) failure; has a compression zone along a side face and failure is caused by yielding of the longitudinal reinforcement on the opposite side face and in the transverse reinforcement along the three face in tension.
- The mode III (dominant negative flexural moment); has a compression zone along the bottom side and failure is opposite of mode I failure type.

Combined action (torsion, bending, and shear) phenomenon with the pure torsion of hooked steel fiber shows a skewed bending failure (i.e. failure mode 1 and 2), where a spiral crack along the three faces of the beam is noticed [12].

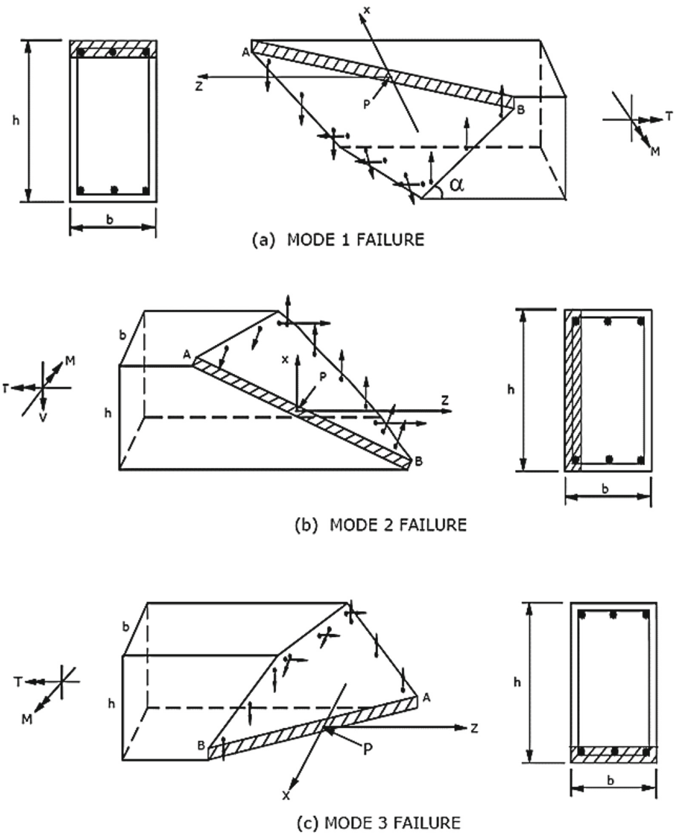

Fig. 2. Failure modes in skew bending theory [9].

Laboratory investigation on capturing the elastic stage or pre-cracking stage up to the first cracking where reinforcement steel has a negligible effect on torsional response and the post cracking behavior is examined by Chalioris [13] through utilization of two analysis techniques for the pre and post cracking stages namely by smeared cracking approach [14, 15] and the softened truss model [16, 17] respectively. The analysis result shows a good agreement with the tested 15 reinforced concrete beams in initial torsional stiffness, ultimate torsional strength, and cracking torque moment. This is significant because it highlights that the softened truss model can capture the post cracking stages where a structure's ultimate carrying capacity is established.

It is similarly described (space truss model) can be used for the case of SFRC under pure torsion [18] which surprisingly confirmed in the earlier analytical and experimental study of Mansur, Nagataki [19] by considering a simplified tensile stress-strain relationship of steel fiber on Hsu and Mo [16] softened truss model of concrete.

3 Effect of SFRC in Torsional Members

The increase in tensile strength or overall enhanced post cracking behavior of concrete due to addition of steel fiber benefits the torsional response of both reinforced and unreinforced concrete beams [11, 18–20]. The crack arresting behavior as boldly said before contributes for the enhancement in torsion for concrete that is well known by its brittle failure nature in twisting actions too. Steel fibers overall enhancement begins from adding in members that contain both transverse and longitudinal reinforcement up to replacing especially the transverse reinforcement [21, 22]. The factors that affect the enhancement are concrete grade or type, the geometry of fiber, volume fraction of fiber, aspect ratio, and cross section type [22].

Analytical investigation of SFRC beam under torsion was studied affirming torsional strength is indeed enhanced by the inclusion of steel fibers in concrete beams [4, 12, 18, 19, 23, 24]. Most importantly, the models were based upon modification of the tensile strength characteristics of concrete to account the enhancement gained from fiber addition of both in the skew and space truss models recommended for concrete beams. However, a lack of standardized test methods for torsion of SFRC gives different results among several experiments starting from no enhancement up to a 100% improvement in torsional strength [6]. The reason for this as stated in Bentur and Mindess [6] is probably the difference in test specimen geometry and testing procedure.

3.1 Concrete or Matrix Strength

The concrete grade that determines the matrix strength, stiffness and most importantly, the fiber-matrix bondage also assessed in different literature for torsional behavior. Rao and Seshu [11] exploit four different grades of concrete (20, 30, 40 and 50 MPa) with fiber contents that stretch up to 1.2% (i.e. F4) at a 0.3% increasing interval. Though, the grades of concrete are under the class of normal strength concrete (NSC) a significant difference in the improvement of both strength and ductility was noticed as shown in the Fig. 3. In their study, the higher concrete grade that is 50 MPa shows a higher improvement in ultimate torque, ductility (twist angle), initial torsional stiffness and torsional toughness (i.e. from the area of torque twist curve).

Lightweight concrete and normal weight concrete effect was studied by Yap, Khaw [25] considering three fiber aspect ratios (55, 65 and 80) with an identical steel fiber volume ratio of 0.5%. Compared to the normal weight concrete matrix, light weight concrete shows more significant enhancement due to the addition of steel fiber in torsional ductility and torsional toughness (see Fig. 4). The cracking torque, ultimate torque, ultimate twist, twist at failure and torsional toughness of lightweight steel fiber reinforced concrete increased by 56%, 56%, 54%, 25% and 125% respectively when it is compared to the control lightweight concrete specimen.

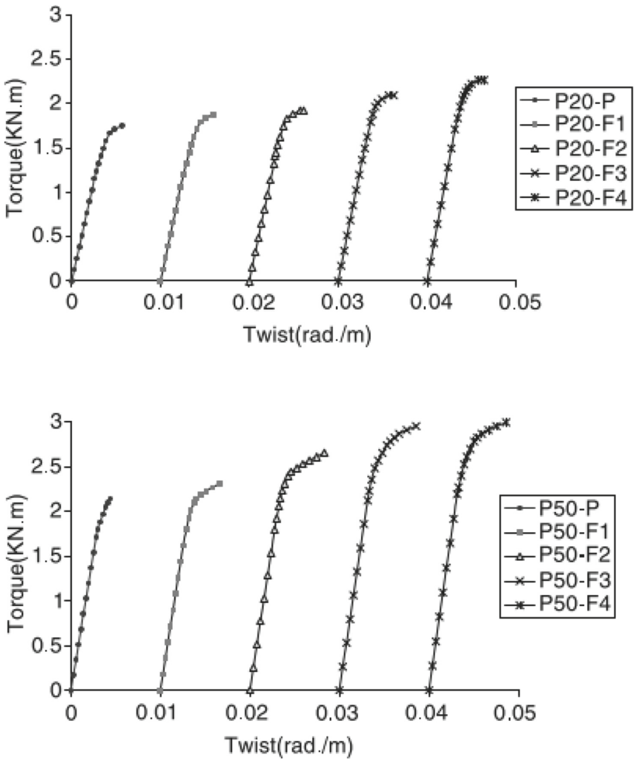

Fig. 3. Torque Twist response of 20 MPa and 50 MPa plain concrete beam series [11].

In other study by Fehling and Ismail [26], Fehling, Ismail [27] ultra-high performance concrete having a cylindrical compressive strength of 200 MPa shows an effective load carrying mechanism at a lower fiber volume ratio (0.9%) unlike the NSC. A similar study by Yang, Joh [28] that utilizes an ultra-high performance concrete (i.e. compressive strength greater than 150 MPa) confirms an improvement is noticed as fiber volume fraction increases. This is may be due to the fact that the increase in brittle nature of the concrete as the concrete grade hereto called matrix strength increases.

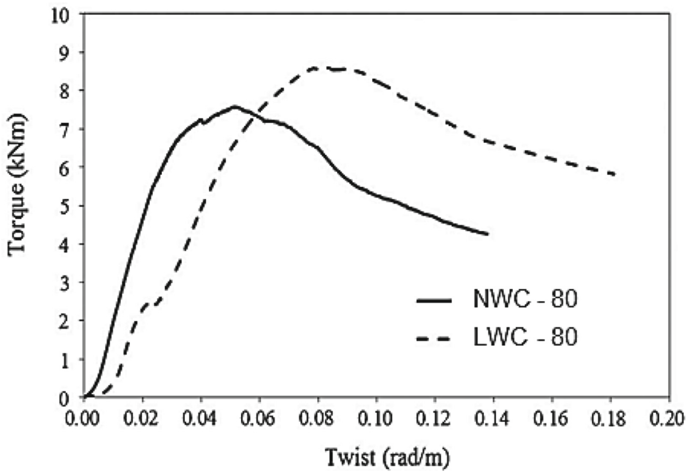

Fig. 4. Comparison between Normal strength concrete (NSC) and Light weight concrete (LWC) containing 80 aspect ratio steel fiber [25]

3.2 Fiber Aspect Ratio

Steel fiber length which is dominantly known by the aspect ratio (fiber length to diameter ratio) has a direct relation with strength of FRC as it symbolizes the pull-out characteristic of a fiber from the matrix. In a torsion induced beam the aspect ratio has a crucial part to perform like its pull-out behavior under a tensile load.

An investigation has been made on this respect by considering small fiber length (30 mm length and 0.5 mm diameter), large fiber length (50 mm length and 0.5 mm diameter), and combination of both [20]. The investigation detected that a small fiber length is not able to surpass both large length fiber and the combination of small and large length fiber in ultimate torque capacity and rotational capability.

Most importantly Mansur and Paramasivam [4] confirmed the reason of the increase in torsional strength as the fiber aspect ratio increase is due to the fact that longer fiber can develop an interfacial bond stress. As the length increase friction is enhanced between the matrix and the fiber, the bond is therefore increased and finally a good strength improvement is handy. But tests on this regard unlike fiber content are still limited. The fundamental cause possibly is as the aspect ratio and volume fraction increases the workability become uncertain for the FRC mix.

3.3 Fiber Volume Ratio

The volume fraction addition clearly shows an effect on the behavior of a steel fiber reinforced concrete. In the analytical study of Ju, Kim [23] the experiment undertaken for 1.5% and 2.0% volume fraction of steel fiber creates 54% and 81% increase in torsional strength. On another study [11] having a fiber volume fraction of 0.3, 0.6, 0.9 and 1.2% with a beam dimension of 100 × 200 × 2000 mm an improvement in torsional strength that is led from an increased tensile strength, ultimate torque, torsional toughness and torsional stiffness is confirmed.

However, the question that should be raised here is how much percentage does it needs to promote a significant enhancement in the overall twisting behavior of a beam. ACI Committee 544 [29] emphasizes 1.2% by volume of fiber cannot show a multi-tracking behavior. But the paper underlines (i.e. ACI Committee 544) improvements in ductility were possible at a dosage of 0.9% where sudden brittle separation of beam is avoided. This argument is also supported by Rao and Seshu [11] even though around 88% increase in angle of twist for the 50 MPa concrete grade (that is the maximum concrete grade of all the examined) with a 0.6% of fiber is noticed where a matrix strength illustrates its effect on the decision of the fiber dosage (see Fig. 3).

For the case of multitracking behavior contrasting ACI Committee report current research [18] on reinforced concrete with and without fiber proves the possibility to see a small crack localization at a percentage of steel fiber of 30 kg/m^3 (i.e. around 0.4% volume fraction) that is below 1.2% (see Fig. 5). This is worth noting as it clarifies even at a considerably lower amount of dosage improvements can be able to captured in the structural performance of the beam.

In another similar study by Facconi, Minelli [30], a longitudinally reinforced beam sample with a volume fraction of 25 kg/m^3 (i.e. 0.32%) and a fiber aspect ratio of 86 (i.e. having a length of 30 mm and diameter of 0.35) shows an increase in torsional strength of 10% with an improved torsional toughness. In addition, the experiment unravels improved ductility that shows a stable fracture process characterized by a post peak softening in such a lower fiber volume fraction when it is compared to the sample without SF.

As a concluding remark, it is understood improvements are prevailed especially in ductility with a relatively lower fiber volume fraction in torsion. However, torsional strength improvement is not easily prevailed as the volume fraction reduces. The limiting fiber volume ratio for overall torsional behavior is not much advanced and needs further investigations. But from the standing point of workability or in general rheological properties of fiber reinforced concrete [31] this limitation may be taken. The usual limiting fiber content except the case of higher fiber dosage of SIFCON or SIMCON is in between 1.5% and 2.0% (see [8, 31] perhaps the later might need a small sized coarse aggregate or no coarse aggregate options to a high super plasticizing admixture to make a slurry of flowing concrete.

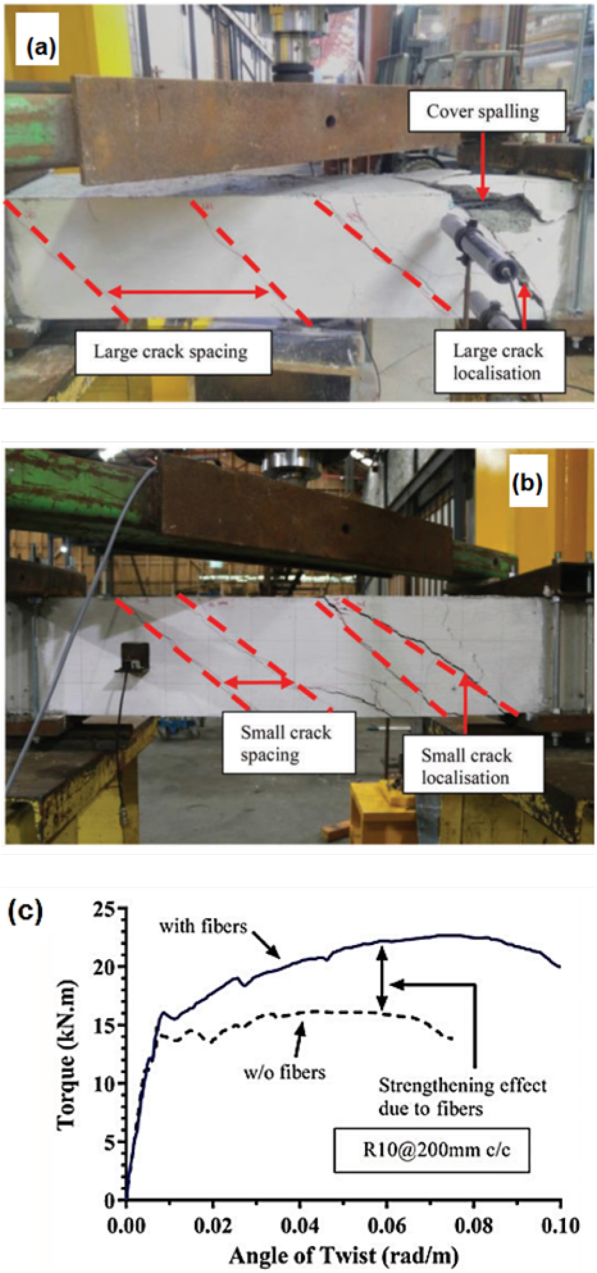

Fig. 5. Failure mechanism of beam diameter 10@200 mm under pure torsion a) without fiber b) with 30 kg/m^3 fiber c) test result [18].

3.4 Steel Fiber as a Reinforcement Option

The proximate uniform distribution of steel fiber gives rise to several advantages over replacing or use in partial replacing with conventional reinforcement known as a hybrid system. The random distribution that is assumed to be uniform in the member at a closer spacing than the smaller diameter conventional reinforcing bar which cannot able to control smaller cracks that rise to a larger crack leads to reinforcement yielding, the fibers capability of increasing first cracking tensile strength and ultimate tensile strength of the member and shear friction strength is increased due to pull out behavior and crack bridging effect are the leading reasons that makes it viable [8].

In torsional load similar to other load type steel fibers effect begins to sought after the matrix crack commencement and thus the usual reinforcing effect starts at this stage [13]. Chalioris and Karayannis [22] investigated steel fiber as the alternative to replace shear torsional reinforcement considering 1% and 3% volumetric ratio of steel fiber. A comparison of the behavior of non-fibrous reinforced concrete having both longitudinal bar and stirrups with that of SFRC with longitudinal reinforcement of rectangular beam is described in Fig. 6. Under this investigation flanged and rectangular beam cross sections are used and the replacement of stirrup by fiber shows for rectangular beam (with torsional transverse reinforcement ratio of 0.63%) was efficient (see Fig. 6) than the flange beams.

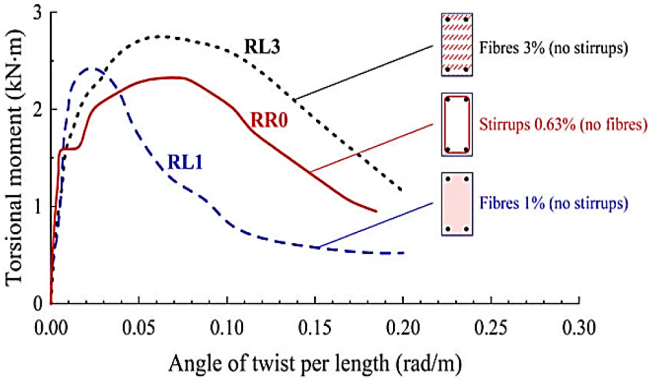

Fig. 6. Steel fiber as shear torsional reinforcement (stirrups) [22].

In another similar investigation both partial and full replacement of stirrups and longitudinal reinforcements are investigated by Narayanan and Kareem-Palanjian [21]. In this investigation the reinforcement ratio of longitudinal or transverse reinforcement (stirrups) is totally and partially replaced by the fiber volume fraction. A significance gain in ultimate strength is found in both the partial and full replacement of transverse reinforcement. Unlike the partial replacement of transverse reinforcement, the replacement of longitudinal reinforcement is not substantial since ductility is reduced [21].

In both of studies [21, 22] NSC is used for the investigations. However in another study [26, 27] ultra-high performance (UHPC) concrete matrix with 0.5 and 0.9% volume fraction is used to see the alternative of reinforcement replacement. This investigation disregards the ideology of the impossibility of longitudinal reinforcement replacement. But as a concluding remark usage of both transverse and longitudinal reinforcement with an appropriate volume percentage yields an outstanding performance in both of the pre and post cracking stages of twisting force.

Even though the experimental work of [21, 22] come up with a positive result a refined investigation and additional tests are needed to conclude its possibility. As that of shear reinforcement replacement discussed before [32] in the torsional stirrup case full replacement is not convenient because of fibers which fails mainly by pull out cannot bring the required ductility that can be provided by the conventional reinforcement stirrups were a great plastic deformation failure could appear [22]. Regarding the ductility behavior of fiber and stirrups, the area is still open for investigation in addition to the limited database of strength behavior.

4 Conclusion

Based on the findings of literatures discussed in the subsequent sections the following conclusions with a recommendation are drawn;

- Steel fiber reinforced concrete shows an improved torsional strength and ductility even if the pre-cracking stage effect of steel fiber reinforced concrete is negligible in a relatively lower percentage volume of fiber (i.e. volumetric ratio less than 2 or 3%).
- Failure of the beams tested shows almost similar pattern with that of normal concrete beam except in fiber addition multi cracking due to its crack arresting attribute was seen. In torsion-bending loading the skew bending theory holds and in pure torsional member the usual 45-degree spiral crack controls the failure pattern.
- Matrix strength is also affecting the overall performance of steel fiber and it is dominant in case when the strength of concrete matrix increases because brittleness increases. In addition, even though additional investigation is needed torsional response of light weight concrete (LWC) is highly improved compared to normal weight concrete (NWC).
- The possibility of fibers replacing concrete is promising except the steel cross sectional area, yield strength and combination of with high strength reinforcement needs further investigation.
- Furthermore, SFRC particularly SIFCON, SIMCON and ECC should be investigated for torsion to see if their strain hardening and ductility behavior can manifest.

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