IMPROVEMENT OF DUCTILITY IN SHEAR FAILURES OF REINFORCED CONCRETE DEEP BEAMS BY DIAGONAL CONFINEMENT

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ABSTRACT

The shear behavior of concrete beam with no transverse reinforcement is investigated using Strut & Tie Model. The effect of spiral confinement on diagonal tension failure of the concrete beams is investigated by simulations using a software package called ATENA. Four series of geometrically similar beams of different depths are compared. Beam heights range from 350mm to 1000mm and al1 the beams have a constant shear span to depth ratio of 1. The assumed inclined diagonal strut of concrete is confined by spirals to improve triaxial strength of the concrete strut. The variables introduced in the present work are member depth, amount of inclined confinement in shear region for which varying parameters of spirals are diameter of wire & pitch of the spiral. It has been observed that the confinement of inclined diagonal strut is effective to improve ductility of the beam failing in shear.

INTRODUCTION

The vast majority of structural members in reinforced concrete have to resist shearing forces. The shear forces seldom act on their own but rather in combination with flexure, axial loads and torsion. The behavior of reinforced concrete beams at failure in shear is distinctly different from their behavior in flexure. Shear capacity of an RC beam is defined as the maximum shear force that can be sustained by a critical section of the beam. Though there are different mechanisms that govern shear failure in beams, it is confirmed that shear transfer in reinforced concrete beams relies heavily on both tensile and compressive strength of concrete. Shear reinforcement is provided in order to carry that portion of the shear force which cannot be sustained by concrete alone. The failure of member in shear is relatively more brittle. Consequently an attempt must be made to suppress such drastic failures.

In earthquake resistant structures, a heavy emphasis is placed on ductility but when ductility is essential the shear strength of member must be in excess of the maximum flexural strength in the member. Further to increase the strength of beams, engineers design large size beams and the failure becomes more brittle due to increase in size. It is a common design practice, first to design an RC beam for flexural capacity and then to ensure that any type of failure, other than flexural (that would occur when the flexural capacity is attained), is prevented.

Strut-and-tie modeling (STM) provides design engineers with a more flexible and intuitive option for designing structures, or portions thereof, that are heavily influenced by shear. STM is developed by Ritter (1899) and Morsch (1909) nearly a century ago based on Truss Analogy. The STM proposes that a cracked reinforced concrete beam acts like a truss with parallel longitudinal chords, a web composed of diagonal concrete struts, and transverse steel ties. When shear is applied to this truss, the concrete struts are placed in compression, while tension is produced in the transverse ties and in the longitudinal chords. This method allows for the stress flows within a structure to be approximated with simple truss-elements that can be designed using basic structural mechanics.

SCOPE OF WORK & OBJECTIVES

It has been observed experimentally that shear failure in beams is due to diagonal tension in shear span. Concrete beams fail abruptly without sufficient advance warning, and the diagonal cracks that develop are considerably wider than the flexural cracks. Failure of inclined strut resembles the failure of short columns. In practice the columns are generally confined by spirals or hoops to increase its strength in compression which also increase its lateral tensile strength. More than that, its ultimate strain or in other words ductility is increased. Hence increment in shear capacity of a beam can be achieved by confinement of the anticipated inclined strut.

A software package called ATENA is used for the analysis of beams. A set of geometrically similar beam models with different sizes are simulated and analyzed in ATENA. The models for simulation are based on the simple truss models with truss heights or beam depths of 350mm, 500mm, 750mm and 1000mm. All the beams have a constant shear span/depth ratio equal to 1 and without any transverse reinforcement. It is confirmed by the analysis that the confinement of inclined struts improves the shear strength and ductility of beam with considerable amount.

SHEAR FAILURE IN REINFORCED CONCRETE BEAMS

Shear Failure is one of the failure modes of RC structure. The behavior of reinforced concrete beams at failure in shear is distinctly different from their behavior in flexure. They fail abruptly without sufficient advance warning, and the diagonal cracks that develop are considerably wider than the flexural cracks.

The shear span to depth ratio determines the failure modes of the beam. Generally, shear failure occurs when the shear capacity of a critical cross-section is exceeded. Shear resistance is mainly offered by the portion below the neutral axis with the help of "aggregate interlock" & "dowel action" in the absence of shear reinforcement. For beams with shear reinforcement shear force is sustained by a different mechanism.

The present work, deals with "Diagonal Tension Failure" which is usually known as "Diagonal-splitting".

DIAGONAL TENSION FAILURE

The diagonal tension cracking failure is supported by experimental investigation on the behavior of RC beams, subjected to two-point loading with various shear span to depth ratios (a/d) which has been published by Kotsovos (1987) & many other investigators to date.

In diagonal tension failure, cracking starts with a few fine vertical cracks at mid span, followed by loss of bond between the reinforcing steel and surrounding concrete at the support. Thereafter without ample warning of impending failure, two or three diagonal cracks develop at about 1.5d to 2d from the face of the support. As they stabilize, one of the diagonal cracks widens in to a principal diagonal tension crack and extends to the top compression fibers of the beam. It is noticeable that the flexure cracks do not propagate to the neutral axis in this essentially brittle failure mode with relatively small deflection at failure.

STRUT & TIE MODEL

Strut-and-Tie Modeling (STM) is a method of design for reinforced and prestressed concrete. STM reduces complex states of stress within a structure to a collection of simple stress paths. The stress paths result in truss members loaded with uniaxial stress that is parallel to the axis of the stress path. Truss members that are in compression are called struts, while the force paths that are in tension are named ties. The intersections of struts and/or ties form the nodes. The collection of struts, ties and nodes is called a truss mechanism or model. The forces within a strut-and-tie model can be calculated using static equilibrium if the truss is statically determinate. Such a reduction in complexity allows for simple design of structural concrete.

Elements of a strut-&-tie model

Each of the types of elements in a strut-and-tie model serves a unique purpose, but must act in concert to describe accurately the behavior of a structure. Following are the types of elements in Strut-&-tie Model.

Struts

Struts are the elements within strut-and-tie models that carry compressive stresses. The geometry of a strut varies widely and depends upon the force path from which each individual strut arises. The most basic type of strut is prismatic which develops in two -point loading. Prismatic struts have a uniform cross section over their length as in Fig.1. The compressive stress block of a beam in a section of constant moment is an example of a prismatic strut. When the flow of compressive stresses is not confined to a portion of a structural element, a bottle-shaped strut can form as in Fig.1. In this case, the force is applied to a small zone and the stresses disperse as they flow through the member. As the compression disperses, it changes direction forming an angle to the axis of the strut. To maintain equilibrium a tensile force is developed to counteract the lateral component of the angled compression forces.

Ties & Nodes

Ties are the elements within a strut-and-tie model that carry tension, and are generally confined to reinforcing or prestressing steel & Nodes form where struts and ties intersect.

FAILURE OF STRUT-&-TIE MODEL

STM is assumed to fail due to yielding of ties, crushing of the struts, & failure of nodal zone. Failure of nodal zone is assumed to reach their capacities when the compressive stresses acting on the ends of the struts or on the faces of the nodal zones, reach the appropriate effective compressive strengths. The present work is concerned with the failure of strut before yielding of ties.

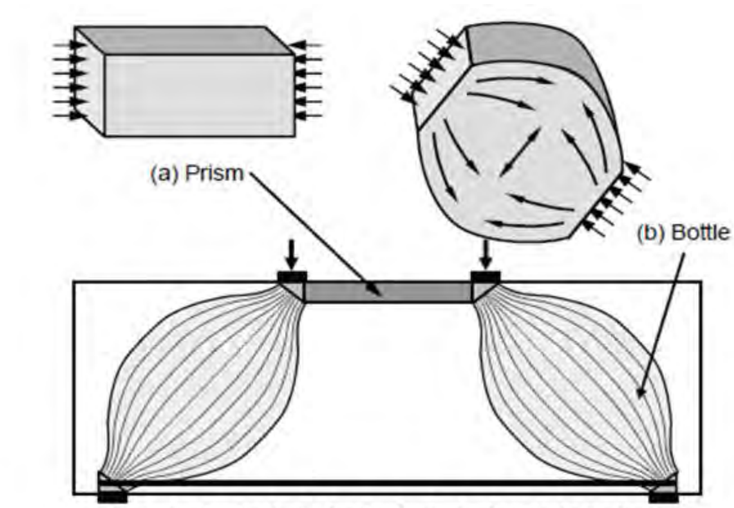

Fig 1: Struts in two point loaded beam

CONFINEMENT OF CONCRETE

In practice, concrete can be confined by transverse reinforcement, commonly in the form of closely spaced spirals or hoops. At low levels of stress in the concrete, the transverse reinforcement is hardly stressed, hence the concrete is unconfined. Concrete becomes confined at stresses approaching the uniaxial strength; the transverse strains become very high because of progressive internal cracking & the concrete bears out against the transverse reinforcement, which then applies a confining reaction to the concrete.

Thus transverse reinforcement provides passive confinement. Tests by many investigators have shown that confinement by transverse reinforcement can considerably improve the stress-strain characteristics of concrete at high strains. The increase in ductility due to confinement is very significant.

ACTION OF SPIRALS

Several Experimental investigations have demonstrated that circular spirals confine concrete much more effectively than rectangular or square hoops. After limit of proportionality of stress & strain has been reached, the increase in the rate of lateral deformation serves to generate stress in the steel spirals. At the stage when splitting & failure of plain concrete begin the action of spiral column is quite different. There is undoubtedly a tendency for splitting, but since such an action would in turn produce a rapid increase in the lateral compression exerted by the spirals the splitting is restrained or retarded. The lateral pressure develops as the concrete bulges outward against the spiral. The lateral support is afforded by the tensile strength of surrounding uncracked concrete elements. As the lateral deformation progresses splitting takes place and the support of surrounding uncracked element vanishes. This loss of support allows further lateral deformation & the needed lateral restraint is secured from the spiral reinforcement. The equilibrium is acquired by the external loads & the lateral pressure of the spiral reinforcement.

It is evident that the maximum load on a spirally reinforced member is reached when the increase in lateral compression produced by the spirals fails to keep up with the loss of cohesion between particles. There seems to be a minimum rate of development of spiral stress required, since failure of columns occurs before the spiral steel reaches its ultimate strength.

Hence confining concrete by spirals can be a better way to avoid shear failures, which are basically tension failures. As confinement improves the triaxial strength of concrete, it can be used in beams to confine the inclined strut to secure it by failing in shear.

COMPUTER SIMULATION

To study the behavior of confined compression strut in beams failing in shear, a set of beam models are simulated in a software package ATENA [5]. ATENA is software for Analysis of Concrete and Reinforced Concrete Structures. It simulates the behavior of concrete and reinforced concrete structures including concrete cracking, crushing and reinforcement yielding.

Simulation of standard size Cylinders

Before running simulations on beam model, it was necessary to check the response of ATENA for analysis of the proposed work. Hence for simplicity, a number of cylinders of standard size 150mm diameter & 300mm height, with confinement by spiral reinforcement as shown are simulated using ATENA. Confinement wire diameter & pitch of the spirals are varied but the spiral diameter is kept 100mm constant. Load-deflection curves are obtained by simulations for each cylinder. The results of simulated cylinders are compared with the experimental data. It is found that the ATENA is capable of capturing confinement effect very well as showed in Fig.2.

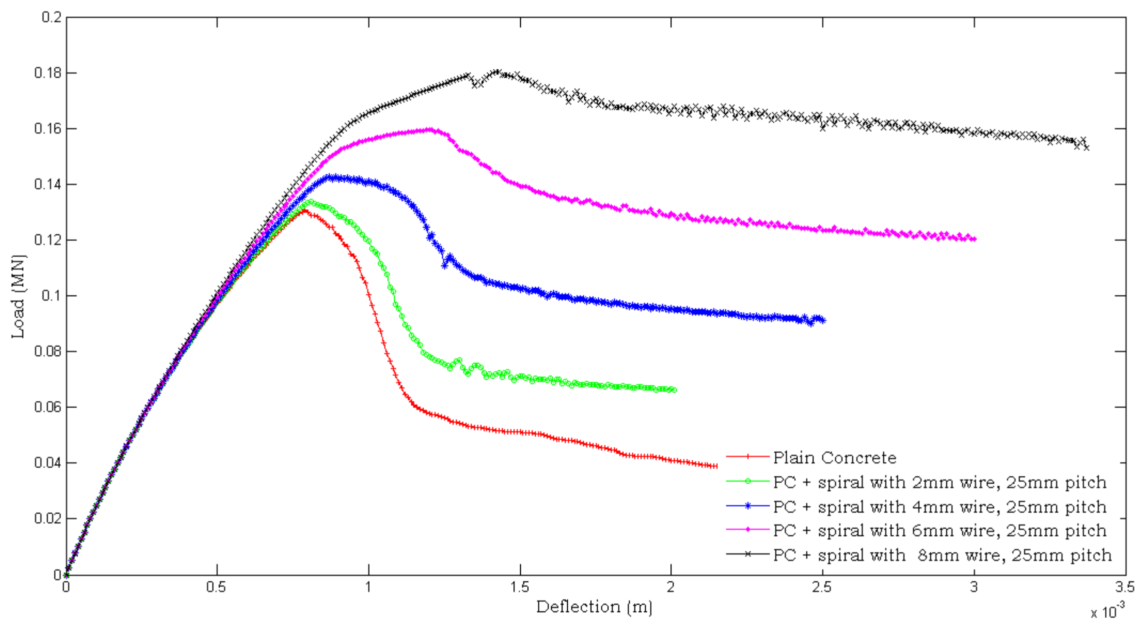

Fig 2: Load Vs Deflection curves for standard Size Cylinders

SIMULATION OF BEAM MODELS

The Beam models for simulation are designed intentionally to fail in shear by avoiding flexure failure. Flexure failure is secured by providing sufficient longitudinal flexure reinforcement. The various dimensions of beam models are given in Table 1 & shown in Fig.3.

For all beams the constant shear span to depth ratio is 1. The width of beams is also constant 150mm. Transverse reinforcement is not provided to any type of beam. Each size of beam has two types, one with only longitudinal flexure reinforcement & the other with both longitudinal flexure reinforcement & confined compression strut. Flexure reinforcement is 0.3% of the cross sectional area for all sizes & types of beams. As a/d ratio is 1, the strut angle is taken as 45^0 joining the loading & support points for simplicity.

The variables introduced in the above simulations are beam depth & confinement parameters. As Spiral confinement is used for inclined strut, the diameter of spiral, pitch, diameter of steel rods & yield strength of steel used for spirals are shown in Fig.3. Out of the above four parameters, the diameter of spiral is kept constant equal to100mm for all sizes of beams & yield strength is also kept constant. Several simulations are performed by varying the diameter of steel rods & pitch of the spirals. The rod diameter varies from 2mm to 12mm & spiral pitches are 25mm & 50mm.

Table 1

Beam	D(mm)	L(mm)	a(mm)	c(mm)	b(mm)	d(mm)	Pt (%)
B35	350	1330	350	350	150	320	0.3
B50	500	1900	500	500	150	470	0.3
B75	750	2850	750	750	150	720	0.3
B100	1000	3800	1000	1000	150	970	0.3

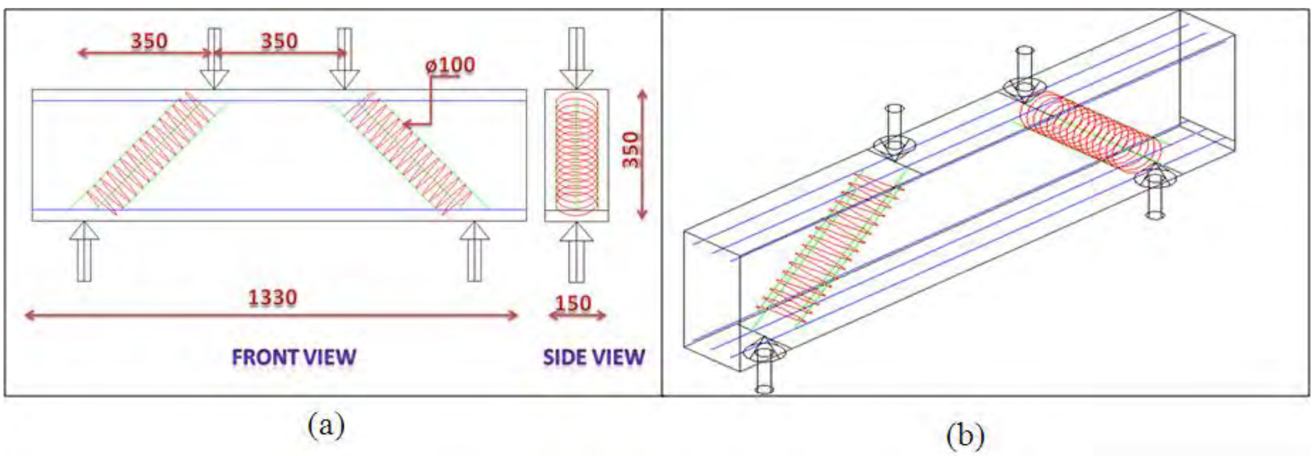

Fig 3: (a) Beam of depth 350mm, (b) Isometric view of the Beam

RESULTS

In simulation of beams, the Load-Deflection curves are obtained to study the comparative effect of inclined strut confinement. The maximum deflection at mid span is tracked & plotted to its respective applied load. Plain concrete beams are compared with beams having only flexure reinforcement & with beams having inclined confined strut with flexure reinforcement. After a few simulations on 350mm deep beam, it has been observed that a wire of 2mm diameter with 25mm pitch & also with 50mm pitch does not have significant effect on ductility compared with 8mm diameter wire as shown in Fig.4. Similarly the wire of 12mm diameter with 50mm pitch does not have any significant effect on ductility as shown in Fig.8. Hence for further simulations of 500mm, 750mm & 1000mm deep beams, wires of 2mm & 12mm diameter have not been used. Fig.4, Fig.5, Fig.6 and Fig.7 shows the load versus deflection curves for beams of depth 350mm, 500mm, 750mm & 1000mm respectively.

Note: In following figures LFR is longitudinal flexure reinforcement & ICR is inclined confined reinforcement. Nomenclature in legends of following figures is as follows
"LFR + 100mm Φ Spiral, 4mm Φ wire, 25mm pitch" can be understood as Beam with longitudinal flexure reinforcement having inclined diagonal spiral confinement of 100mm diameter of 4mm diameter wire & 25mm pitch of the spiral.

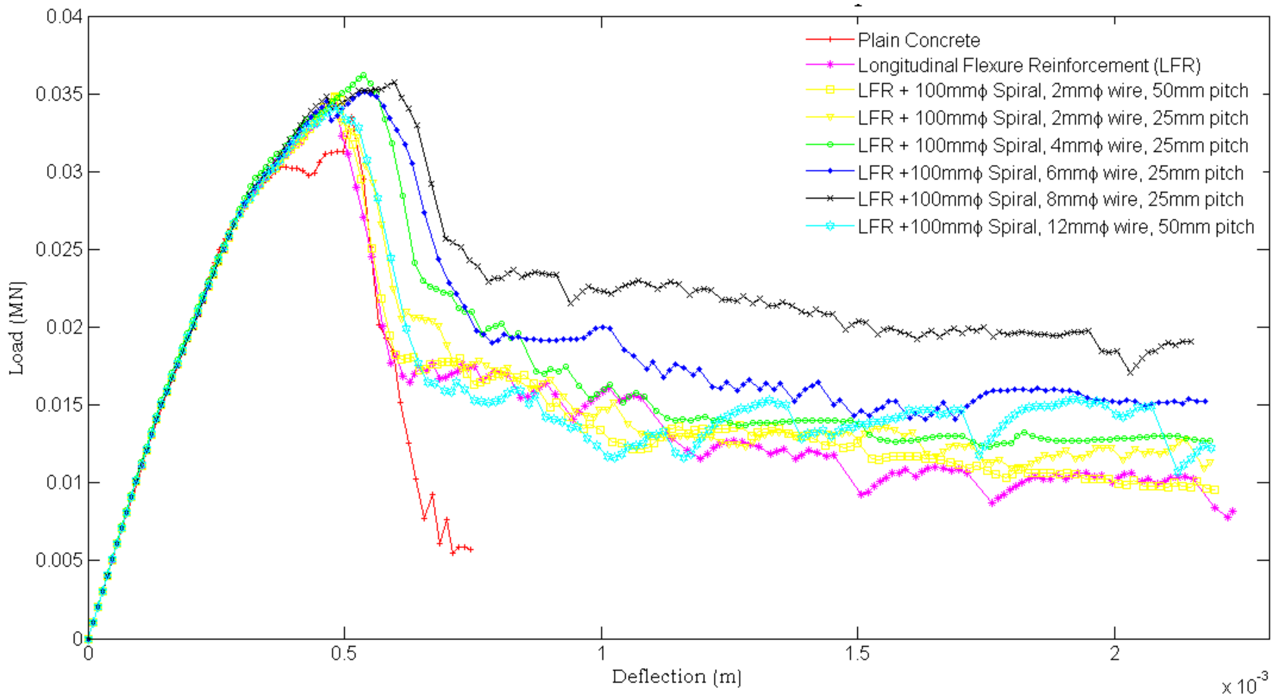

Fig 4: Load Vs Deflection curves for 350mm deep beams

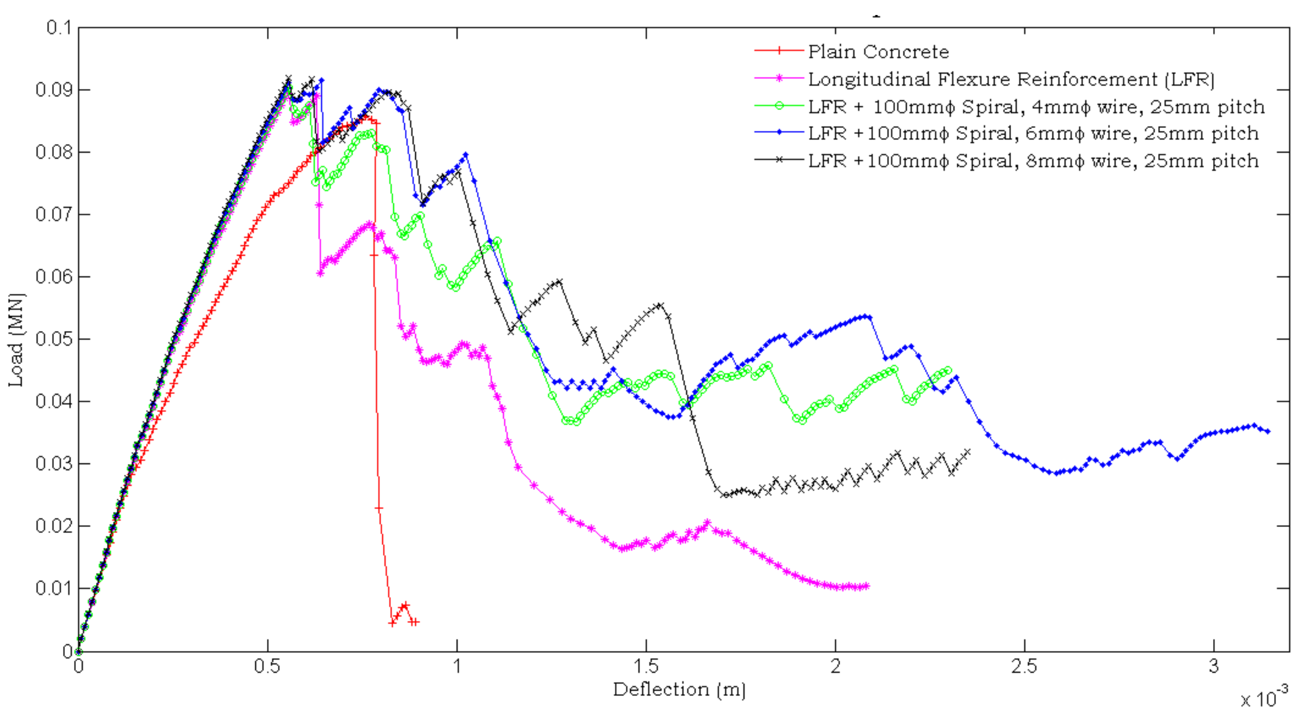

Fig 5: Load Vs Deflection curves for 500mm deep beams

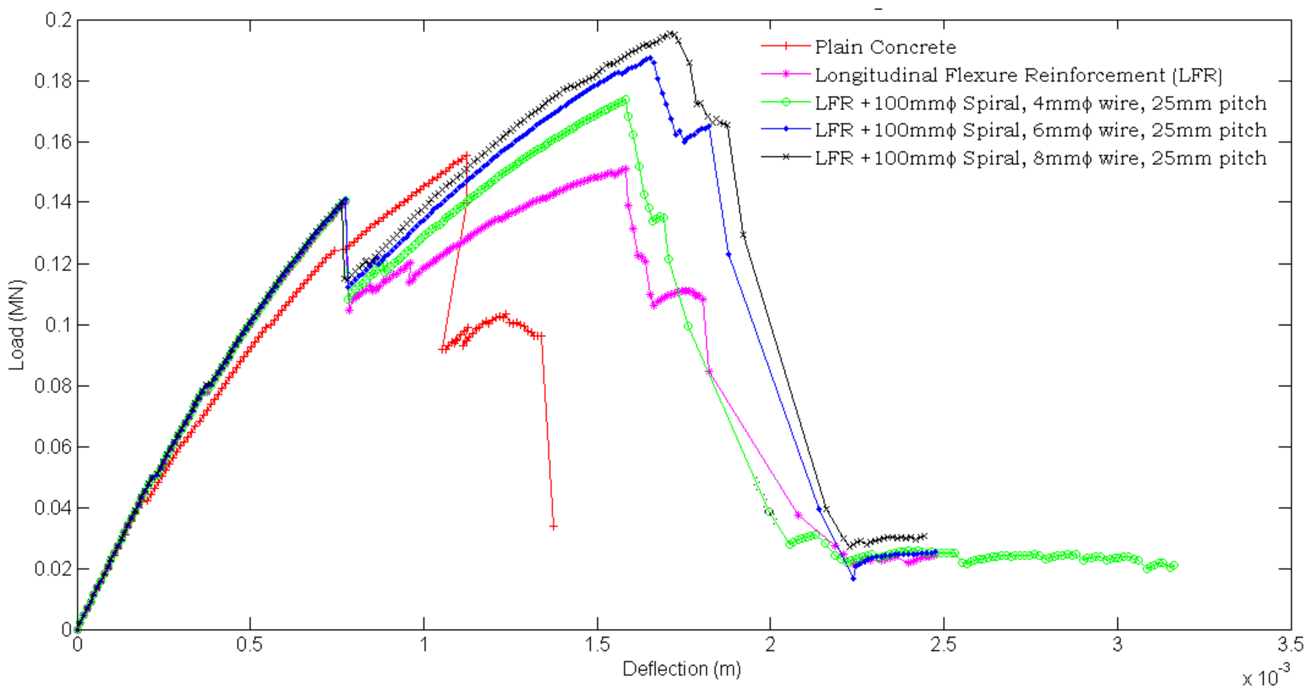

Fig 6: Load Vs Deflection curves for 750mm deep beams

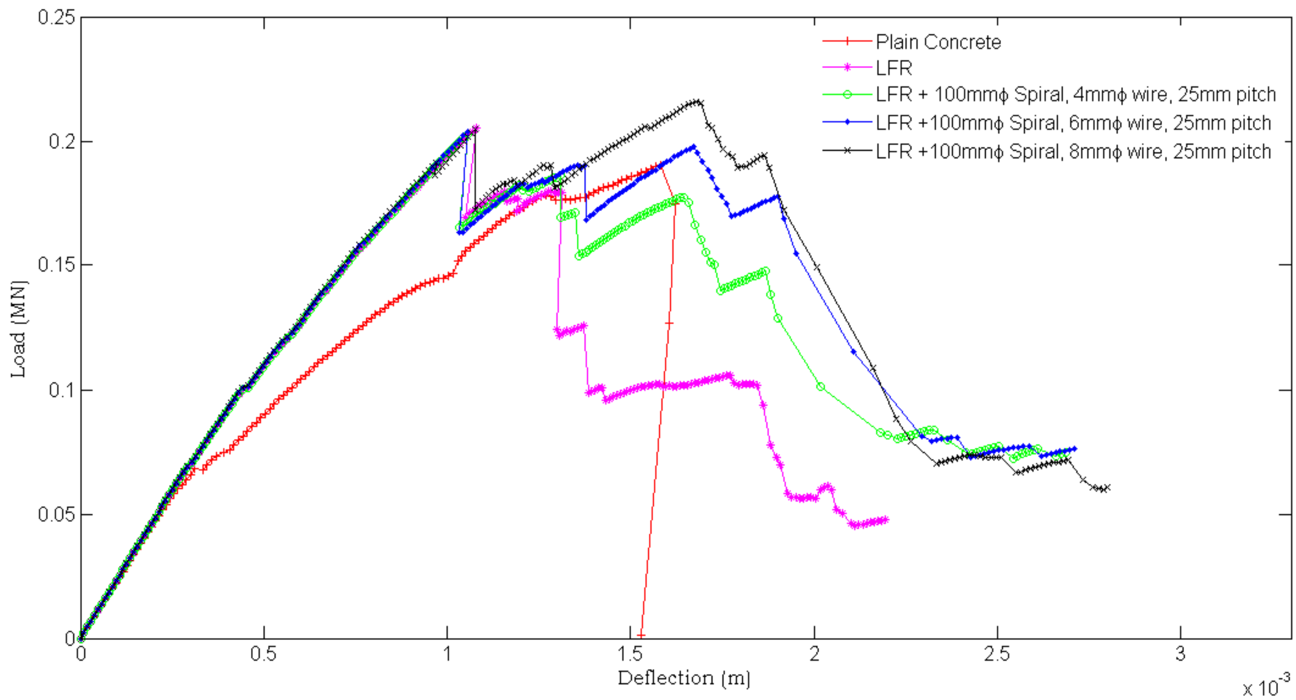

Fig 7: Load Vs Deflection curves for 1000mm deep beams

CONCLUSIONS

Confinement of compression strut improves the ultimate strain to nearly 0.0045 & which improves the ductility of the strut. Improvement of ductility of the strut improves the ductility of the entire beam failing shear. As depth of the beams increases the danger of shear failure due to size effect also increases. But due to confined compression strut, the improvement in ductility is more significant in larger beams. Hence the provision of confined compression strut in beams will be more effective to avoid shear failures & to improve ductility.

Therefore, it is recommended to adopt inclined confined compression struts in reinforced concrete beams in addition to stirrups mainly to improve the ductility particularly in shear failures of beams which is most desirable. The need will be felt in very deep transfer girders in tall buildings particularly when the buildings have to be seismic resistant.

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