ISSN: 2643-6876
DOI: 10.33552/CTCSE.2023.09.000732
Current Trends in
Civil & Structural Engineering
Iris Publishers

Review Article

New Concept of Global Reinforcement of a Beam

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Received Date: November 02, 2023

Published Date: November 10, 2023

Abstract

This paper presents a new concept related to the global reinforcement of reinforced and prestressed beams with fibers. What is new in this concept is to propose to install, in beams with high depth, additional longitudinal (parallel to the beam length) rebars where the shear stress is maximum. More, it recommends using different type of fiber reinforced concretes when reinforced concrete or prestressed concrete structures are concerned. Some information about the required mix design of fiber reinforced concretes in relation with each type of structure is proposed. Finally, this paper focus on the use of non-linear finite element models as the best tools to optimize the design of beams with a view to achieving relevant eco-constructions.

Keywords: Fiber reinforced concretes; Beams; Prestressing; Reinforcements; Design optimization; non-linear finite element models; Eco-construction

Introduction

Concrete, although being the most widely used construction material in the world, has poor resistance to tensile stresses and cracks under these stresses. This cracking occurs whatever the type of mechanical stress, whether bending, shear or compression [1-3]. This is why engineers have used different reinforcement strategies for this material since the end of the 19th century. Among these reinforcements, passive then active reinforcements and finally fibers appeared, chronologically speaking.

Passive reinforcements (reinforced concrete)

These passive reinforcements are intended to control the cracks propagation and their opening and not to prevent them. They are, therefore, positioned in areas of a concrete structure where the risk of cracking is greatest. For example, in the context of a beam, they are positioned in zones where the tensile stresses are direct or uniaxial (very important, in the tensile part of the beam in the case where it is subjected to bending) and in zones where these tensile stresses are indirect (less significant), as in compressing zones or in shear zones (stirrups).

Active reinforcement (prestressed concrete)

These reinforcements, also called prestressing bars, impose an initial compressive stress in areas which would normally be subjected to direct tension. The objective is then to prevent any appearance of cracks in these areas when the beam is mechanically loaded. It is a technical solution of great interest:

a. It makes it possible to reduce greatly the total quantity of passive reinforcement in the structure. All that remains is the reinforcement in the compressed zones and those in the shear stress zones.

b. It makes it possible to design beams with larger spans, because for the same mechanical loading, the prestressed concrete beam has a much smaller deformation than the same reinforced concrete beam.

c. It is a solution that presents some disadvantages, a part from the fact that it is more complex to implement than reinforced concrete:

d. Due to the significant creep of concrete in compression, the prestressing imposed on the concrete decreases over time. This loss of prestressing must be considered in the calculation of the initial prestressing to be imposed on the beam. This calculation can sometimes lead to approximations or errors.

If, due to an erroneous calculation of prestressing losses or unforeseen stresses in the design of the beam, cracks appear in the prestressed zones and propagate to the prestressing steels, the beam may fail in a very brutal way:

a) Over-tensile stresses in the prestressing bars can locally occur when cracks cross them.

b) Corrosion of these prestressing rebars due to the cracks created (chloride penetration through the cracks) can accelerate their failure (stress corrosion).

Fibers (fiber reinforced concrete)

Fibers have the same role than rebars. They are used to control cracks opening and propagation. They have some difference with the last ones:

a) They are a lot of shorter (maximum length of around 60 mm).

b) They are part of the material mix design and, so, are casted at the same moment than the concrete.

These two points have some consequences:

a. They can control cracks with opening shorter than those controlled by rebars. They are especially efficient to control cracks with opening no larger than 0.5 mm (service limit state cracks opening) [4-7]. They are still efficient for larger cracks opening around 1 or 2 mm, depending of the fiber dimensions [4-7].

b. They have preferred orientations within the structure depending on its geometry and the casting method adopted. Therefore, their mechanical efficiency depends on their orientation compared with the directions of cracks propagation.

These last years, fibers have been used with reinforced concretes or with prestressed concretes (hybrid reinforcements) but not often in a good way and not with an optimization requirement. This objective of optimization is the main topic of the present paper.

New concept of Global Reinforcement of a Beam Section

The fact that fibers are very efficient to control cracks opening no larger than 1 or 2 mm allows to replace, in reinforced and prestressed concrete beams, traditional stirrups and rebars in the compressive zone, by fibers [7-12].

Fibers in prestressed concretes

In prestressed concrete structures as beams, if shear cracks appear before bending cracks, they are confined between two compressive zones: the zone of prestressing application and the compressive zone. This strong confinement leads to the existence of shear cracks with low openings. However, fibers are very efficient to control these cracks. This efficient crack control leads to the existence of numerous shear cracks weakly open. That leads to a kind of ductile shear stress behavior. The problem is that shear cracks opening increases with the beam depth. It is a pure geometrical aspect. Therefore, the efficiency of fibers to control the shear cracks propagation also decreases with this depth increasing. A way to solve this problem constitutes a first innovation in the global reinforcement concept of beams: it is proposed to add longitudinal rebars (it means parallel to the beam length) located in the zone where the shear stress is maximal. This solution is technically easy to perform. A longitudinal rebar is mechanically also effective than a traditional vertical stirrup to control a shear crack which is inclined.

Moreover, this solution would provide an improvement in the bending behavior of the beam if an unwanted bending crack propagated along the section of the beam. This possible crack would then be controlled at both ends (at level of the prestressing bars and the level of the rebars). In this innovative solution, the number of additional rebars will depend on the depth and the geometry of the beam section. It is also interesting to focus on another point of interest to consider this association between prestressing and fibers. It is about the appearance of bending cracks in the prestressed zone linked to a loss of prestressing during time (see, chapter 4). In this case, fibers are capable to control the opening and the propagation of these cracks. This joint action of prestressed bars and fibers leads to a partial prestressing, well-known in classical prestressed structures. During this cracking process in the prestressed zone, compression stresses outside the cracking zone remain important due this prestressing. That constitutes a kind of confinement of the cracking zone. This mechanical situation, associated with a very good efficiency of fibers to control fine cracks, leads, logically, to generate a multi-cracking process made up of fine cracks. This type of multi-cracking process is more important in the case of prestressed reinforced concretes with fibers than for traditional reinforced concretes with fibers (where there is less confinement of the cracking zone).

Fibers in reinforced concretes

A large part of what concerns fibers in prestressed concretes is true concerning fibers in reinforced concretes. Thus, fibers can also replace stirrups in shear zone and rebars in the compressive zone. However, there are, despite everything, some differences between these two technical solutions: shear cracks are more opened and less numerous in reinforced concretes than in prestressed concretes. There are several reasons for that:

a) The shear cracks are less confined in reinforced concretes (see chapter 4.1).

b) They are, generally initiated, by bending cracks.

However, the fibers are less efficient to control shear cracks in reinforced concretes than in prestressed concretes. This point is very important. Indeed, this implies that the fibers length has to be larger in reinforced concretes than in prestressed concretes to obtain good efficiency with respect to the shear stress force. This choice of longer fibers is also interesting in relation with the bending cracks that are always geometrically more opened than the shear cracks. Concerning the proposal to use longitudinal rebars where the shear stress stresses are maximal in large depth beams (see chapter 4.1), it is also valid for reinforced concretes. However, shear cracks opening is larger than for the prestressed concretes. It is also important to point out that the presence of bending rebars at two levels of the beam section (bending part and shear stress part) leads to get a strong control of the bending cracks. Another important point on the multiscale reinforcement using rebars and fibers has to be considered as an innovative proposal: with the presence of fibers, it is possible to use, in the bending zone of the beam, rebars with larger diameters than usual. Indeed, fibers can control possible cracks linked to tensile stress concentrations generated by large diameter rebars.

General comments

The replacement of stirrups in shear zone and rebars in the compressive zone by fibers is relevant and efficient only if the content of fibers is enough. This point is linked to the fact that, during casting, fibers are distributed randomly throughout the beam that, thus, becomes spatially heterogeneous. To be sure that there is a minimum of fibers at every point of the beam, it is therefore necessary to introduce a high percentage of fibers. Therefore, it is recommended to use a minimum of 78kg/m^3 of fibers in reinforced concrete or prestressed concrete beams. The second point, very important concerning the global reinforcement of reinforced or prestressed concrete beams, is the related to the evolution of the mechanical characteristics of steel rebars. Indeed, quite recently, new qualities of steel have been developed. These steels have a tensile strength increased by approximately 70% compared to the steels conventionally used, today, in rebars [13]. This innovation should lead, in the future, to significantly reducing the percentage of rebars in concrete structures. The third comment concerns the choice of fiber reinforced concrete depending on the type of application, in this case, in a reinforced beam or in a prestressed beam. If what has been said previously regarding the difference in cracks opening in reinforced beams and in prestressed beams is considered, the most suitable fiber reinforced concrete will be different. So:

a) For prestressed beams, it is preferable to use a fiber reinforced concrete having a compressive strength greater than or equal to, approximatively, 80 MPa with fibers length around 30 mm.

b) For reinforced beams, it is preferable to use a fiber reinforced concrete having a compressive strength between 40 and 60 MPa with fibers length around 60 mm.

Finally, the last comment is related to the best way to optimize the design of the reinforced and of the prestressed beams with fibers. It is a key point in the field of eco-construction [14]. It is also a key point to improve the safety of the concrete structures. Standards, as Eurocode 2, do not constitute the good tools to achieve this objective [14]. Indeed, they are not efficient:

a. To properly consider the cracking process of fiber reinforced concretes, especially at the service state of the structure and when this one has an hyperstatic behavior;

b. To properly consider the improvement of the concrete/ steel bond with the presence of fibers [15 - 17].

At the contrary, non-linear finite element models constitutes relevant tools to take up this challenge [14].

Conclusions

This paper presents a new concept related to the global reinforcement of reinforced and prestressed beams with fibers. This concept is mainly based on the fact that, on the one hand, the fibers control crack openings smaller than those controlled by the traditional rebars and that, on the other hand, they are distributed in a more or less random manner in the structure. What is new in this concept is, first of all, that beyond the now classic replacement of stirrups in the shear zone and rebars in the compressive zone of beams, it is proposed to install additional longitudinal (parallel to the beam length) rebars where the shear stress is maximum. This additive reinforcement is proposed when the beam depth becomes too high for an efficient cracks control by fibers. This paper focus, also, on the fact that fibers are more efficient to control shear cracks opening in prestressed concrete beam than in reinforced concrete beams. For these two types of structural elements, it is specified that the optimal fiber reinforced concrete to be used is different:

a) For prestressed concretes structures, it is recommended to use fiber reinforced concretes having a compressive strength greater than or equal to, approximatively, 80 MPa with fibers length around 30 mm.

b) For reinforced concrete structures, it is recommended to use a fiber reinforced concretes having a compressive strength between 40 and 60 MPa, with fibers length around 60 mm.

In all cases, it is recommended to use a minimum of around 78 kg/m^3 of fibers. Finally, this paper focus on the fact that it is essential to use non-linear finite element models to enable an optimized design of these beams with a view to achieving relevant eco- constructions.

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