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Strengthening and evaluation of reinforced concrete beams for flexure by using external steel

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Abstract: The strength upgrading techniques for reinforced concrete (RC) beams with external steel sections or fiber reinforced polymers are used commonly to enhance the flexural capacity of structural elements. Using external steel members, strengthening of RC beams for flexure is considered as one of the most favorable and implementable technique. In this papera research study is presented,investigating and evaluating the flexural response of rectangular RC beams strengthened in flexure with steel bars and steel angles. Five RC beams designed with minimum steel ratio were tested. One specimen without external steel element was tested as control RC beam. Two beams were strengthened by attaching external steel bars and two beams by attaching external steel angles.For strengthening the area ofexternal steel bars and steel angles were calculated on the basis of maximum steel ratio as per the ACI 10.3.5.The external reinforcing bars and angles were attached to the internal reinforcing steel bars by welding. All the specimens were tested under third point loadingin positive bending. Test result showed a better distribution of cracks and enhancement in the flexure capacity. The spacing and throat area of the weld played an important role in the ultimate load carrying capacity.

Keywords: *Strengthening and Evaluation, Beams, Steel Angles, Steel Bars, Welding, Concrete Finishing Cover Cracks, Deflection, Ductility*

Introduction :

Strengthening of reinforced concrete (RC) structures is commonly needed due to overloading, corrosion of the steel reinforcement, inadequate maintenance, change in use or in code of practice, and/or exposure to unfavorable conditions like earthquakes and blasts. In the past several decadesmany strengthening techniques have been usedto augment the members in their resistance strength. Each of the techniques is better suited for a given situation and has some merits and demerits. Currently Pakistan was stuck by catastrophic earthquake, flood and is passing through tragic situation of terrorism due to which most of the existing RC structures are damaged which need repair/strengthening. Also the existing structures which are in good conditions are under more loading demand and thus require strengthening of the structural members. This work aims at strengthening the RC beams which are deficient in flexure resistance. An experimental study were carried out to evaluate the enhanced flexural strength capacity of RC beams by placing steel bars and steel angles to their bottoms with the help of welding. This technique will make use of the locally available materials and is hoped to be easy in use and could be applied effectively while the structure is in use with minimum disruption. This will not grow size of the beam substantially and thus will not lead to head room problem

In view of the simplicity and popularity of the external steel bars and steel angles as endorsed by its proliferation in field application, laboratory investigation into the performance of this technique started in the 1960s. Since then, considerable experimental work has been reported on the performance of this strengthening technique when employed for strengthening of existing structural beams. However, only limited data has been published on the performance of beams when strengthened by external steel bars and steel angles. It has been reported that the overall response of the strengthened beams was significantly enhanced by using structural steel angles for partially confinement of RC beams [1]. The total capacity was increased up to 3.2 times that of the control RC specimen, leading to higher shear and moment resistance in the strengthened specimen. Christopher M. Foley and Evan R. Buckhouse in 1998 used steel channels as an external reinforcing steel to strengthen beams for flexure [2]. They reported that overall, the design methodology proposed for the external reinforcing of existing beams is adequate. Both, strength of the member and stiffness are improved. One deficiency of the reinforced member is lack of ductility at failure.At ultimate load the deflection of strengthened beamreduces as the degree of strengthening increases and correspondingly the ductility of the composite beam reduces [7'8]. Balendran, R. Vused 1 mm thickness CFRP sheets for strengthening of plain concrete beamsand reported that the moment capacity was increased by 120% and stiffness by 40% [9]. Using steel plates as an external reinforcement with sound structural design, appropriate detailing, quality of materials and good workmanship will result in high flexure strength and good ductility [3, 4]. The flexural strength of cracked beam may be enhanced by 1 to 17% and 70 to 94% depending upon the thickness of external steel plates and welding is a successful technique for attaching the external plates [6].

As the tensile flexure capacity of steel is well recognized so this research is primarily focused on the flexure behavior of beams partially reinforced with steel bars and steel angles to promote confidence in local builders and owners to use external steel for flexural re-strengthening of existing beams rather than to demolish them.

Limited work has been carried out in Pakistan on the flexural strengthening of beams. This study has been taken as an initiative work for flexural strengthening of the existing beams.

Experimental setup:

Five reinforced concrete beam specimens having rectangular x-section were constructed. Based on space requirements in the laboratory, 11 feet length was selected for beams. The depth and web dimension are 12 in (30.48 cm) and 9 in (22.86 cm) respectively. The 28 days compressive strength of concrete was taken as 3000 psi (20.86 Mpa). The design summary of the five specimens is described in table 1.

a. Design of Control Specimen:

The moment capacity of the control specimen $(M_n)c$ shown in Figure 01 is determined by using basic concepts for the rectangular reinforced concrete beams as given in the ACI code ACI-318-08 [10].For the comparison of results the beams were designed with minimum steel ratio i.e.

$$As_{min} = 3\frac{\sqrt{f_c'}}{f_y}bd \quad \geq \quad \frac{200}{f_y}bd(a$$

On the basis of As_{min}each beam was provided with two #4 (13mm) grade 60 steel bars as a flexural reinforcement. For stirrup holding two #4 (13mm) grade 60 steel bars were placed at the top of the beam web.

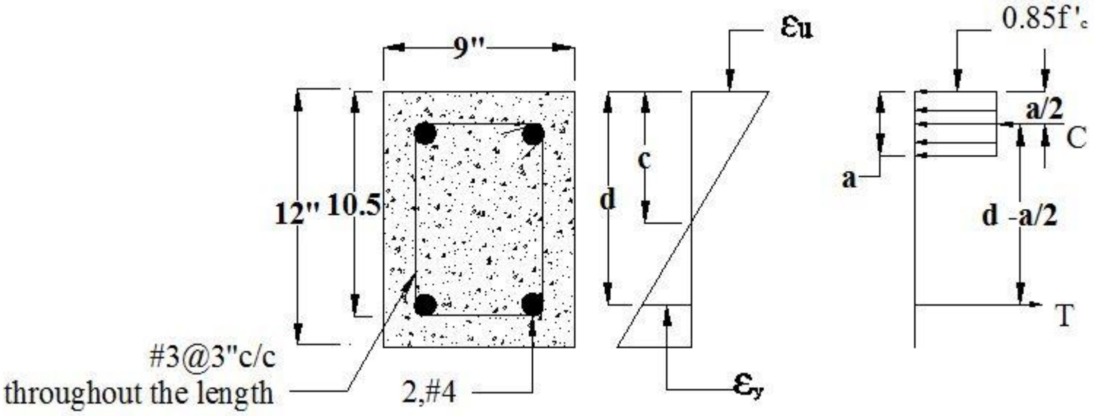

Figure.1(a) X-section of Beam (b) Strain Diagram c) Equivalent Rectangular Stress Diagram

The beam was designed strong enough against shear. Maximum shear force was found on the basis of A_{smax} calculated after the strengthening design.

$A_{smax} = 0.015 bd_{ave}$ (b)

$$(M_n)_c = A_{smax} f_y (d_{ave} - a/2) \quad (c)$$

$$P = \frac{3(M_n)c}{L} \quad (d)$$

Where:

P = Maximum shear force

$(M_n)_c$= Moment capacity of control specimen

For the above maximum shear force beams were designedand provided with #3 (10 mm) 60 grade steel bar placed at 3 inches on center throughout the length of beam as shown in Figure: 1, (a).

b. Design of Strengthened beams :

Out of five, one beam was used as a control specimen, two were strengthened with external steel angles and two were strengthened with external steel bars.The flexural design of externally reinforced RC beam requires the same design procedure as used for regular rectangular RC beams. Christopher M. Foley, et al (1998) used the strain compatibility and rectangular stress diagram to find the steel area for the external reinforcement[2]. This procedure is same as the ACI method for RC flexure members. The steel area for the externally reinforced beam was calculated on the basis of regular formulas used in the design of reinforced concrete beams. The additional steel area was treated as a second tensile force acting at the centroid of the external steel. The analysis and design procedure is same for both the externally reinforced with steel bars and the externally reinforced with steel angles beams.The internal equilibrium of forces for a flexure member containing internal reinforcing bars and external reinforcement can be represented as shown in Figure 2 and 3

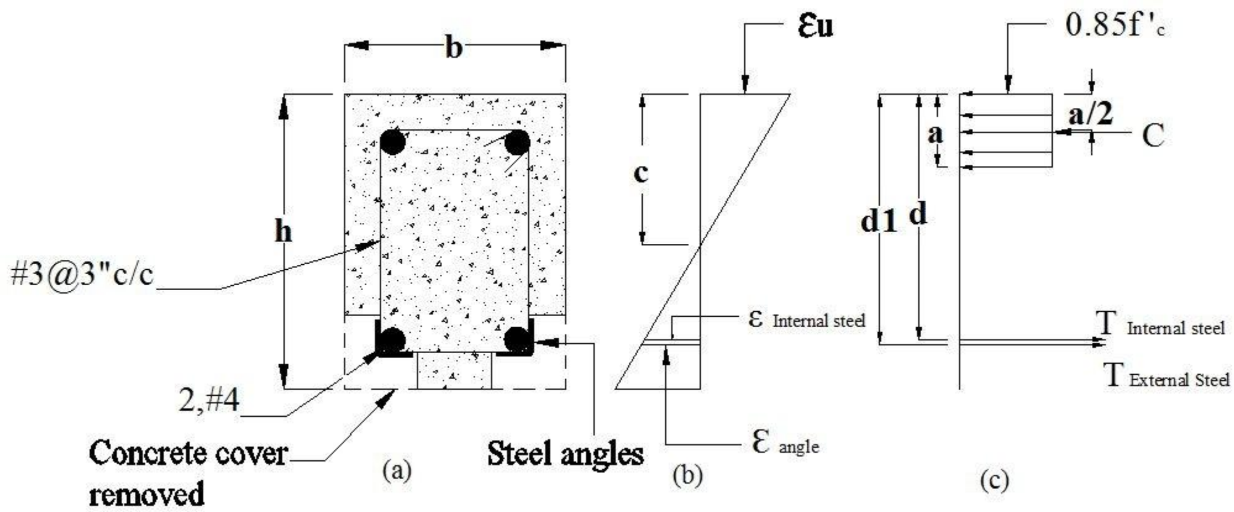

Figure2 a) X-Section of Beam b) Strain Diagram c) Rectangular Stress Diagram

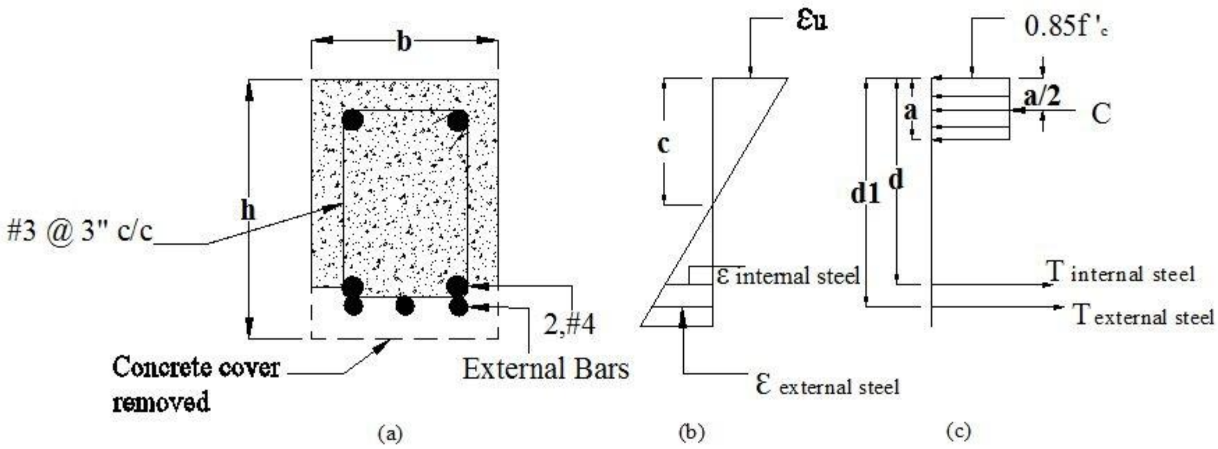

Figure3 a) X-Section of Beam b) Strain Diagram c) Rectangular Stress Diagram

The design procedure for strengthening of beams for flexure with external steel members was based on maximum steel ratio i.e. $\rho_{max} = \rho_{balance}$ as given under ACI-codesection 10.2. The calculated maximum steel area was divided in two parts i.e. internal steel area $(As)_c$ and external steel area $(As)_{ext}$.

$(As)_{ext} = As_{max} - (As)_c$ (e)

Where:

$(As)_c$= steel area provided to control specimen

$(As)_{ext}$ =external steel area provided for strengthening purpose

The moment capacity of strengthened beam shown in Figure 2 and 3 is calculated as:

$(M_n)_{total} = (As)_c f_y \, (d-a/2) + (As)_{ext} f_y \, (d_1 - a/2)$ (f)

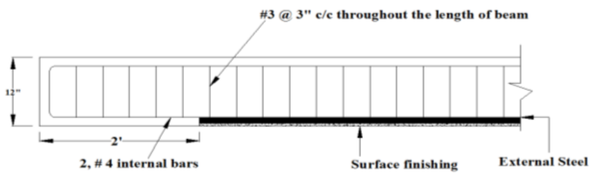

Figure04 Half Section of Strengthened Beam

c. Design summary of strengthened beams:

Welding was used for the attachment of external steel members to the existing shear reinforcement.Two steel angles of grade 60 with nominal size of 1 ½" x 1 ½" x 3/16"(L 38.1 mm x 38.1 mm x 4.8 mm)were attached at the corner of the beam web with the stirrups (Figure 03, a). Three external steel bars of grade 60 were welded with the stirrups of the beam. Two # 6 bars were attached with corners of the stirrups and one #4 bar at the center of beam web (Figure 03, b). The longitudinal extension of bars form the center of beam towards the ends was calculated from the bending moment diagram, drawn after the strengthening design. With the cutting of 71 % steel for simply supported beam, the external steel members were extended 3.5 feet on each side from the center as shown in Figure 04:

Table: 1 Design summary of the beams

Mark of Specimen	*Cross-section b_w x h (inches)*	*External Steel Bars Bar No. (ø inches)*	*External Steel Angles L.(w,h,t) inches*
TS1	*9 x 12*	------	------
TS2	*9 x 12*	*2, # 4 + 1, # 6*	------
TS3	*9 x 12*	*2, # 4 + 1, # 6*	------
TS4	*9 x 12*	-------	*1½ x 1 ½ x 3/16*
TS5	*9 x 12*	-------	*1½ x 1 ½ x 3/16*

Test result:

All the beams were tested as a simple supported under third point loading. The loadswere placed at an equal spacing of 3.33 feet (1015 mm). In this section the test results of the fivebeams aredescribed.

a. Control RC specimen (TS1):

The control RC specimen TS1behaved elastically up to a load of 4.5 kips and the corresponding deflection at elastic load is of 0.04 inches. Beyondelastic load of 4.5 kips, the degradation of stiffness was started and the relation was again linear. The maximum load and deformation were 14.5 kips and 0.5 inches respectively.Figure 05 shows the load-deformationrelationship of the control RC specimen.

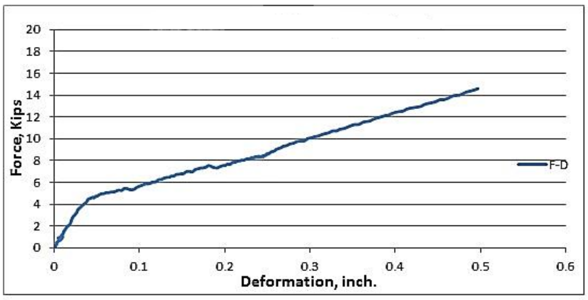

Fig:05 Force deformation relationship of control specimen (TS1)

The beam was failed in flexure as shown from the figure 06.First flexure crack was initiated at the bottom of the beam surface at a load of 7.7 kips (3.5 tones) and propagated quickly towards the upper face of the beam. The deflection at first crack was recorded as 0.19 inches. This crack was in the region of the maximum bending moment. The yield load and corresponding deflection were analytically calculated and is 4.9 kips and 0.08 inches respectively. The flexural yield strength, ultimate strength and shear capacity of the section required for the application of load were calculated and are 3 kip, 9.7 kips and 31.3 kip respectively. The measured flexure strength of the specimen is more than the calculated value and this is because of the high strength of steel used for flexure.

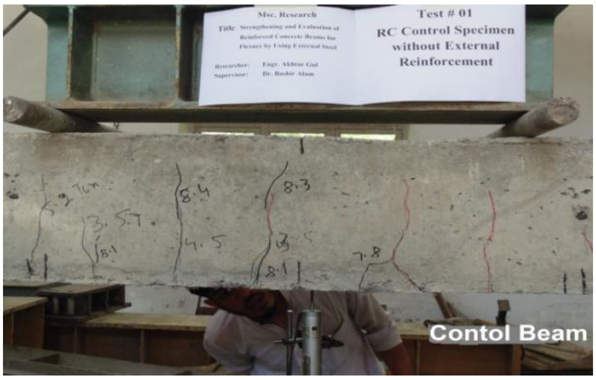

Figure: 06Failure of Control Specimen TS1

b. RC beam provided with external steel bars and steel angles for flexural strengthening:

It was noted that TS2 and TS3 showed almost identical elastic behavior.The yielding load of the two specimens started at 22.4 kip and 24.23 kip. The deflections at yield loads were 0.43 inches and 0.47 inches respectively. The two specimens TS2 and TS3 showed the elastic stiffness which was almost equal to that of the control specimen TS1. In the inelastic phase, the maximum measured loads and corresponding maximum deflections for TS3 were 22.83 kip and 0.57 inches and forTS2 24.50 kip and 0.62 inches.

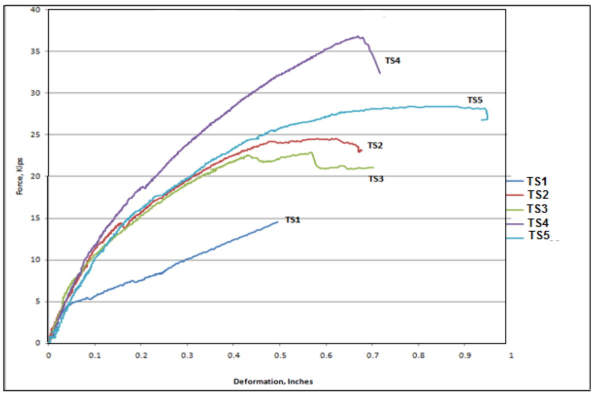

Figure:07 CombinedChart of Samples

The behavior of the specimen strengthened with external steel angles TS4 and TS5 was also almost identical up to the elastic range. The yield load for TS4 and TS5 ranges between 18.50 kip and 26.7 kips and the corresponding deflections are 0.20 inches and 0.62inches respectively. Theultimate measured loads and the maximum corresponding deflections for TS4 and TS5 in the inelastic phase are 36.70 kips and 0.67 inches; and 28.44 kip and 0.84 inches respectively. The specimen strengthened with steel angles showed more stiffness than TS2 and TS3 specimens.

It was noted that the degradation of stiffnesswas faster in specimen TS2 and TS3 as compared to TS4 and TS5.This was due to two reasons, first the compact area of steel angles in a small region of the tension zone contributed in high elastic range, second the welding distributed along both side of the angles was more effective to resist the delaminating of angles from the beam stirrups as compared to steel bars as shown in Figure 08 and 09.

Figure: 08 Failure of Beam Strengthened with External Steel Bars

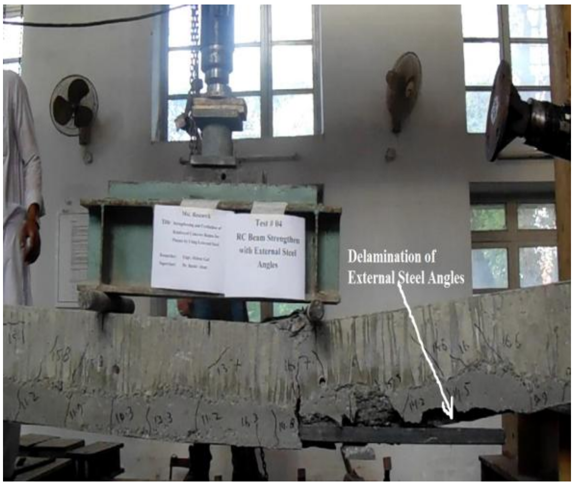

Figure: 09 Failure of Beam Strengthened with External Steel Angles

Table: 02 Comparison of loads

Series	Specimen ID	Ultimate Computed Loads (kips)	Ultimate Experimental Loads (kips)
Control	TS1	10	14
Steel Bars	TS2	31	23
	TS3	31	25
Steel Angles	TS4	31	36
	TS5	31	29

Table: 03 Comparison of ductility Index m= Du/Dy

Series	Specimen ID	Deflection at yieldload Dy (inch)	Deflection at ultimate loadDu (inch)	Ductility Index m = Du/Dy
Control	TS1	0.08	0.5	6.25
Steel Bars	TS2	0.43	0.62	1.44
	TS3	0.47	0.57	1.21
Steel Angles	TS4	0.20	0.67	3.35
	TS5	0.62	0.84	1.35

Table: 04Enhancement of Strength

Series	Specimen ID	% increase
Control	TS1	------
Steel Bars	TS2	74
	TS3	80
Steel Angles	TS4	110
	TS5	93

Discussion of test results:

With the attachment of external steel bars and steel angles, the flexural strength was significantly increased. The pattern of cracks of the tested beam specimens As shown in Figure 08 and 09the crack pattern in specimen TS2 and TS3 is flexural failure whileshear-flexural failure mode inTS4 and TS5. Flexural cracks were initiated at the maximum bending moment region and propagated towards the supports. On the other hand localized flexural failure was observed in at the mid span of the control specimenTS1.

The contribution of external steel bars and steel angles was nominal in overall stiffness of the strengthened beams. Therefore, the elastic stiffness of the control beam and strengthened beams was almost equal. The strengthened beams showed greater yield load than the control specimen. A logical expression for this result is that the bending curvature of the strengthened beam forced the external steel to bend and enhance the strength of the strengthened beam.It was observed that the spacing and quantity of weld played an important role in the enhancement of the strength and ductility of the beams. In the post yield region the external steel was supposed to contribute in significant amount to enhance ductility but the delaminating of the external steel at the early stage is the reason for this phenomenon.

Conclusions:

The following conclusionswere made from this research work.

1. The flexural capacity of reinforced concrete beams strengthened with external steel members was greatly enhanced.
2. Strengthening of beams for flexure showed uniform distribution of flexure cracks.

3. The failure of strengthened beam resulted in a very favorable mode as compare to the control RC beam specimen.
4. Beams strengthened with steel angles enhanced the load carrying capacity more than the beams strengthened with external steel bars, indicating high flexural resistance.
5. Better ductility was showedby the RC beam, strengthened with external steel angles than the RC beams strengthened with external steel bars.
6. The bond between the finishing cover and the existing concrete was strong enough.
7. Welding was provided as per the design code of LRFD but the de-bonding of steel bars and steel angles requires further investigation.

The proposed research work shows the significance of flexural strengthening techniques of RC beams by practicing engineers looking for more ductility and highflexure capacity. The strengthening technique can now be implemented practically for strengthening beams both in building and bridges.

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