SHEAR DEFORMABILITY CHARACTERISTICS OF FRP (FIBER-REINFORCED POLYMER) STRENGTHENED RC BEAM

Shubham Kumar[1], Shilpa Pal[2], H. C. Arora[3]
[1]P.G Scholar, Civil Engineering, Gautam Buddha University
[2]Asst. Prof. Civil Engineering, Gautam Buddha University
[3]HOD, Asst. Prof., Civil Engineering, Gautam Buddha University, CSIR – CBRI
Email: Shubhamthakur22@gmail.com[1], Sh6281pa@gmail.com[2], hc.arora@rediffmail.com[3]

Abstract
Deterioration of concrete structures leading to its failure & collapse is most common problem of construction industry. Failures that can be predicted before actual collapse of structure are still safer than the failures which are difficult to predict accurately leading to sudden collapse of structure, called shear or diagonal tensional failure. Since complete replacement of structure takes huge amount of money, it is beneficial to strengthen such critical members in shear. The use of corrosion resistant, light weight and strong Fiber-Reinforced Polymer (FRP) is most beneficial method. This paper presents comprehensive review on Shear behavior of FRP strengthened beam. The review covers past efforts in FRP strengthening against shear failure using EBR method and also validates the literature by experimental programs done by investigators. Concept of shear failure, application of FRP in Civil Engineering and recommendations for future research are also presented.

Index Terms: Externally Bonded Reinforcement (EBR), Fiber-Reinforced Polymer (FRP), Shear failure, Shear resistance.

I. INTRODUCTION

In the rapid urbanization, reinforced concrete is widely used material. It has extensive use all over the world in construction industry. The main advantages that lead to increase in uses of reinforced concrete are chemical resistance, high modulus of elasticity, freeze thaw resistance and low permeability, creep and shrinkage. Besides these various advantages there are various types of failure modes that exist in reinforced concrete structures. The predominant failure in reinforced concrete beam and other critical structural components is diagonal tension failure or shear failure which is sudden and gives no pre attention and warning to his user. Various researches had been carried out an numerous experiments had been performed on beams with and without web reinforcement and found following factors that influences the behavior of beams in shear. Those factors are shear span to effective depth ratio (av/d), aggregate type, longitudinal steel ratio, loading type, concrete strength and support conditions of member.

The main objective of all researchers is to find the accurate judgment of shear failure or to predict the more accurate shear strength capacity of structure. When a beam is loaded, it is subjected to two main components shear force and bending moment. Variation of shear force is such that it will be maximum when bending moment is minimum and will be minimum when bending moment is maximum. These components when acts on a member can lead to its failure by following ways also shown in Fig. 1.

(1) Diagonal Tension Failure/Shear Failure

This failure occurs under large shear force and lesser bending moment resulting in formation of cracks at 45°.

(2) *Flexure Tension Failure*

This failure occurs under large bending moments and cracks are at 90°.

(3) Diagonal Compression Failure

This failure occurs under large shear force when beam is reinforced against heavy shear leading to crushing of concrete.

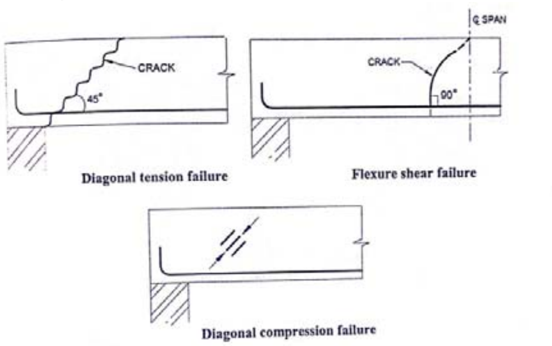

Fig. 1. Types of failure

II. Shear Failure

Shear failure of reinforced concrete beam more properly called diagonal tension failure is difficult to predict accurately[13]. These failure are undesirable because of their brittle nature which does not allow any warning or little warning. These failure occur under action of large shear force and less amount of bending moment and finally leading to development of cracks at 45° to the horizontal surface as shown in Fig. 2. When principal tensile stress reaches to tensile strength of concrete, cracks will occur and opens normal to the direction of principal tensile stress or in other words parallel to the direction of principal compressive stress. Therefore the shear forces generated at ultimate load in a member always results in inclined cracks called shear or diagonal cracks. So as to avoid shear failure, beams are provided with transverse reinforcement whose behavior is based on av/d ratio. The chances of shear failure are more when the value of av/d lies between 2.5 and 6.

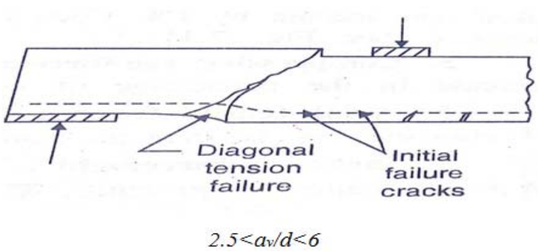

Fig. 2. Diagonal tension failure/shear failure

The provision of transverse reinforcement is still not enough so as to avoid this brittle and abrupt failure, the concept of FRP is used which is more effective in shear strengthening of member.

III. Factors Affecting Shear Resistance Of Concrete

(1) *Grade of concrete*

Higher grade of concrete has higher characteristic strength which in turns results in higher tensile strength, greater dowel shear resistance, greater aggregate interlock capacity and greater concrete strength in compression zone.

(2) *Percentage and grade of longitudinal tensile reinforcement*

The increase in percentage of longitudinal tensile reinforcement results in increase in dowel shear. However higher grade of steel results in lesser shear resistance because percentage required of steel for high grade is less.

(3) *Ratio of shear span to effective depth*

Shear capacity decreases with decrease in av/d ratio.

(4) *Compressive force*

Presence of axial compressive force results in increase of shear capacity

(5) *Compressive reinforcement*

The shear resistance is found to increase with the increase in percentage of compressive steel.

(6) *Axial tensile force*

Axial tensile force marginally reduces the shear resistance of concrete.

(7) *Shear reinforcement*

The shear resistance of beam increases with increase in shear reinforcement ratio. It is because of two reasons, firstly the concrete gets confined between stirrup spacing and secondly the shear reinforcement itself provides shear resistance.

IV. Fiber-Reinforced Polymer (FRP)

FRP is a composite material which is made up and composed of polymer matrix and reinforced with fibers. The fibers define the type of FRP. The fibers are of carbon, glass, aramid and other fibers such as wood or asbestos have also been used. When the fibers that are used in production of FRP are of glass, the composite is called Glass Fiber-Reinforced Polymer (GFRP) and when the fiber used is carbon, composite is called Carbon Fiber-Reinforced Polymer (CFRP).

A. Application Of FRP In Civil Engineering

Due to properties like light weight, non corrosive, high specific strength and high specific stiffness, FRP are increasingly being considered as an enhancement or substitute for construction components namely concrete and steel. Because of these advantages, FRP is included in construction and rehabilitation of structures and have uses as reinforcement in concrete, bridge decks, form work, modular structure, external reinforcement for strengthening and seismic upgrade.

B. Methods Of Using FRP In Beams

Strengthening can be done as shown in Fig. 5. FRP can be used mainly by two methods which are

1. *Near Surface Mounted (NSM) Method*

In this method, FRP bars or strips are embedded into grooves made on concrete cover by elements to be strengthened [3] as shown in Fig. 3.

2. *Externally bonded reinforcement (EBR) Method*

In this method the FRP laminates plates or sheets are generally applied externally on surface of structural element to be strengthened using an adhesive as shown in Fig. 4. This adhesive is high strength epoxy resin used to bind the FRP sheets with concrete surface. This paper presents the effort of researchers in shear strengthening of FRP beams using EBR techniques.

Fig. 3. NSM Method [3]

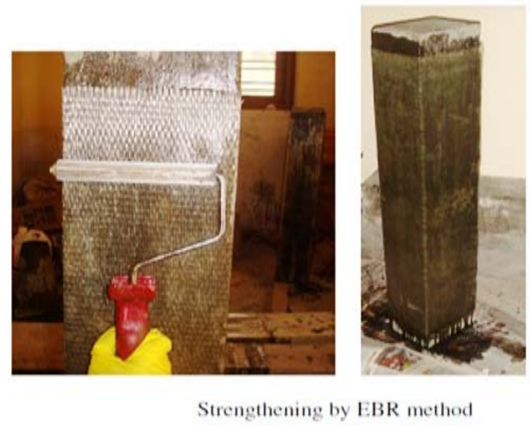

Fig. 4. EBR Method [3]

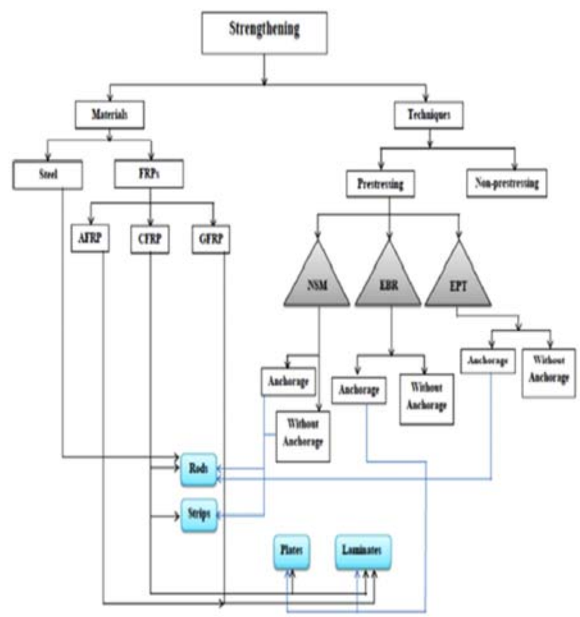

Fig. 5. Strengthening processes [9]

V. Research Progress On Externally Bonded FRP Reinforcement

The concept of using the EBR technique for shear strengthening of RC beams has been examined for many years by researchers. The use of FRP sheets to shear strengthen reinforced concrete beam has been studied and proven repeatedly since it started in 1982. However, numerous strengthening configurations and materials can be combined with FRP to maximize the increase in strength and repair.

Kotsovos [8] described the experimental evidence that causes shear failure exhibited by RC beams are associated with stress conditions in region of path along which compressive force is transmitted. The behavior of concrete beam was compared according to that concept and found out that the studied behavior is compatible with cause of shear failure. Later Shibata and Goto [11] investigated on members that are subjected to shear with diagonal tension like as footing in beams in high rise buildings. The experimental study was carried out to investigate the shear behavior of such members and it was found that there was a remarkable reduction in shear cracking strength of almost 30% from the past proposed equation derived from compressive loading test results. Arathy and George [3] studied the properties of RC beams strengthened with glass fiber reinforced polymer with control beam. Beam was investigated with both types of failure which are flexure failure and shear failure. In first scheme, flexural strength was done by using both EBR and NSM methods. In second scheme shear strengthening is done by using both EBR and NSM methods. A two point loading was adopted an deflection was observed at end of each test. It was concluded that the load carrying capacity was increased by using GFRP and when number of GFRP sheets were increased.

Bousselham and chaallal [1] studied the shear strengthening of RC beams with EBR polymer (FRP) composites. They contributed to the understanding shear resistance mechanism involved in RC beams strengthened in shear. The results based on experimental program composed of 17 tests helped to establish the contribution of concrete, FRP an transverse steel under increasing load to shear resistance of beam. It was found that contribution of concrete to shear resistance starts from loading and attains constant value due to occurrence of first diagonal crack, contribution of FRP is activated after formation of first diagonal crack and does not vary linearly and is dependent upon strain in different regions. Also, contribution of transverse steel starts after formation of first diagonal crack and is not quite linear due to evolution of strain. Later Bousselham and Chaallal [2] again investigated for maximum shear strength of RC beams retrofitted in shear with FRP composites by developing an alternative equation as an upper limit for shear strength against web crushing failures in such structures. The prediction of equations analytically were compared with those obtained from tests reported in literature and various other codes and was found out to be in well agreement.

Chen et al. [5] developed a new model for shear strengthening of beams with FRP by composing the adverse shear between the internal steel shear reinforcement and external FRP. It was found out that proposed shear strength model performs the best among model compared and performance of other shear strength model can be significantly improved by including the proposed shear interaction factor.

Later Sabol and Priganc [10] investigated the increase in shear capacity of beam by one of other methods called near surface mounted NSM method by using combination of epoxy and FRP system. It was concluded that based on experimental research, numerical analysis and analytical approach, NSM method is also an effective way of shear strengthening of concrete elements. Zhang et al. [12] proposed a mechanics based segmental approach, a generic closed form solution was derived for quantifying the shear capacity of RC beams without stirrups. The design recommendation shows a reduction to different degrees in measured to predicted shear strength ratio for proposed approaches.

Baggio, et al. [4] investigated the effectiveness of using commercially manufactured carbon FRP (CFRP), glass FRP (GFRP) and fiber reinforced cementitious matrix (FRCM) sheets to increase shear capacity RC beam. The experiment was carried out to investigate the maximum effectiveness of all of these sheets. Experimental results revealed that applying FRP sheets increased the overall shear capacity and full depth U wrapped FRP sheets performed better as compared to partial depth U wrapped sheets. Spadea, et al. [6] studied the composite action of externally bonded plate with a RC beam. The relevant aspects like increase in shear strength, ductility and ability to dissipate internal strain energy were illustrated by a extensive ongoing experimental investigation. It was shown that how a stable and controlled progressive failure of RC beams strengthened with

FRP materials can be obtained by holistic approach which is concept of performance factor. Farooq and Bedi [13] studied the shear behavior of RC beams with help of ATENA. ATENA is the new FEM based software that do nonlinear analysis of RCC structures. Study was carried out to investigate the influence of span to depth ratio, percentage of longitudinal reinforcement and concrete grade on shear strength of beam. It was concluded that graph between load and deflection for experimental observation were well in agreement with values obtained with software ATENA.

Lately Yu et al. [7] investigated the efficiency of externally bonded L-shaped FRP laminates in strengthening seismically damaged RC joints. Retesting after retrofitting showed that average peak strength of CFRP strengthen specimen increased approximately by 20%.

VI. Experimental Validation Of Literature Showing Effects Of Externally Bonded FRP On Various Properties Of Beam

Spadea et al. [6] investigated the shear behavior of externally bonded FRP strengthened beam by experimenting on 7 beams (series B2 and B3) designed to be identical in every aspect expect for the test loading regime, internal shear reinforcement and external reinforcement in shear span. The beam B2 was provided with 6 mm diameter stirrups at 150 mm center to center, three under load and two over each support. The beam of series B3 had internal shear reinforcement of 3 mm diameter stirrups at 150 mm center to center. Beams B2 and B2.1 were used as control beams without any external reinforcement. B2 and B2.1 were tested with av/d ratio of 6.9 and 3.4 so they fail in bending and shear respectively. The details of external reinforcement are shown in Fig. 7. Strains in concrete, internal steel reinforcement and CFRP lamina were measured at various sections along the span using strain gauges. All beams were tested under displacement control regime and applied loads were measured by high accuracy load cell with load sensitivity of 0.1 kN.

VII. Test Results and Discussion

The load and deformation behavior of beams tested in shear is analyzed. The structural behavior of beams tested in shear is presented in terms of their load-central deflection at mid span section as shown in Fig. 6. The results drafted in Fig. 6 and Table 1 shows that the capacity for shear strength and deformability of control beams and of simply strengthen beam tested in shear were drastically reduced and their overall performance are also very much affected. On the other hand factor related to beams with an external anchorage system shows that an external anchorage system can significantly improve structural performance both in terms of strength and deformability.

VII. Concluding Remarks

The role of external shear reinforcement serves two purposes, firstly it increases the shear strength capacity of beams in all respect and secondly it protect the beams from adverse effects of environments, chemical actions etc. These FRP sheets are light weight, so do not increase the overall weight of structure and also increases the load carrying capacity and control the deflection of beam. Hence these lightweight, strong, durable and corrosion resistant FRP sheets are best effective way to strengthen a member against failure or to retrofit an already existing member. Scope for future research can be explored and broadened by experimenting on different combinations and orientations of externally bonded FRP plates and effects due to change in strip widths and strips spacing can be investigated.

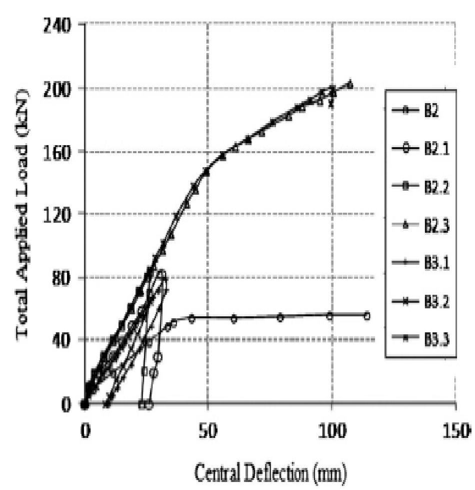

Fig. 6. Load deflection diagram in shear [6]

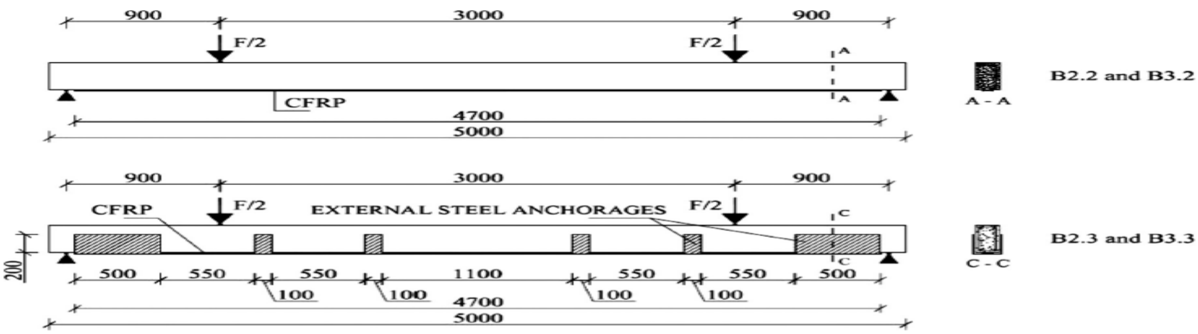

Fig. 7. External strengthening of beams tested in shear [6]

Table 1. Summary of test results of beams tested in shear [6]

Tested beams shear loading regime (a/d = 3.4)	Beam label	First visible flexural crack (kN)	(% FL)	Tension steel yielding load (kN)	(% FL)	Failure load (kN)	Max concrete strain at failure (µm/m)	CFRP strain at failure (µm/m)	Mode of failure
Control beams	B2.1	10.1	12.2%	No	Yield	82.5	871	–	SC
	B3.1	7.5	9.4%	No	Yield	80.1	893	–	SC
(a/d = 6.9)	B2	9.1	15.8%	48.8	84.9%	57.5	3667	–	CC
Beams with only CFRP	B2.2	10.4	12.7%	No	Yield	82.1	1063	1981	SC
	B3.2	9.0	10.9%	No	Yield	82.7	1020	1922	SC
CFRP + external links	B2.3	10.3	5.0%	134.9	65.4%	206.3	2706	8669	SCS
	B3.3	7.4	3.6%	120.2	59.1%	203.5	2735	8474	SCS

FL = Failure load.
SC = Shear crack.
CC = Concrete crushing.
SCS = Slice end concrete section.

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