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NUMERICAL INVESTIGATION OF THE BEHAVIOR OF RETROFITTED FLEXURAL CRACKED BEAM WITH EXTERNAL PLATE BONDING

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The aim of this paper is to study the effectiveness of using "External Plate Bonding" in flexural retrofitting of reinforced concrete (RC) beam. A simply supported rectangular RC beam is considered for this study. The steel plate and the CFRP (Carbon Fiber Reinforced Polymer) sheet are taken into consideration as bonded plates for retrofitting of RC beam. General purpose finite element program (ANSYS 11.0) is used to carry out non-linear analysis of uncracked, cracked and retrofitted RC beam. Based on the results obtained from numerical investigation it is seen that cracking in RC beam reduces the load carrying capacity of the beam. When retrofitting technique using steel or CFRP plate bonding externally is applied, stresses at the crack tip reduce significantly. Therefore, external plate bonding could be effectively applied in retrofitting of RC beam.

Key words: CFRP sheet, Flexural crack, Plate bonding, Non-linear analysis, Retrofitting, Steel plate

1. INTRODUCTION

Reinforced concrete (RC) is one of the most widely used construction material in both the developing and developed countries since more than a century. RC structures are often suffering damage before reaching their intended design life. There are several factors responsible to this distress of these structures, such as improper design, faulty and quick construction, change in building usage, overloading, natural disasters (like earthquake, Tsunami, Cyclone, Flood etc.), various environmental effects like corrosion, fire, etc. Buildings, which are deteriorated due to such factors, need quick attention and scientific approach in finding the causes of distress and also need suitable remedial action to make the building functional.

Beam is one of the primary elements of the frame structure building and is mainly responsible for the lateral stiffness of the structure. A beam fails when the load acts on it is higher than the load for which it is designed (Kaish and Hassan, 2008). It may also fail under service load due to loss of its stiffness caused by various deteriorating factors discussed above. To mitigate the unexpected failure various methods are proposed to retrofit the beam. External post tensioning, plate bonding, ferro-cement laminating and RCC jacketing are among them.

External plate bonding technique is one of the efficient and well-known method of repairing or retrofitting of beam (Devid et. al., 1998). Steel plate is the traditional material used in the retrofitting of flexural beam member. But its low corrosion resistance and handling problem forced engineering community to look for alternatives (Gorji, 2009). Fiber Reinforced Polymer (FRP) emerges as an effective alternative of steel plate. It becomes a popular material for structural re-strengthening because of its high tensile strength, low weight and high corrosion resistance properties (Hollaway and Leeming, 1999).

Several experimental and analytical investigations have been conducted on the use of FRP sheets as flexural retrofitting/re-strengthening of RC beams

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(Shahawy et. al., 1996; Saadatmanesh et. al., 1997; Sharif et. al., 1994; Chajes et. al., 1995; Khaloo and Gharchorlou, 2005 and Panazopoulou et. at., 2001). The behavior of re-strengthened beam is also available in terms of load-deflection, load-strain, failure patterns and structural ductility (Gorji, 2009).

Laboratory and numerical studies show the efficacy of externally bonded FRP plates in enhancing the flexural capacity of RC beam. However, there are limited studies conducted on the behavior of flexural cracked RC beam retrofitted with external plate bonding using steel plate or FRP sheet. In this paper numerical investigation to the behavior of flexural cracked RC beam retrofitted with externally bonded steel plate or CFRP sheet are reported.

2. FINITE ELEMENT MODELING OF RC BEAM

Simply supported reinforced concrete beam of ten feet span was considered to carry out numerical analysis. Four beams were modeled for this purpose. One of which was an un-cracked beam (considered as benchmark specimen) denoted as UB. A cracked beam (denoted as CB) of crack depth of 20% of the full depth of beam was also modeled. The two beams were modeled as retrofitted cracked beams. One of which was retrofitted by steel plate (denoted as RS) and the other one was by CFRP sheet (denoted as RF). Simulations were carried out by using one of the most powerful finite element software ANSYS (11.0). Two-dimensional finite element model was developed for simplicity in analysis and reducing computational effort. Geometry, loading and boundary condition of uncracked, cracked and retrofitted beam are shown in Fig. 1.

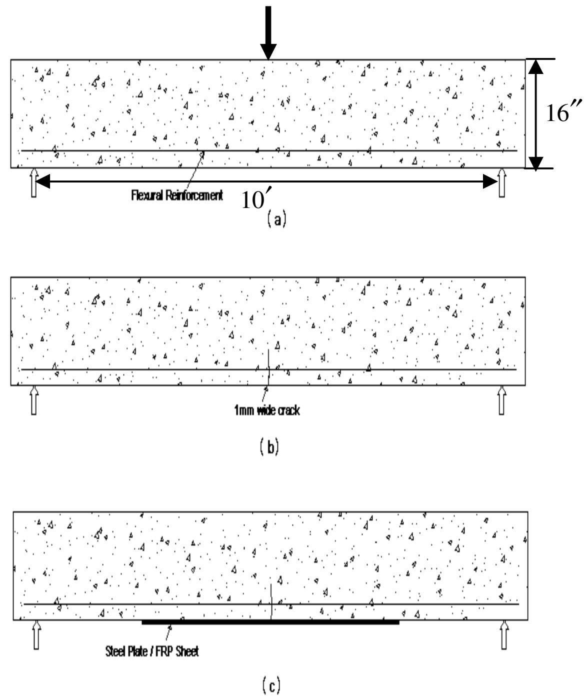


Fig. 1: RC beam; (a) Un-cracked beam, (b) Cracked beam and (c) Retrofitted beam.

2.1 Element Types

Eight-nodded quadratic plane stress element (PLANE82) having two degrees of freedom at each node (translation in the nodal x and y directions) available in ANSYS finite element program was used to model the concrete. This element has capability to model plasticity, creep, swelling, stress stiffening, large deflection, and large strain capabilities. Geometry of node numbering of PLANE82 element is shown in Fig. 2.

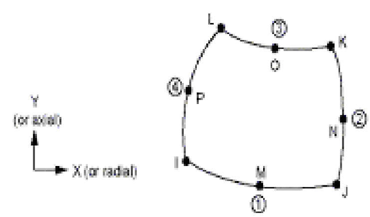


Figure 2: Geometry of PLANE82

One-dimensional (link1, 2-D spar) element was used to model the reinforcement. This element is a uniaxial tension-compression element with two degrees of freedom at each node (translations in the nodal x and y directions). Steel plate and CFRP sheet were also modeled using PLANE82 element.

2.2 Material Properties

2.2.1 Concrete: In the present study concrete was assumed as a homogeneous material. In usual practice, linearly elastic-perfectly plastic model is used for concrete crushing though many researchers have proposed piece-wise linear model. The linearly elastic-perfectly plastic model gives a good prediction of ultimate loading and displacement to the specimens (Zhang, 2004). Linearly elastic-perfectly plastic model of normal concrete is shown in Fig. 3.

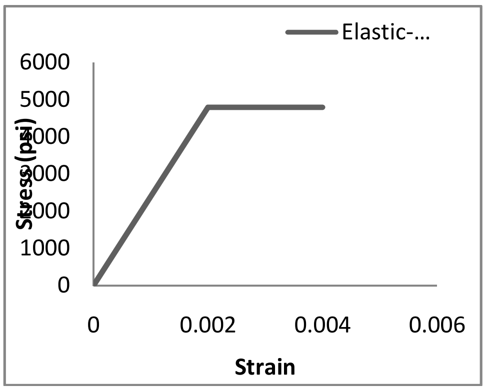


Fig. 3: Linearly elastic-perfectly plastic stress-strain relationship of normal concrete.

In the present study smeared cracking approach was used in modeling the concrete. Following properties were defined for concrete element:

Elastic modulus (E=3949075 psi),
Poisson's ratio (ν=0.2),
Shear transfer coefficients for an open crack (0.3),
Shear transfer coefficients for a closed crack (0.9),
Uniaxial tensile cracking stress (f_r=520 psi),
Uniaxial crushing stress (f'_c=4800 psi).

The shear transfer co-efficient represents the condition of cracked face. The shear transfer coefficient for a closed crack is widely accepted within 0.9 to 1.0. The value of shear transfer coefficients for an open crack used in many studies of reinforced concrete structures varies between 0.05 and 0.25 (Bangash, 1989; Huyse et. al., 1994 and Hemmaty, 1998). Convergence problems were encountered with shear transfer coefficients for an open crack dropped below 0.2 (Wolanski, 2004). Zhang (2004) mentioned that shear transfer value of magnitude 0.3 gives a good agreement with the change of stiffness of the specimen as well as the ultimate loading. Therefore, shear transfer value of magnitude 0.3 was taken into consideration in this study

2.2.2 Steel Reinforcement and Steel Plate: For the finite element modeling, steel reinforcement is assumed as linearly elastic-perfectly plastic material and identical in both tension and compression. Elastic modulus and Poisson's ratio assumed for steel reinforcement were 29×10^6 psi and 0.3, respectively. Steel plate used in FEM was assumed as linearly elastic material with the same elastic modulus and Poisson's ratio of the steel reinforcement. Thickness of the steel plate was taken into consideration as 3mm. Linearly elastic-perfectly plastic model of steel is shown in Fig. 4.

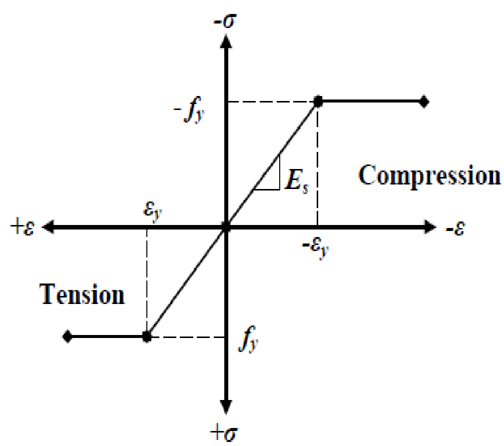
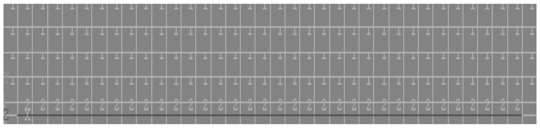


Fig. 4: Linearly elastic-perfectly plastic stress-strain relationship of steel.

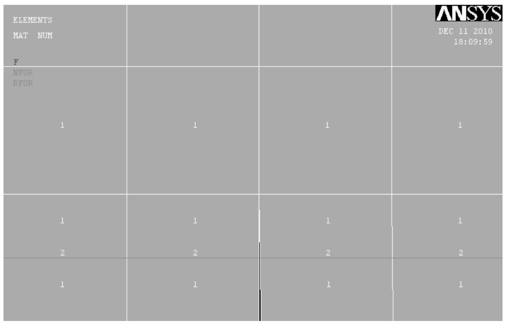
2.2.3 FRP Sheet: Carbon fiber reinforced polymer (CFRP) was used as FRP sheet. A linear elastic property was assumed for CFRP. Elastic modulus and Poisson's ratio used for CFRP were 21.75×10^6 psi and 0.25 respectively. Thickness of CFRP sheet was taken 3mm.

2.3 Finite Element Modeling Procedure

The entire beam was modeled first with simply supported boundary condition. In case of cracked beam, flexural pre-crack was introduced by creating a gap (1mm) between elements at the bottom of mid-section of beam. The steel reinforcement was simplified in the model. Only bottom (flexural) reinforcement was modeled for simplicity in modeling and analysis. Both the top and shear reinforcement was omitted in the model. Perfect compatibility between concrete and steel reinforcement was assumed in this study. Finite element modeling of uncracked beam and closed view of crack are shown in Figs. 5(a) and (b).



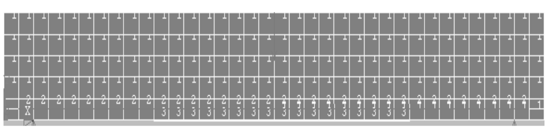
(a)



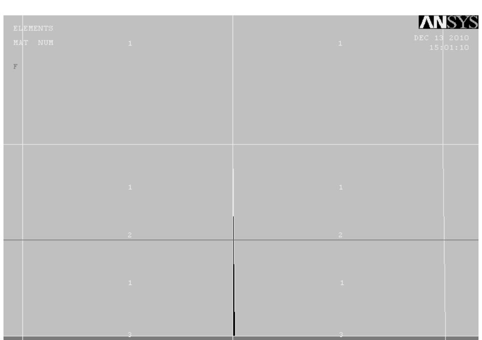
(b)

Fig. 5: Finite element meshing of beam; (a) Un-cracked beam and (b) Closed view of crack.

Steel plate and CFRP sheet in retrofitted beam were modeled in the same way with consistent thickness but with different material properties. Epoxy bonding layer was omitted in the model. Usually epoxy is much stronger than concrete and therefore not a weak link exists in between concrete and steel plate or FRP sheet. Perfect bonding (concrete and epoxy strength are considered as same) between concrete and steel plate (or CFRP sheet) was assumed in the analysis. This was done by directly joining the nodes of steel plate (or CFRP sheet) with concrete elements. Finite element modeling of retrofitted beam is shown in Figs. 6(a) and (b).



(a)



(b)

Fig. 6: Finite element meshing of retrofitted beam; (a) Retrofitted beam and (b) Close view of crack location.

3. RESULTS AND DISCUSSION

Results obtained from the numerical analysis of four beams are summarized in Table 1 and discussed in the following subsection.

3.1 Load-Deflection Response

The load-deflection response of uncracked (UB), cracked (CB) and retrofitted beam (RS and RF) are shown in Table 1 and Fig. 7. It is seen that cracked beam shows a brittle mode of failure just after the yielding of reinforcement. Retrofitted beams show significant ductile behavior before failure. However, this ductility is not as much as the un-cracked one.

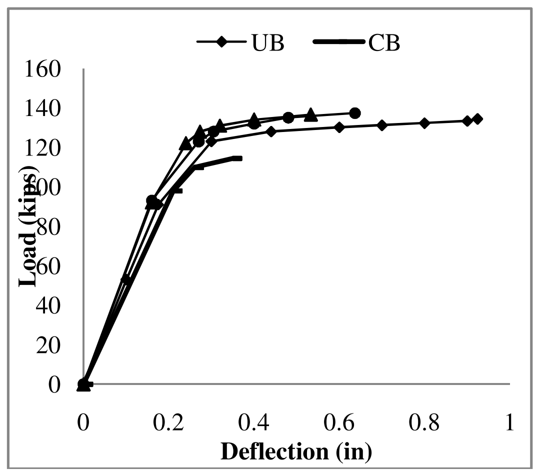


Fig. 7: Load-deflection response.

3.2 At the development of first crack

From Fig. 7 it is seen that first crack occurs in the cracked beam at higher load than un-cracked beam. This may be due to the energy absorbed by the pre-crack, which allows higher deflection at the same load. First crack occurs in both the retrofitted beam (Type RS and Type RF) also at slightly higher load than un-cracked beam. This is due to additional stiffness of steel plate or CFRP sheet.

3.3 At Failure

It is seen from Table 1 that a crack of 20% of full depth reduces the ultimate load carrying capacity approximately 18%. Pre-cracking also reduces the ultimate deflection. Table 1 also shows that, load carrying capacity of retrofitted beam increases at a value slightly higher than the un-cracked beam. Both the retrofitted beams show a lower value of ultimate deflection than the un-cracked beam but higher than the cracked beam.

Table 1: Summary of numerical analyses results.

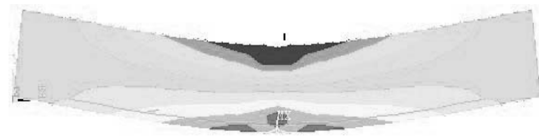
Type	At First Crack		At Failure	
	Load (kip)	Deflection (in)	Load (kip)	Deflection (in)
UB	91	0.175	134.42	0.924
CB	97.9	0.21	114.32	0.35
RS	92.2	0.16	136.66	0.532
RF	93	0.16	137.32	0.636

3.4 Stress Response

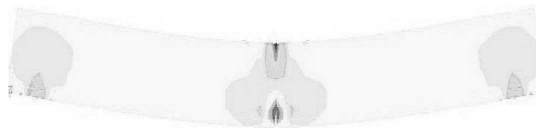
Table 2 shows the stress responses at different locations of beams. All stresses were calculated at a load of 91 kips, which was the lowest first cracking load (occurred in uncracked beam). It is seen from Table 2 that cracking in RC beam causes increased stress at crack tip. Stress, σ_y (stress in local y-direction) increases significantly than σ_x (stress in local x-direction) due to crack. However, for retrofitted beam stresses at the crack tip effectively reduces. At the point of stress transfer, an increased stress is noticed due to retrofitting. However this increased stress lies within allowable limit. Stress contour plot of local stresses (σ_x and σ_y) of cracked beam is shown in Figs. 8(a) and (b). It is seen that stresses concentrate at the tip of crack.

Table 2: Stresses (σ_x and σ_y)

Type	Stress, σ_x (psi)		Stress, σ_y (psi)	
	At crack tip	At transfer	At crack tip	At transfer
UB	4135	2233	-110.89	0.1824
CB	4265	2232	1636	0.1808
RS	4152	2466	386.94	35.14
RF	4184	2408	438.74	28.103



(a)



(b)

Fig. 8: Stress contour plot of cracked beam, (a) σ_x, (b) σ_y.

4. CONCLUSION

Based on the results obtained from numerical analysis, the following conclusions can be drawn:

- Cracking in RC beam reduces the load carrying capacity of the beam.
- Significant stress concentration occurs in the beam due to cracking.
- External plate bonding reduces the stress concentration at crack tip.
- External plate bonding causes an increased flexural stress in concrete at stress transfer zone. However, this increment in flexural stress lies within allowable limit.
- Plate bonding using both the steel plate and CFRP sheet could effectively retrofit cracked beam by increasing its load carrying capacity.

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