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Strengthening of Shear Deficient Reinforced Concrete Beams Retrofitted with Cement-based Composites

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ABSTRACT

The restoration of strength and stiffness of damaged reinforced concrete beams with deficient reinforcements, through retrofitting, was experimentally and numerically studied. Retrofitting is carried out by wrapping glass fiber strips using cement-based composite binders. Six beams of size 1500mm (length) x100mm (width) x 150mm (depth) have been tested in four-point bending. Three beams are used as reference beams, whereas the other three are cast as shear deficient beams and loaded up to first few cracks.The damaged beams were repaired, cured and retrofitted. Flexure test is carried out to find the average ultimate load, maximum deflection, maximum moment, stiffness, energy absorption and crack pattern of reference and preloaded retrofitted beams. Numerical analysis is carried out for the similar shear deficient beams. It is concluded that the ultimate load and moment carrying capacity were restored in preloaded retrofitted beams. The stiffness and energy absorption are improved in preloaded wrapped beams with deflection at ultimate load being reduced.

KEYWORDS: Experimental analysis, Numerical analysis, Shear deficient beams, Glass fiber strips, Cement-based composites.

INTRODUCTION

Many concrete structures fail to cater the specific needs due to change in the design standards, unexpected loading, corrosion, design and construction errors and due to random loading in the form of earthquakes. Damaged structures are to be replaced or retrofitted. Shear in the beam is primarily resisted by the stirrups provided as shear reinforcement. Beam members with insufficient stirrup bars require retrofitting in high shear region, in order to enhance their shear strength. Cement-based composites have good workability and maintain excellent bond with the base concrete.

Earlier research was carried out to get the properties for polymer modified mortar and concrete to be used as repair materials, by conducting different tests on polymer-based admixtures by (Ohama, 1998). Kurtz and Balaguru (2001) concluded that the post yield stiffness is high for inorganic cement based binders and that the deflection of the beam with this binders was 25% less than that of the beam with the organic epoxy binders and without any delamination.

Procedure to enhance the bond between carbon fibers and cementitious matrix is discussed, and the proper blending of cement with polymers is designed

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by (Badanoiu and Holmgren, 2003). The mechanism to prepare precast carbon fiber strips to strengthen and rehabilitate damaged reinforced concrete beams is discussed by (Alace and Kaihaloo, 2003). Blanksvard (2007) mentioned the significance of cementitious binders in strengthening techniques.

A new term, mineral-based composites, has been introduced by (Taljsten and Blanksvard, 2007). They concluded that slab strengthened with carbon fibers using epoxy binders showed brittle failure mode, whereas ductile failure mode was noted for slabs with mineral-based binders. Sundaraja and Rajamohan (2009) concluded that GFRP inclined strips using epoxy as binder restricted the development of diagonal cracks and prevented brittle failure of the beam strengthened in the shear region. Ludovico et al. (2010) studied the use of cement mortar as binder along with basalt sheets to provide a good solution to enhance the compressive strength and ductility of concrete members and to overcome the limitations of epoxy-based FRP laminates.

Past study by (Wu et al., 2010) showed that cement-based composite sheets for *in situ* structural retrofit are possible with excellent bonding and without delamination using carbon fiber sheets. Obaidat et al. (2011) found that increasing the CFRP plate length in the flexural region, beyond the middle one third length of the beam, enhances the flexural and shear behavior of preloaded beams.

Low-density glass fiber sheets with clear spacing between individual rovings allow effective impregnation of cement mortar as was confirmed by (Francisco et al., 2012).

Beylergil et al. (2013) found that even the damaged wooden beams could be successfully retrofitted and enhanced in load carrying capacity. Haddad et al. (2013) compared the effectiveness of carbon and glass fiber sheets and strips, for enhancing the properties of shear deficient beams damaged by sulfate attack. Experimental results were validated through an analytical model.

Al-Rousan and Haddad (2013) created a non-linear finite element model and validated the experimental results of the behavior of strengthened sulfate damaged reinforced concrete beams. They concluded that glass strips provided at an angle of 45º are effective in strengthening the beams in the shear región.

Finite elements analysis helps understand the behavior of retrofitted beam members effectively and economically. Many studies were carried out to justify the validity of modelling and analysis of structural members using ANSYS. Wolanski (2004) concluded that deflection and stress at the center line compared well with experimental data obtained for reinforced concrete beams. Initial and successive cracking of the finite element model were noted as well. Santhakumar et al. (2004) presented the load-deflection behavior and crack pattern for control and shear retrofitted beams. Ibrahim and Mahmod (2009) concluded that the numerical solution could be adopted to study the ultimate shear strength of concrete beams reinforced with FRP laminates. They also found that the numerical method adopted is a quick and effective way compared to full-scale experimental test.

Majeed (2012) concluded that effective 3D modelling and non-linear analysis of steel fiber reinforced concrete deep beams are possible using ANSYS. The stress-strain plot along the depth of a deep beam for various L/D ratios is effectively analyzed through ANSYS by (Patil et al., 2012).

The above studies concluded that glass fiber sheet bonded with cement-based composites could be effectively used to strengthen the beam in shear at supports. It was also confirmed that ANSYS could be used to model retrofitted reinforced concrete beam members to study effectively the load–deflection behavior, stress distribution, strain distribution and crack patterns. The results could be validated through experimental works. The aim of this study is to investigate the restoration of strength and stiffness in shear damaged beams through retrofitting.

EXPERIMENTAL INVESTIGATION

Materials

Laboratory tests were conducted to determine the properties of cement, fine aggregates and coarse aggregates. The various properties for metakaloin, super plasticizers, viscosity modifying agent and bidirectional glass sheet are as provided by the supplier.

Ordinary Portland cement of grade 43 with a specific gravity of 3.1 was used. It conforms with IS 1727-1967. Sand used for the work was locally procured. It conforms with IS: 383-1970. Testing of aggregates was as per IS 2386-1963. Sand was sieved through BIS 4.75 mm sieve to remove any particles greater than 4.75 mm. Grading of fine aggregates corresponds to zone II, with a fineness modulus of 3.24. The material which was retained on BIS test sieve 4.75mm was the coarse aggregate. Locally available coarse aggregates having the maximum size of 20 mm were used in the work.

Metakaolin is a dehydroxylated form of clay mineral kaolinite with a specific gravity of 2.5. Woven roving is made from continuous glass fiber rovings which are interlaced heavy weight fabrics, compatible with most binder systems. The physical properties of E-glass sheet are given in Table 1.

Table 1. Orthotropic material properties for glass sheet (MPa)

Element	EX	EY	EX	PRXY	PRYZ	PRXZ	GXY	GYZ	GXZ
Solid 46	179000	6900	6900	0.26	0.26	0.3	1400	1700	2550

Glenium B233 admixture used in this work is based on polycarboxylic ether. This super plasticizer is free of chloride and compatible with all types of cements. The specific gravity is 1.08 with pH > 6. Glenium stream 2 is a premier ready-to-use, liquid, organic, viscosity-modifying admixture, specially developed for producing concrete with enhanced viscosity and controlled rheological properties. The specific gravity is 1.01. The design of concrete mix is according to IS 10262-1982 to achieve a characteristic compressive strength of 30MPa with a w/c ratio of 0.37 and a slump of 60 mm. The concrete mix proportion is 1:0.96:2.33.

Casting of Specimens

Concrete cubes (150 mm x 150 mm x 150 mm) and cylinders (height of 150 mm and diameter of 300 mm) were cast to confirm the characteristic compressive strength of the design mix. Reinforced concrete beam with four-point bending was considered for analysis to achieve uniform moment between load points. The beams have a rectangular cross-section of 100 mm width, 150 mm height and 1500 mm length. Reference beams (RB) were cast with two 10 mm bars, both at top and bottom along with stirrups at 100 mm c/c. Shear deficient (SD) beams were cast with reduced stirrups to obtain inclined shear cracks by increasing the spacing to 400 mm.

Testing of Specimens

Testing of Cubes and Cylinders

All the cubes and cylinders were tested in saturated condition, after wiping out the surface moisture at 28 days of curing using compression testing machine of 3000 kN capacity. The tests were carried out at a uniform stress of 10 kg/cm^2/minute after the specimen has been centred in the testing machine.

Testing of Beams

Reference Beams

The reference beams were tested in four-point bending. The span between the supports was 1200 mm, and the test was carried out in a Universal Testing Machine of 1000 kN capacity. Deflection and load were recorded during the test.

Preloading of Beams

To simulate damage in SD beams, they were preloaded before retrofitting. The preloading was done with the same setup as done for the control beam. They were loaded up to first few cracks.

Repairing of Preloaded Beams

The beams were removed from the test machine. The surface of the beams was roughened by sand paper and loose particles were removed using a wire brush. The cracks were sealed with polymer mortar (Ohama, 1998). Cement and sand were taken at 1:3 ratio with W/C as 0.44. Styrene butadiene rubber latex polymer was added to the mortar at 0.2% of the weight of water. Polymer-based mortar was applied to seal all cracks and defects. The beams were allowed to cure.

Retrofitting of Shear Deficient Beams

The cured beams were turned over to retrofit them with glass fiber strips. The surface of the beam was roughened with sand paper and loose particles were removed using a wire brush. Cement and metakaolin were mixed uniformly. Water to cemet-metakaolin ratio W/ (C+M) was 0.28. Amounts of super plasticizer and viscous modifying agent used were 0.3% and 0.004% of weight of cement and paste was prepared as shown in Fig.1 (Wu et al., 2010). A layer of cementitious bonding agent was applied on the primed base concrete surface. The glass sheet was provided as inclined strips on three faces of the beam at an inclination of 45° to horizontal. The width of the strip was taken as 25mm and the spacing of strips was maintained at 55mm as shown in Fig. 2. Spacing was according to ACI Committee Report (ACI 440R 1996), which restricts the maximum spacing as (d/4 + width of the strip), where d is the effective depth of the beam. The retrofitted shear deficient beams (RSD) were allowed to cure.

Figure (1): Preparation of cement based composites

Figure (2): Wrapping with glass fiber strips and cement based composites

Testing of Retrofitted Beams

RSD beams were loaded such that the glass sheet was not loaded directly. Testing pattern was similar to that of RB. After the concrete starts to crack, the glass sheet composite starts to take additional load up to failure of the beam.

Shear force at the supports of the beam is shared by each component of the beam as follows (Sundarraja et al., 2009):

$$V_T = V_C + V_S + V_f + V_M. \quad (1)$$

Shear carried by concrete at support is expressed by:

$$V_c = \tau_c \, bd. \quad (2)$$

Strength of shear reinforcement is:

$$V_s = \frac{0.87 f_y A_{sv} d}{s_v}. \quad (3)$$

$$V_{fi} = \frac{0.7 A_{fi} f_{fi} d\,(\sin\propto + \cos\propto)}{s_{fi}}. \quad (4)$$

Contribution of inclined strips is:

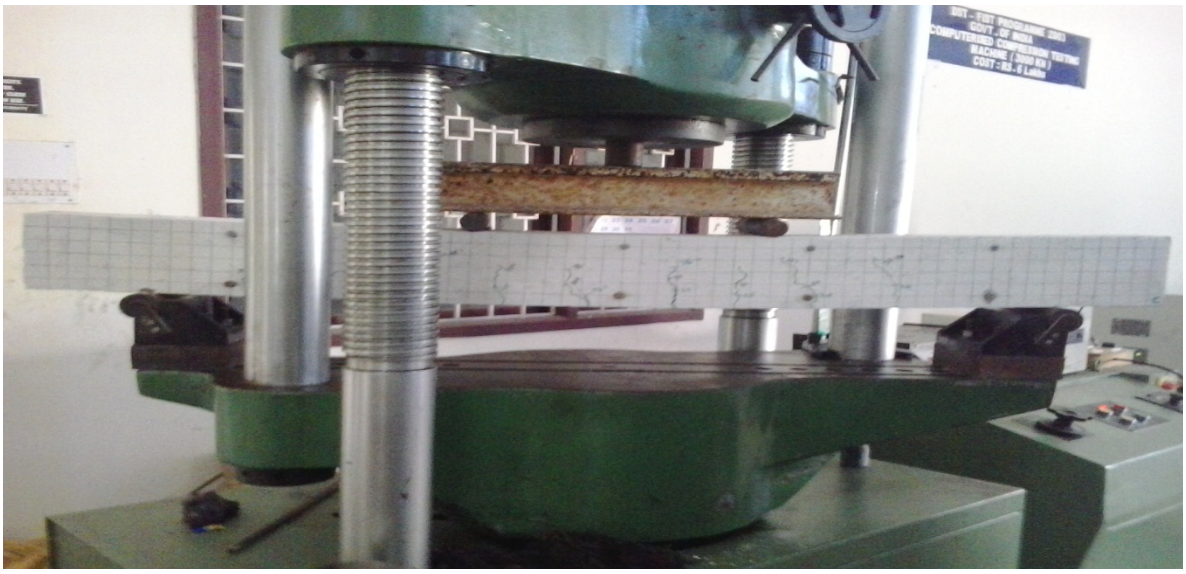

Figure (3): Crack pattern in RB with sufficient flexure and shear reinforcements

Figure (4): Shear cracks in preloaded SD beam prior to repair

Contribution of cement-based composites as inclined binder is: $V_{Mi} = \frac{1}{3} t_M \frac{h_e}{sin\propto} f_M$ (5)

where τ_c is the shear stress in concrete; *b* is the breadth of the section; *d* is the effective depth of the section; f_y is the yield stress in steel; A_{sv} is the area of stirrup bar; s_v is the spacing of stirrups; A_f is the area of one strip of fiber sheet; f_f is the effective tensile stress in the fiber sheet; s_f is the spacing of fiber sheets; α is the angle of inclination of fiber sheet with longitudinal axis of the beam; t_M is the total thickness of mineral-based composites; h_e is the effective height of the mineral-based composites in bearing the shear; f_M is the tensile strength of mineral-based mortar.

Numerical Investigation

Numerical Model

Symmetry of the beam was utilized to model only one half of the beam. Displacement in the right end of the model was applied zero to simulate symmetry boundary condition.To avoid stress concentration, square steel plates of size 100 mm× 100 mm x 5 mm were provided at point of loading and supports. Keypoints, lines, areas and volumes were used to create the model of concrete, steel reinforcement, steel plates and glass sheet as wrapping.

Elements for Meshing and Boundary Conditions

The elements used were solid65 to model concrete and binder, link8 for reinforcement, solid45 for steel plates and layered solid46 for glass sheet composites. The solid65 element has eight nodes with three degrees of freedom at each node – translation in the nodal *x*-, *y*- and *z*-directions. This element is capable of plastic deformation, cracking in three orthogonal directions and crushing. Link8 element was used to model steel reinforcement. It is a 3D spar element having two nodes with three degrees of freedom as translation in the nodal *x*-, *y*- and *z*-directions and also has the capacity of plastic deformation. Solid45 element has eight nodes with three degrees of freedom at each node– translation in the nodal *x*-, *y*- and *z*- directions. Layered solid46 elements were used to model fiber sheet. Supports were hinged and load was applied at the corresponding nodes. Numerical model for RB along with boundary conditions is shown in Fig.7. Model of RSD along with wrapping is shown in Fig. 8.

Figure (5): Initial flexural cracks in retrofitted damaged RSD beam

Figure (6): Retrofitted damaged RSD beam loaded to failure

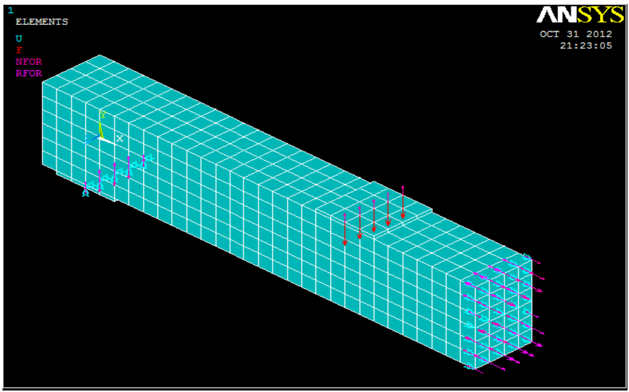

Figure (7): Numerical model with boundary conditions

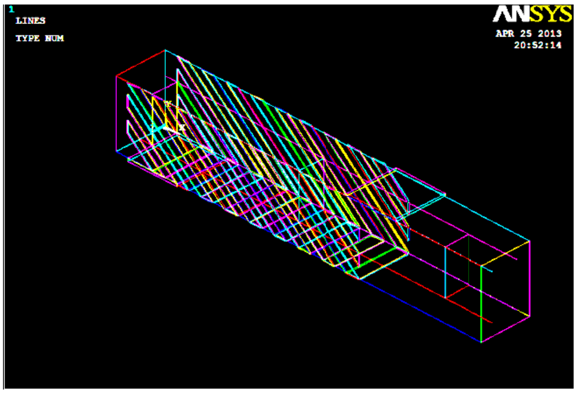

Figure (8): Numerical model with wrapping

Material Properties for Elements

Solid65 and link8 elements were input with elastic material properties. The multilinear stress –strain values for concrete and inelastic bilinear isotropic stress-strain values for link8 element are as shown in Fig.9 and Fig.10, respectively. The orthotropic properties of glass sheet are provided for three orthogonal directions. The input values of shear coefficients of open and closed cracks are 0.35 and 1 as given for solid65 elements.

Static Analysis

Preloading of SD beams was simulated through static analysis. The load on the beam was increased and analysis was stopped when the first few cracks appeared in the beam. Wrapping on the beam was modelled.

Nonlinear Analysis

In nonlinear analysis, the ultimate load applied to the model was split into a series of load increments as load steps. At the end of each load increment, the stiffness matrix of the model was modified to reflect nonlinear changes in structural stiffness. Newton-Raphson equilibrium iterations are used for convergence within tolerance limits.

RESULTS AND DISCUSSION

Beams were cast and tested. Results from both experiments and numerical analysis are tabulated and compared.

Compressive Strength of Concrete

The average characteristic compressive strength of concrete through cube test amounted to 38 MPa. The average compressive strength of cylinders was 32 MPa. The stress-strain plot for concrete cylinders was utilized in numerical modelling.

Load-Deflection Behavior of Beams

The load deflection behavior was recorded for the RB. Widening of flexural cracks occurred at the mid span along with limited shear cracks as shown in Fig.3. The RB, being under reinforced section, undergoes large deflection before failure with an average ultimate load of 38.01kN and an average ultimate moment of 7.62kNm. Preloading of the SD beam initiated the shear cracks as shown in Fig.4, even at low load values. Repaired and retrofitted SD beam was loaded up to ultimate load. Strengthening of SD beams in the shear region allowed for flexural cracks to appear initially, instead of shear cracks as shown in Fig.5. Loading up to failure leads to ductile flexure failure as shown in Fig.6. Results are compared with that of RB. Analyses of the similar beams were carried out in ANSYS. Restoration of stiffness and energy absorbing capacity are compared in Table 2.

Table 2. Flexure behavior of shear deficient beams

Beam	Stiffness (N/m)	Energy absorption (Nm)
RB-Experimental	2521.3	161500
RSD-Experimental	3311.1	212850
RB-ANSYS	3673.4	163200
RSD-ANSYS	4898.2	219050

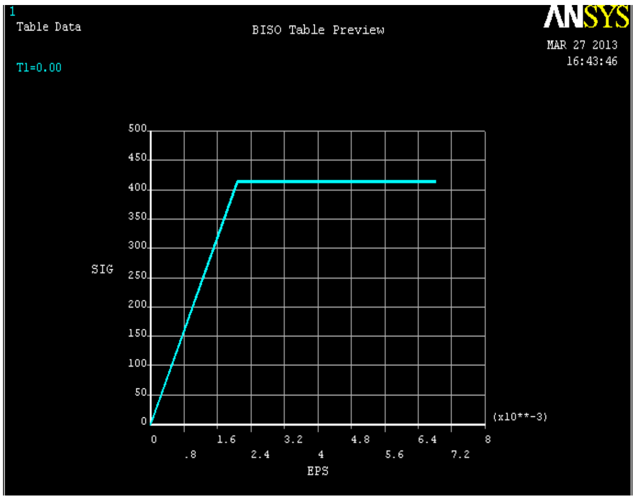

Figure (9) :Bilinear stress-strain curve for steel

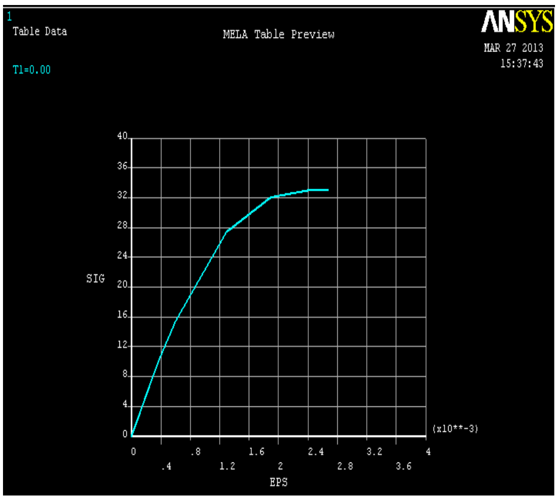

Figure (10) : Multilinear stress-strain curve for concrete

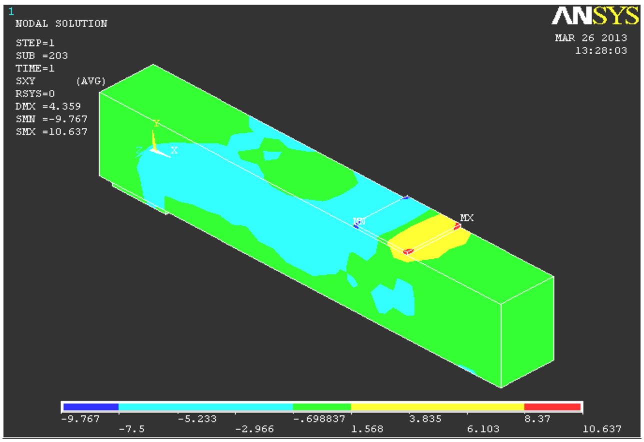

Figure (11): Stress distribution in SD

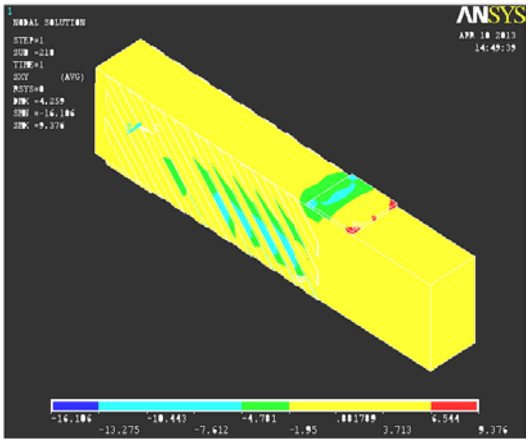

Figure (12): Stress distribution in RSD

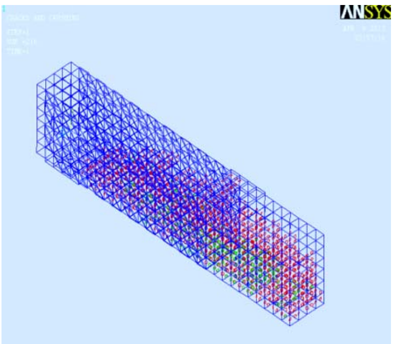

Figure (13) :Crack and crush plot in RSD

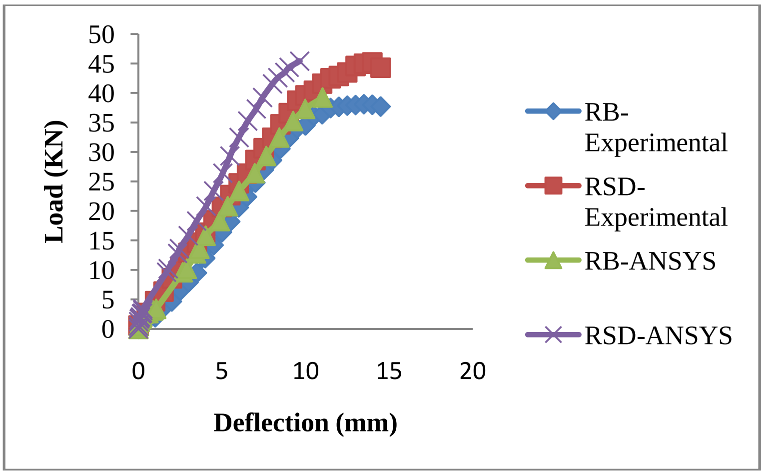

Figure (14) : Comparison of load-deflection behavior

Load-deflection plots are compared as shown in Fig.14. Percentage increase in ultimate load for RSD is 18.63%, compared to RB. Ultimate moment carrying capacity is also increased by 13.51%. Compared to RB, energy absorption is enhanced by 31.57% and stiffness for the beams showed a restoration of 31.35%. Similar load-deflection plot behavior was observed in numerical analysis, but the utilization of symmetry made the numerical model a little bit stiff compared to experimental beams. The corresponding increases in percentages are 21.62%, 15.2%, 34.2% and 33.3%, respectively.

Crack and Crushing

Experimental test of RB to full failure shows the wider cracks formed in the flexure region at bottom and crushing of concrete on top. In case of RSD beams, formation of shear cracks is suppressed due to the inclined strips. Major flexural cracks appeared in the mid span of the beam and the failure was not catastrophic. Similar cracking and crushing appeared in the model as shown in Fig. 13.

Stress and Strain Distribution

Stress distribution in SD and RSD is as shown in Fig.11 and Fig.12, respectively. Retrofitting the beam in the shear region reduces the shear stress in the concrete. Variation of shear stress and shear strain across the depth of the beams are plotted in Fig.15 and Fig.16, respectively. The percentage decrease in shear stress and shear strain for RSD is 29.46% and 24.2%, respectively, compared to RB.

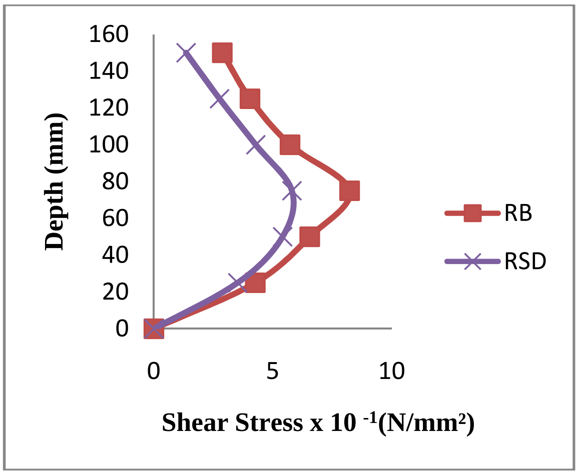

Figure (15) :Comparison of shear stress distribution

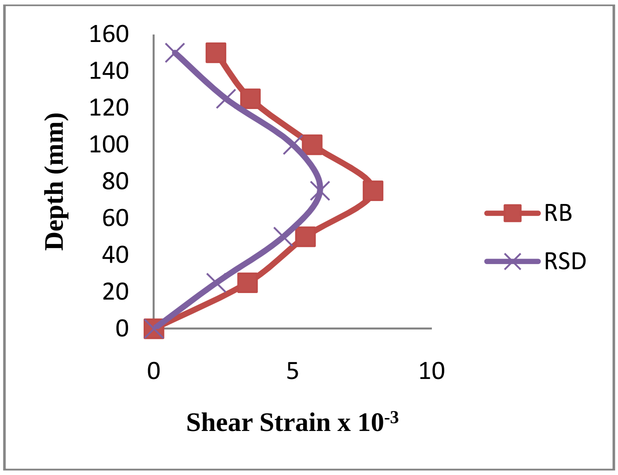

Figure (16) : Comparison of shear strain distribution

CONCLUSIONS

This paper investigated the structural behavior of shear deficient damaged reinforced beams, retrofitted with glass fiber strips using cement-based composite as binder. Beam members are made shear deficient by providing insufficient stirrups. Damages in deficient beams are simulated by preloading them up to the first few cracks. Preloaded beams are repaired for cracks using polymer mortar and then cured. The cured specimens are retrofitted. The retrofitted beams are cured and tested up to failure. Numerical analysis is carried out using ANSYS. Static non-linear analysis for RB and RSD was carried out. Retrofitting of beams with glass fiber strips sandwiched between cement-based composites as binder is modelled. Comparison of results leads to the following conclusions.

- In retrofitted damaged shear deficient beams using cement-based composites as binder, load carrying capacity is enhanced and the formation of shear cracks is arrested. Failure of the beam is ductile with the development of flexural cracks in the mid span region.
- Experimentally, the percentage increase in ultimate load of RSD is 18.63%, compared to RB. Numerically, the corresponding increase is 21.62%.
- Experiment results show that the deflection at ultimate load for RSD is reduced by 11.1%, compared to RB. The corresponding value, when checked numerically, gives the difference as 12.43%.
- The percentage increase in ultimate moment for RSD is 13.51% experimentally and 15.2% numerically, when compared with RB.
- Experiments gave the percentage increase in stiffness for RSD, compared to RB as 31.35%. Numerical analysis gave the corresponding increase as 33.3%.
- Experimentally, the percentage of energy absorption for RSD is improved by 31.57%, compared to RB. Numerically, the respective improvement is 34.2%.
- The percentage decrease in shear stress and shear strain for RSD is 29.46% and 24.2%, respectively, compared with RB.
- Both in experimental and numerical analysis, after

concrete starts to crack, the glass sheet composite starts to take further load without any delamination.

- Restoration of strength and stiffness of beams, damaged due to insufficient shear reinforcement, was achieved through retrofitting with inclined glass strips and cement-based binders. The results are validated through numerical analysis. Utilization of symmetry made the model stiffer compared to real beam.

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