Numerical Modeling of Flexural Behavior of RC Beams Strengthened with Fiber Concrete Jackets

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Abstract:

Reinforced concrete (RC) beams are significant structural members in load transferring process in structural skeleton. The load carrying capacity of beams may be decreased due to several reasons such as design or execution errors and difference between the designed and actual loads. To overcome this problem, various strengthening techniques can be used. Strengthening with steel fiber-reinforced concrete (SFRC) jackets can enhance the capacity, and stiffness of RC beams. It is also capable of decreasing the induced deformations. Moreover, it has many advantages over the other methods of strengthening such as the reduced thickness of the jacket, fire resistance and invulnerability against corrosion. The available information on behavior of RC beams fail in flexure strengthened with SFRC is limited.

The objective of this study is to develop non-linear three dimensional finite element models to simulate the behavior of simply supported RC beams externally strengthened in flexure with FRC jacket.

The finite element procedure implemented in this study is developed using the available element types from ANSYS element library (Concrete, steel reinforcement bars, interface between concrete and steel, loading plates, supporting plates, FRC jacket, and interface between concrete and FRC jacket).

The validity of the analytical model has been verified by compared the results of analytical model with the experimental results of tests from previous works.

The predicted results of the analytical model have shown a close agreement with the previous experimental results.

Keywords: Steel fiber concrete, Strengthening of beams, Strengthening techniques, bond interface, Shear connector, HSC, NSC, SFRC.

1. <u>Introduction:-</u>

The interest of strengthening of reinforced concrete beams has increased in the last few years because of poor performance under service loading in the form of excessive deflections and cracking, construction faults, design faults, excessive deterioration and the changing in use of structure. In such circumstances, there are various methods for strengthening of R.C beams such as externally bonded steel plates, R.C jacketing and externally bonded fiber reinforced polymer (FRP). All these techniques can be successfully used but have some limits. In particular, the use of externally glued steel plates as well as of FRP may have problems for fire resistance.

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Furthermore, the use of these techniques may not satisfy the minimum requirements for serviceability limit states.

Using of FRC jacketing is a promising technique, as it doesn't include steel bars for the jacket which decrease restrictions for jacket thickness comparing to conventional RC jacketing (i.e. the concrete cover needed for the reinforcing steel bars in case of conventional RC jacketing). FRC jacketing provides more ductile failure for RC elements rather than steel plates jacketing which exhibit sudden failure and suffers from corrosion. Moreover, it has more fire resistance rather than FRP wrapping.

Addition of steel fibers slightly affects the compressive strength of concrete, but it significantly improves direct tensile strength, shear strength, torsion strength, flexural strength and impact resistance. SFRC has more strain capacity and toughness than conventional concrete due to its ductile behavior thanks to presence of fibers. Steel fibers also enhance the durability of concrete in terms of fire, freezing-thawing and corrosion resistance.

Recently, experimental and few theoretical studies have been carried out in order to investigate the shear and flexural behavior of RC beams strengthened with jacket techniques.

M. N. Isa, [1] studied experimentally, numerically and analytical investigations the flexural improvement of plain concrete (PC) beams strengthened with high performance fiber reinforced concrete (Jacket Thickness = 30mm). Four plain concrete beams with dimension of 140 mm x 230 mm x 1400 mm were used in this study. Three different strengthening configurations (bottom side, two side and three side jacket) were the parameters in this study. The results show that the strengthening with HPFRC increases the cracking load, load carrying capacity and stiffness of plain concrete beams.

Beams strengthened at the bottom sides show brittle failure similar to that of the control as such this strengthening pattern is not recommended. Results also show beams strengthened at the longitudinal sides and at the three sides shows more ductile behavior as the steel fibers in the sides' jacket increases the beams resistance to crack propagation giving the beams a more softening behavior after reaching the ultimate load as shown in figure (1).

Finally, the finite element was able to capture the behavior of the strengthened beams with reasonable accuracy and the analytical model is also able to predict the moment capacity of the strengthened beams.

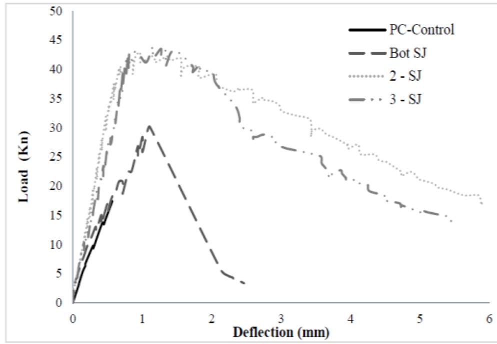


Figure 1: Load-deflection behavior of tested beams,[1].

G. Martinola, et al, [2] studied experimentally an application of high performance fiber reinforced cementitious composites for RC beam strengthening. three beams with dimension of 300 mm x 500 mm x 4500 mm were used in this study. A beam without any reinforcement, and a beam with a low reinforcement ratio (2Ø16 mm in the bottom part and 2Ø12 mm in the top part), have been strengthened with a jacket in HPFRCC having a thickness of 40 mm. A third beam with the same low reinforcement ratio but without HPFRCC jacket, has been used as reference specimen. Reinforcement ratio and strengthening jacket were the parameters in this study. The results show that a simple sandblasting ensures a perfect bond between the base concrete material and the strengthening HPFRCC layer. The application of a layer of HPFRCC having a thickness of 40 mm remarkably increases the maximum load (more than double) as shown in figure (2). Finally, the strengthening layer has provided a remarkable stiffness increase; as a consequence the midspan displacement at service conditions has been reduced of about 12 times. This behavior is comparable to the application of prestressing.

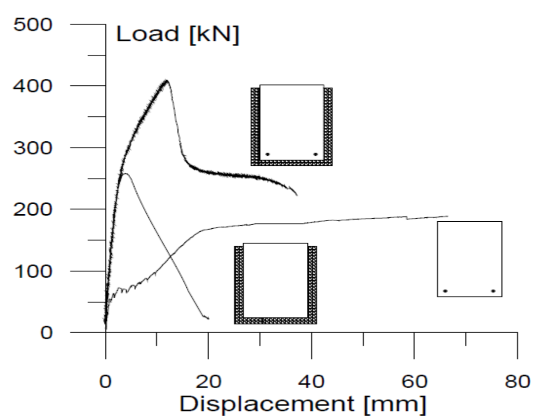


Figure 2: Comparison between the experimental results,[2]

Yehia. A. Hassanean et al, [3] studied experimentally development of steel fiber-reinforced self-consolidating concrete for repairing purposes. twenty one RC beams with dimension of 120 mm x 300 mm x 1900 mm were used in this study. Steel fiber content, jacket thickness shear-span-to-depth ratio and web reinforcement ratio and interface strength were the parameters in this study. The used repairing technique increased the cracking and ultimate loads of the repaired beam comparing to the control beam. Also, it was found more effective to increase the fiber content of the jacket rather than the jacket thickness as shown below.

Using the shear connectors as an additional load transfer mechanism between the original beam and SFRSCC jacket guaranteed prevention of jacket debonding for most cases and decreased the number and depth of the resulted cracks comparing to the beam repaired with no shear connectors. The applied repairing technique also changed the mode of failure from shear-compression failure to diagonal-tension failure.

Finally, at the same load, the repaired beam (B1) exhibited less deflection, compressive and tensile strain than beam (B0). This ensures the great contribution of the SFR-SCC jacket in bearing the applied stresses.

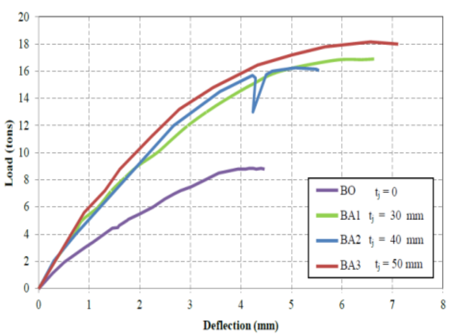


Fig.3: Effect of Jacket Thickness,[3]

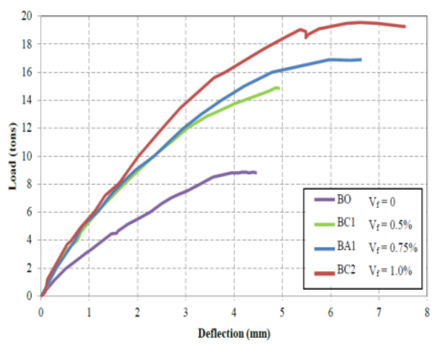


Fig.4: Effect of Fiber Content,[3]

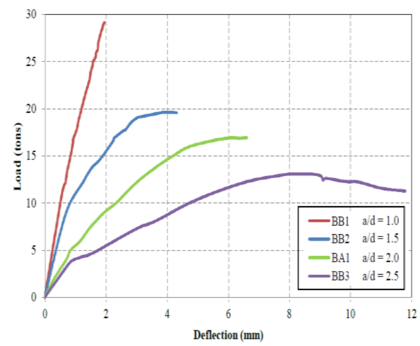


Fig.5: Effect of Shear Span-Depth Ratio,[3]

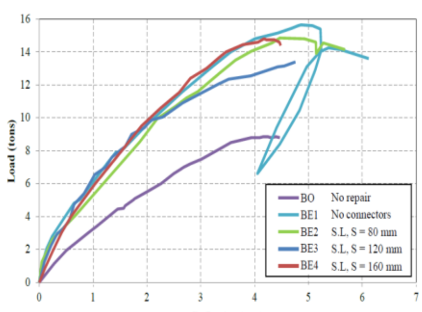


Fig.6: Effect of Single Shear Connector,[3]

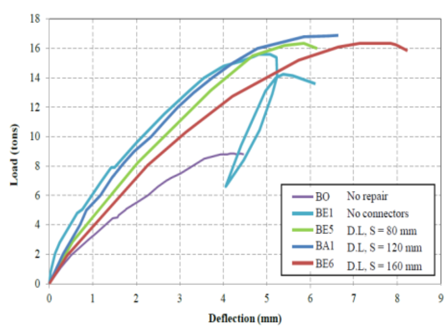


Fig.7: Effect of Double S.C,[3]

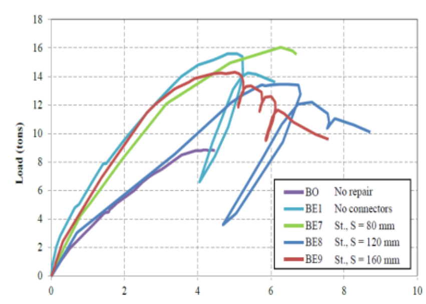


Fig.8: Effect of Staggered S.C,[3]

K.R.Venkatesan, P.N.Raghunath, K.Suguna, [6] studied experimentally flexural behavior of high strength steel fiber reinforced concrete beams. Four beams with dimension of 150 mm x 250 mm x 3000 mm were used in this study. The beam longitudinal reinforcement having three

12mm diameter bar at the bottom section of the beam, two 10mm diameter bar at the top section and shear reinforcement having 8mm diameter bars placed at a spacing of 150mm. Steel fiber volume fractions were the parameters in this study.

It can be observed that the steel fiber reinforced concrete beams exhibit increase in deflection with increase of fibre content at all load levels when compared to the control beam as shown in figure (9). The steel fibre reinforced concrete beams exhibit more number of cracks with lesser widths at all load levels when compared with the control beam. Also, SFRC beams with 1% fibre volume fraction resulted in higher load carrying capacity. The percentage increase ultimate load was 30.03%. SFRC beams with 1% fibre volume showed enhanced ductility. The maximum increase in ductility was 41.34%. Finally, all the beams were failed under flexure mode only.

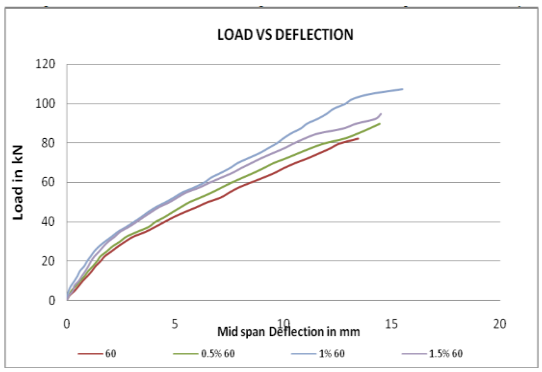


Figure 9: Load-Deflection Responses of Tested Beams,[6]

Yehia. A. Hassanean, et al, [10] studied experimentally behavior of strengthened and repaired R.C. beams by using steel fiber concrete jacket and subjected to short time repeated loading. Eight beams with dimension of 120 mm x 300 mm x 2300 mm were used in this study. Steel fiber content, jacket thickness and interface strength were the parameters in this study.

The results show that the repairing with MSFC jacket decreases the number of cracks and they were concentrated in the middle third avoiding the forming of shear cracks. The application of MSFC jacket on a R.C beam provides an increase of the maximum number of cycles from 2 to 5 times for strengthened beams and from 1.6 to 4 times for repaired beams depending on the fiber content, jacket thickness and the interface strength as shown below.

The beams strengthened or repaired with MSFC jacket but without shear connectors suffered from increasing in mid-span deflection and strains especially in the last stages due to debonding failure. Presences of shear connectors in the jacket play a role in enhancing the bonding between the main beam and the jacket and prevent the debonding failure.

Finally, the proposed technique is more efficient for the strengthened beams than identical repaired beams.

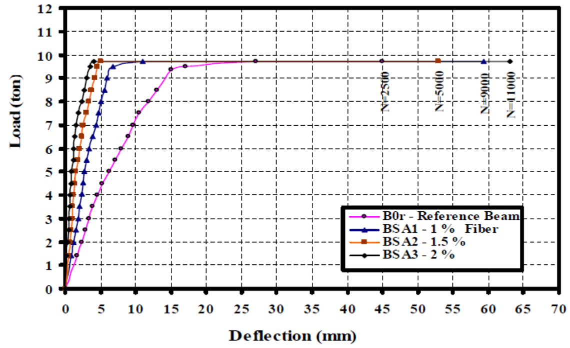


Figure 10: Effect of Fiber Content,[10]

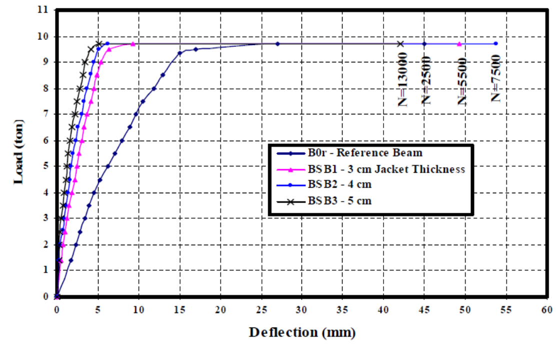


Figure 11: Effect of Jacket Thickness,[10]

Nguyen Van CHANH, [11] studied experimentally steel fiber reinforced concrete. Beams and cube specimens were used in this study. Maximum aggregate size and aspect ratio (l/d) on workability were the parameters in this study. The results show that fibres do little to enhance the static compressive strength of concrete, with increases in strength ranging from essentially nil to perhaps 25%. Fibres aligned in the direction of the tensile stress may bring about very large increases in direct tensile strength. Steel fibres are generally found to have aggregate much greater effect on the flexural strength of SFRC than on either the compressive or tensile strength. Finally, steel fibres have been shown to increase the ultimate moment and ultimate deflection of conventionally reinforced beams; the higher the tensile stress due to the fibres, the higher the ultimate moment as shown below.

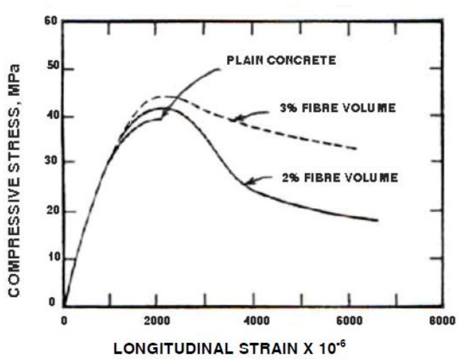


Fig.12: Stress-Strain curves in compression for SFRC,[11]

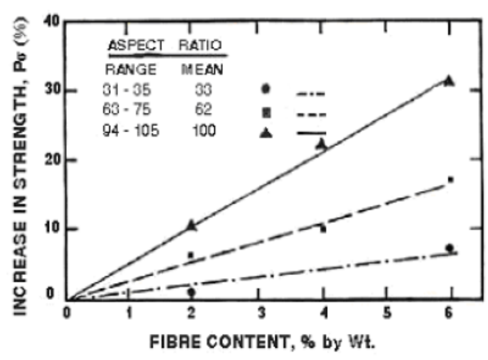


Fig.13:Influence of fibre content on tensile strength,[11]

Based on the aforementioned literature, it's clear that steel fiber-reinforced concrete is a promising material for strengthening and repairing due to its ductile behavior. As it was reported before that strengthening beams with SFRC jackets bonded with epoxy adhesive only suffered debonding of the jackets, and as using shear connectors as an additional load transfer mechanism proved to be effective for repairing RC beams in flexure.

This study is aimed to investigate the shear and flexural behavior of RC beams strengthened with jacket techniques. To achieve this objective, a ANSYS finite element model has been introduced as shown below for the numerical evaluation of RC beams strengthened with steel fiber reinforced concrete (SFRC).

2. Research objectives:-

- Continue after the recent research's on strengthening of RC beams by using steel fiber concrete jacket.
- Develop non-linear three dimensional finite element models to simulate the behavior of simply supported reinforced concrete beams externally strengthened in flexure with FRC jacket.
- Study the effect of bond interface between concrete and SFRC jacket with epoxy adhesive, shear connectors or both theoretically.
- Verify the finite element models by comparing results obtained from the models with results obtained from experimental tests available in the literature.

3. Theoretical Program:-

ANSYS finite element program was chosen for the numerical evaluation of RC beams strengthened with steel fiber reinforced concrete (SFRC). The finite element procedure implemented in this study is developed using the available element types from ANSYS element library as shown in table (1). The model will validate the previous experimental results.

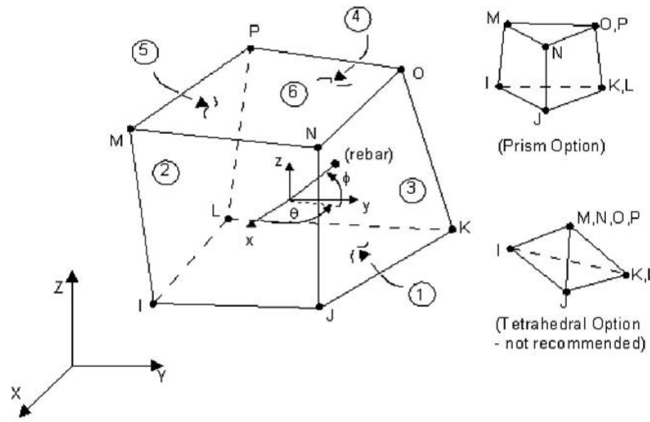
Table.1 : Element Types for ANSYS Flexure and Shear Beams Models.

Material Type	ANSYS Element
Reinforced Concrete	Solid 65
Steel Reinforced	Link 180
Loading and Supporting Steel Plates	Solid 45
Steel Fiber Reinforced concrete (SFRC)	Solid 65
Contact Surface	Conta174 and Targe170
Shear Connectors	Combine39

Element Type for Concrete and Properties

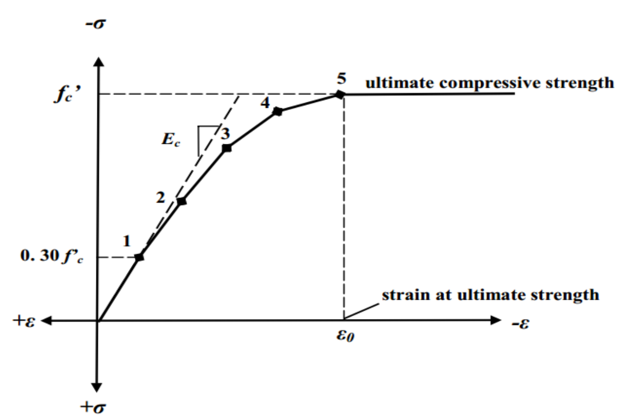
Solid 65 element is used for the three - dimensional modeling of solids with or without reinforcing bars. This element has eight nodes with three degrees of freedom at each node and translations in the nodal x, y and z directions. This element is capable of plastic deformation, cracking in three orthogonal directions, and crushing in compression, creep nonlinearity and large deflection geometrical nonlinearity as shown in figure (14).

Fig.14: Solid 65 Element Geometry,[ANSYS,2014].



ANSYS requires specification of linear isotropic and multi-linear isotropic material properties, as well as some additional concrete material properties, to simulate real concrete behavior. The compressive uniaxial stress–strain values for the concrete model were obtained by the following Equations, which compute the multi-linear isotropic stress–strain curve for the concrete as shown in figure (15).

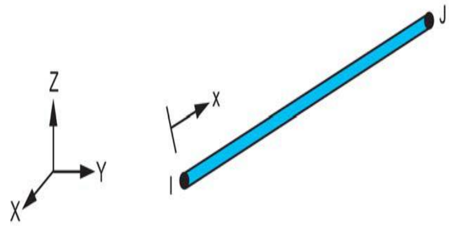
Fig.15: Modified Hognestad Model



Element Type for Steel Reinforcement and Properties

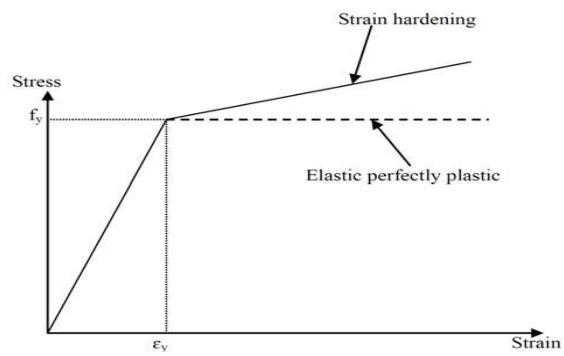
Link 180 element was used to model the steel reinforcement. This element is a 3D spar element with two nodes and three degrees of freedom at each node x, y, and z directions. This element is also capable of plastic deformation. The geometry and node locations for this element type are shown in figure (16).

Fig.16: Link180 Element Geometry,[ANSYS,2014].



The finite element model for the rebar was assumed to be a bilinear, isotropic, elastic–perfectly plastic material, identical in tension and compression as shown in figure (17). The elastic modulus equal to 210 GPa and a Poisson's ratio of 0.3.

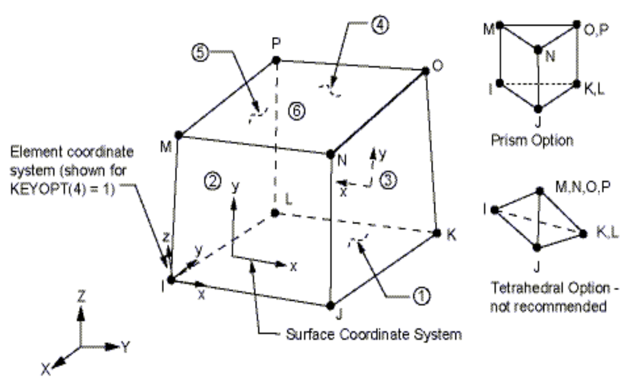
Fig.17: Idealized Stress-Strain Curve for Reinforcing Steel



Element Type for steel plates at the supports

Solid 45 element was used for the steel plates at the supports for the beam. This element has eight nodes, with three degrees of freedom at each node– translations in the x, y, and z directions as shown in figure (18). The steel plates added to the finite element models were assumed to be linearly elastic materials with an elastic modulus of 210 GPa and a Poisson's ratio of 0.3.

Fig.18: Solid 45 Element Geometry,[ANSYS,2014].



Element Type for Contact Modeling

CONTA174 and TARGE170 are two elements define the boundary between the surfaces of the concrete and FRP , and have the ability to model delamination of the two surfaces. In or-der to allow for separation between the concrete and the FRP, a Cohesive Zone Material Model

(CZM) was used. The bond between the concrete and FRP was defined by using the real constant for the con-tact pairs, and the CZM material model inputs. The CZM model has bilinear behavior by using one of two set options; traction and separation distances, or traction and critical fracture energies. In this analysis, the traction and separation distances option was used which has 6 input options; maximum normal contact stress (σmax), contact gap at the completion of debonding (ucn), maximum equivalent tangential contact stress (τmax), tangential slip at the completion of debonding (uct), artificial damping coefficient (η), and an option indicator for tangential slip under compressive normal contact stress (β) as shown in figure (19).

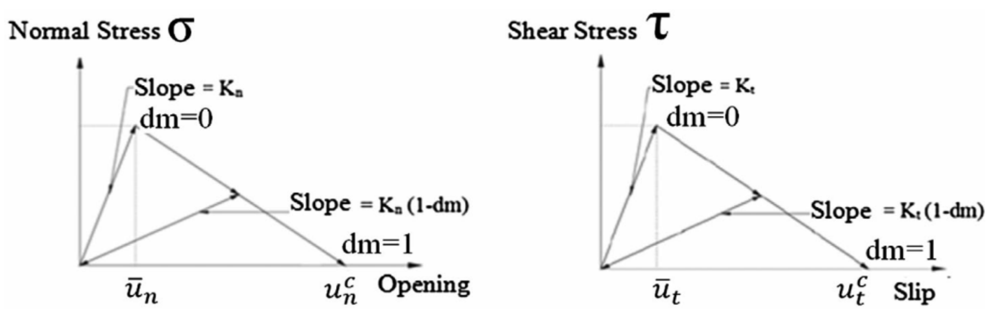


Fig.19: Bilinear models used in the modelling of debonding: (a) normal tension stress–opening, and (b) shear stress–slip.

Element Type for Shear Connectors

Combine39 element is used for the simulation of bond-slip for the adhesive layer between old concrete and new layer. The element is defined by two node points and a generalized force-deflection curve as shown in Figure (20). The element simulates **a spring** with a virtual length that has longitudinal or torsion behavior in up to three directions at each node.

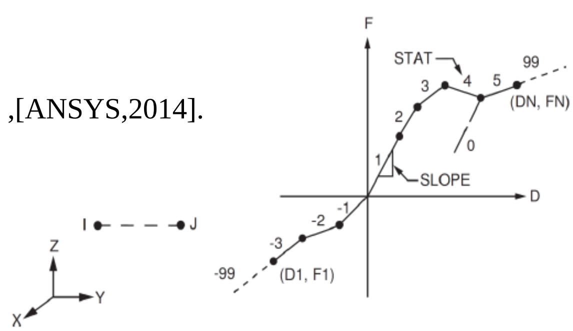


Fig.20: Combin39 Element Geometry and Input Function ,[ANSYS,2014].

Meshing And Forces

After preparing all the input data of material and geometrical properties, the beam models were divided into small elements, the beam model was strengthened with SFC U jacket taking into consideration the effect of shear connector or not as shown in figures (21,22).

The beam model was subjected to flexural loading on their top face simulating the actual loading applied in the experimental tests. The beam is tested in three-point loading as shown in figure (23). The model is loaded with the same conditions as the experimental test.

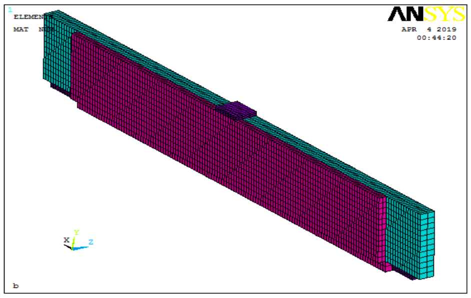


Fig.21: Strengthening beam model.

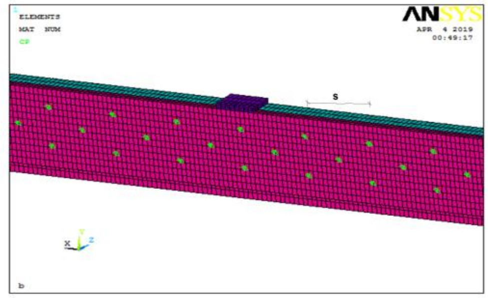


Fig.22: Shear connectors placements.

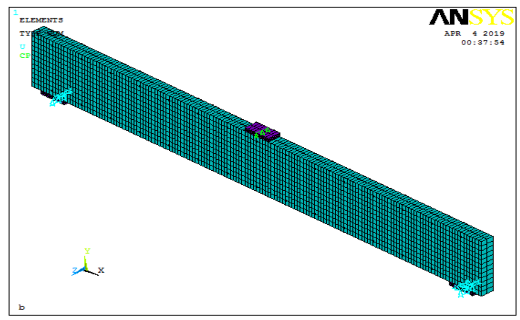


Fig.23: Loading beam model.

4. <u>Validation of the program:-</u>

The suggested analytical program of the study is verified with the experimental results of the study of Yehia. A. Hassanean et al, [3]. They study experimentally development of steel fiber-reinforced self-consolidating concrete for repairing purposes. RC beams with dimension of 120 mm x 300 mm x 1900 mm were used in this study. Dimensions, reinforcement and materials of control and strengthened specimens are shown in table (2).

Table.2 : Dimensions, reinforcement and materials of control and strengthened specimens.

Beam	Fcuj, MPa	Fcu, MPa	Jacket thickness,mm	Vf%	Shear connector	Fy, MPa	S, mm	As, mm2	Cover, mm
BO	-	20	-	-	-	600	-	201	25
BE1	60	20	30	0.75	-	600	-	201	25
BE2	60	20	30	0.75	S.L	600	80	201	25
BE5	60	20	30	0.75	D.L	600	80	201	25
BE7	60	20	30	0.75	S.t	600	80	201	25

The present analytical model is applied on beams have the same dimensions, reinforcement and materials. The results of the present analytical model are in agreement with the results of the experimental study of Yehia. A. Hassanean et al, [3] as shown in figures (24,25,26,27 and 28).

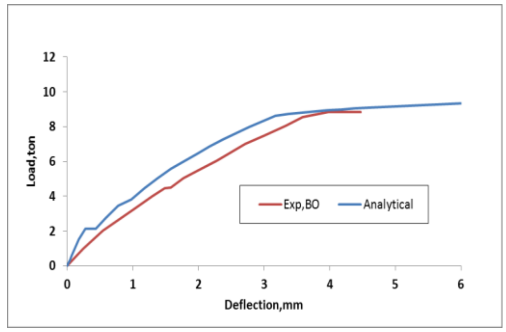
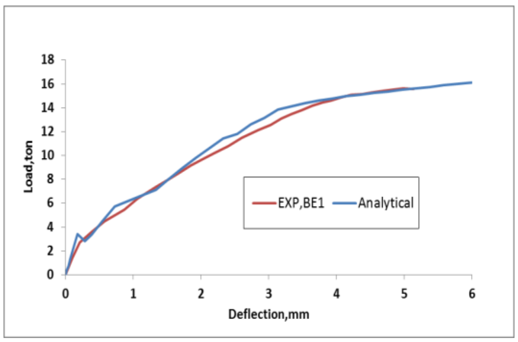


Fig.24: BO control specimen.



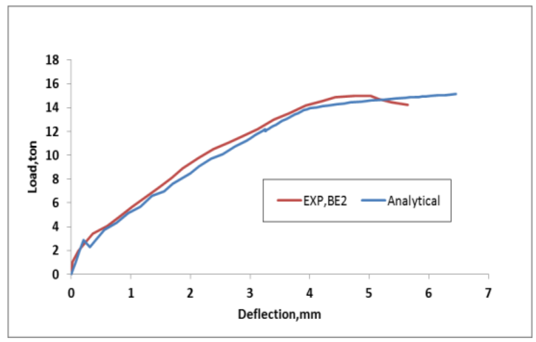
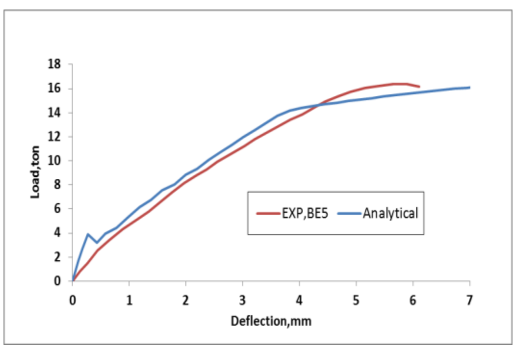


Fig.25: BE1 specimen without shear connector. Fig.26: BE2 specimen with S.L shear connectors.



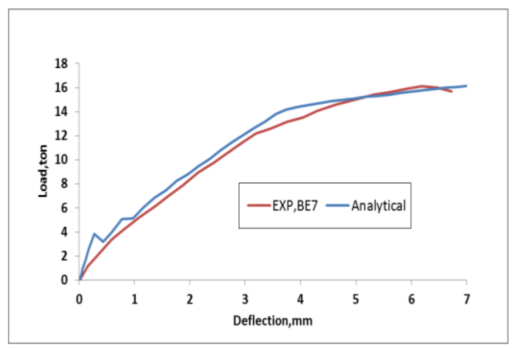


Fig.27: BE5 specimen with D.L shear connectors. Fig.28: BE7 specimen with S.t shear connectors.

Also, the suggested analytical program of the study is verified with the experimental results of Yehia. A. Hassanean, et al, [10]. They study experimentally behavior of strengthened and repaired R.C. beams by using steel fiber concrete jacket and subjected to short time repeated loading. RC beams with dimension of 120 mm x 300 mm x 2300 mm were used in this study. Dimensions, reinforcement and materials of control and strengthened specimens are shown in table (3).

Table.3 : Dimensions, reinforcement and materials of control and strengthened specimens.

Beam	Fcuj, MPa	Fcu, MPa	Jacket thickness,mm	Vf%	Shear connector	Fy, MPa	S, mm	As, mm2	Cover, mm
BOs	-	25	-	-	-	400	-	201	25
BO2	80	25	50	1.5	S.t	400	20	201	25

The present analytical model is applied on beams have the same dimensions, reinforcement and materials. The results of the present analytical model are in agreement with the results of the experimental study of Yehia. A. Hassanean et al, [10] as shown in figures (29 and 30).

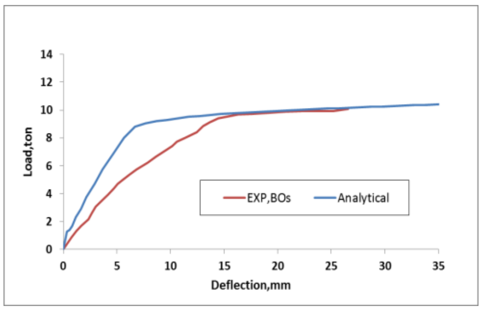


Fig.29: BOs control specimen.

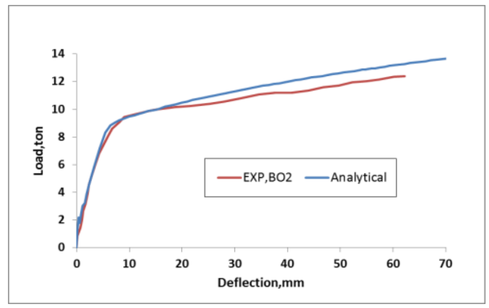


Fig.30: BO2 specimen with S.t shear connectors.

5. Conclusion:-

In this research a study of reinforced concrete beams strengthening by fibers analytically are made to evaluate the effect of the fibers on the flexural, ductility, cracking, and shear behavior of the beams. Based on comparison of the introduced analytical model with the previous experimental studies the following conclusions can be drawn:

- There are agreement between the introduced analytical model and results obtained from previous studies.
- The analytical model shows that the bond has important effect in results, especially using shear connector.
- The best pattern of shear connectors was the double line. This pattern enhanced the diagonal cracking and ultimate loads. On the other hand, the other patterns of shear connectors were less effective comparing to the beam repaired with epoxy adhesive only.
- The strengthened beams results are supposed to introduce good performance in flexural and shear capacity, ductility, and enhance the cracks resistance.

6. References:-

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7. Notations:-

ε	Strain of the concrete.
ε_o	Strain at the ultimate compressive strength.
f	Compressive strength of concrete, (MPa).
f_c	Ultimate compressive strength of concrete, (MPa).
f_t	Tension strength for concrete, (Mpa).
f_y	Yield strength for steel, (Mpa).
ε_y	Yield strain at the yield strength.
F	Shear force at any slip D, (N).
Vf	Volume ratio of fiber content, %.
S	Spacing between shear connector, mm.
As	Area of bottom reinforcement, mm2.
Fcuj	Compressive strength of strengthened jacket, Mpa.
R.C	Reinforced concrete.
SFRC	Steel fiber- reinforced concrete.
FRP	Fiber reinforced polymer.
PC	Plain concrete.
HPFRC	High performance fiber reinforced concrete.