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COMPARATIVE STUDY OF EXPERIMENTAL AND ANALYTICAL BEHAVIOUR OF CRACKING AND DEFLECTION OF FRP STRENGTHENED RC BEAMS

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Abstract: *This paper presents the nonlinear Finite Element Analysis that has been carried out to simulate the behavior of failure modes of Reinforced Concrete beams strengthened in flexure by Fibre Reinforced Polymer laminates. Total six beams are modelled in Finite Element software ANSYS. Out of these Six, two beams are control beam without Fibre Reinforced Polymer Strengthening and other beams are Glass Fibre Reinforced Polymer strengthened beams. From the Finite Element modeling crack pattern and load vs deflection relationships until failure are obtained and compared with the experimental results. Both the observational parameters showed good agreement with the experimental plots with the analytical modeling for the beam without or with strengthening options.*

Keywords*: Fibre Reinforced Polymer; Finite Element Analysis; ANSYS; Glass Fiber Reinforced Polymer; Finite Element Modeling.*

I. INTRODUCTION

The application of Fibre reinforced polymers as external reinforcement has received much attention from structural engineering. FRP laminates has gained popularity as external reinforcement for the strengthening or rehabilitation of reinforced concrete structures. Externally bonded FRP laminates and fabrics can be used to increase the shear as well as flexural strength of RC beams; however, it is likely to be more problematic when they are cast monolithically with slabs.

Nevertheless, bonding Fibre Reinforced Polymer on either the side faces, or the side faces and soffit, will provide some flexural strengthening for such members. FRP composites applied to the RC members provides efficiency, reliability and cost effectiveness in rehabilitation. Experimental based testing has been widely used as a means to analyze individual elements and the effects of concrete strength under loading. While this is a method that produces real life response, it is extremely time consuming and the use of materials can be quite costly.

The use of finite element analysis to study these components has also been used. Analytical modeling has been done for reinforced concrete beams externally reinforced with Fibre Reinforced Polymer laminates using Finite Element Method adopted by ANSYS. The results of the Finite Element Model are assessed by comparison with the experimental results. Such approach of FE models will help in predicting the behavior of beam strengthened with different options. This would be the deciding factor to finalize the amount and type of strengthening pattern.

II. LITERATURE REVIEW

Some of the research work carried out on comparative study between experimental and analytical work in FRP strengthening describe below,

Amer Ibrahim [2] performed Numerical analysis on RC beams by ANSYS finite element program and results show that the general behavior of the finite element models represented by the load-deflection curves at mid span show good agreement with the test data. They also conclude that the load carrying capacity of the Flexure strengthening beam predicted by the finite element analysis is higher than that of the control beam. Saifullah [3] performed destructive test on simply supported beam in laboratory and load-deflection data of that under RC beam. They compared both the computer modeling and experimental data and found that computer based modeling is can be an excellent alternative of destructive laboratory test with an acceptable variation of results. Jayajothi [7] carried out the nonlinear Finite Element Analysis of Reinforced Concrete beams strengthened in flexure and shear by Fibre Reinforced Polymer laminates and they found that the ultimate load carrying capacity of all the strengthened beams is higher when compared to the control beams and general behaviors of the Finite Element models show good agreement with observations and data from the experimental tests. Patil [8] described analysis of deep beams subjected to two points loading with different span to depth ratios using Non-linear Finite Element Method. They found that the smaller the span/depth ratio, the more pronounced was the deviation of strain pattern at mid- section of the beam. As the depth of the beam increases the variation in strength, flexural steel and deflection were found to be more experimentally than the non-linear finite element analysis. Uma [11] performed the flexural response of Reinforced Geopolymer Concrete beam. They compered the results from both ANSYS modeling and experimental data and found that the deflection obtained was found to be low due to meshing of element in the modeling. They also concluded that comparative result gives 20% difference for experimental and ANSYS 12.0.

III. EXPERIMENTAL PROGRAM

Total six beams of size 230mm x 300mm x 2000mm are casted with different strengthening options with M25 and M40 grade of concrete. Out of these six, first beam is control beam means without any strengthening application, second beam is strengthened with Fiber Reinforced Polymer single layer bottom strip and the third beam is with double bottom strip with U shaped vertical double strip in each grade of concrete. The beam notations used are control beam (CB), Bottom Single Strip beam (BSS) and Bottom Double Strip with U Shaped Vertical Double Strip Beam (BDS & UVDS 90°).

The experimental program is proposed such a way that the control beam (CB) is designed to fail in flexure. The flexural strength of the same beam is improved by Bottom Single Strip beam (BSS), hence the beam will in shear. With the next level of improved capacity in shear and flexure, the Bottom Double Strip with U Shaped Vertical Double Strip Beam (BDS & UVDS 90°) is proposed where the beam will fail in flexure. This way the proposed failure pattern is flexure to shear and then again to flexure.

3.1 Materials

3.1.1 Cement: Portland Pozzolana cement conforming to IS 1489 (Part 1): 1991 is used obtained from ultratech cement. The physical properties of cement such as Initial and Final setting time are 170 and 270 minutes. Amount of Fly ash content in the cement is 28%.

3.1.2. Fine Aggregate: Locally available river sand was used as fine aggregate as per IS 383: 1970 and their properties are shown in Table-1.

3.1.3. Coarse Aggregate: Crushed angular aggregate with maximum grain size of 20 mm is used as coarse aggregate as per IS 383: 1970. The properties like bulk density, specific gravity, fineness modulus and water absorption are as tabulated below.

"Table 1. Physical Properties of Fine and Coarse Aggregates"

Properties	Fine Aggregate	Coarse Aggregate
Bulk Density (kg/m^3)	1.23	1.34
Specific Gravity	2.56	2.74
Fineness Modulus	3.20	4.50
Water Absorption (%)	1.4	0.90

3.1.4. Water: Fresh portable water, which is free from acid and organic substance, is used for mixing the concrete.

3.1.5 Glass Fiber Reinforced Polymer: Table 2 and Table 3 shows the properties of the Glass fiber reinforced polymer and Epoxy resin respectively given by the manufacturer.

"Table 2. Properties of Glass Fiber Reinforced Polymer"

Thickness per ply (t_f)	0.358 mm
Ultimate tensile strength (f_{fu})	2300 Mpa
Rupture strain (ε_{fu})	0.045 mm/mm

Modulus of elasticity (E_f)	76000 N/mm^2

"Table 3. Properties of Epoxy Resin"

Aspect	Free flowing liquid
Mixed density	1.16 kg/litre
Volume solids	100%
Mixing ratio, By weight	Part A: Part B = 100: 34.5
Consumption	0.4 to 1.0 kg/m^2
Pot life	65 minute at 30°c
Tensile strength	45 N/mm^2

3.2. Mix Proportions and Mix Details:

Concrete mix design is carried out in this investigation as per IS 10262: 2009 for M-25 and M-40 grade of concrete.

"Table 4. Mix Design Proportions for M-25 Grade"

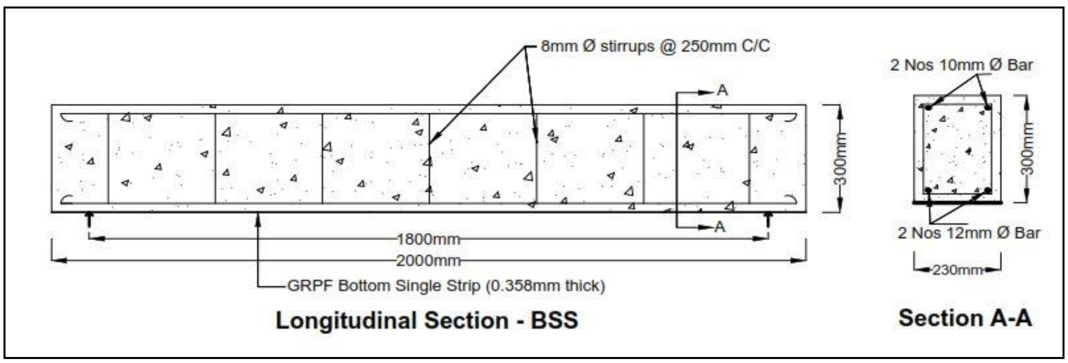
Volume of Concrete	Cement	Water	Fine Aggregate	Coarse Aggregate
By Weight (kg/m^3)	394.32	197.16	669.53	1121.8
By Volume	1.00	0.50	1.70	2.85

"Table 5. Mix Design Proportions for M-40 Grade"

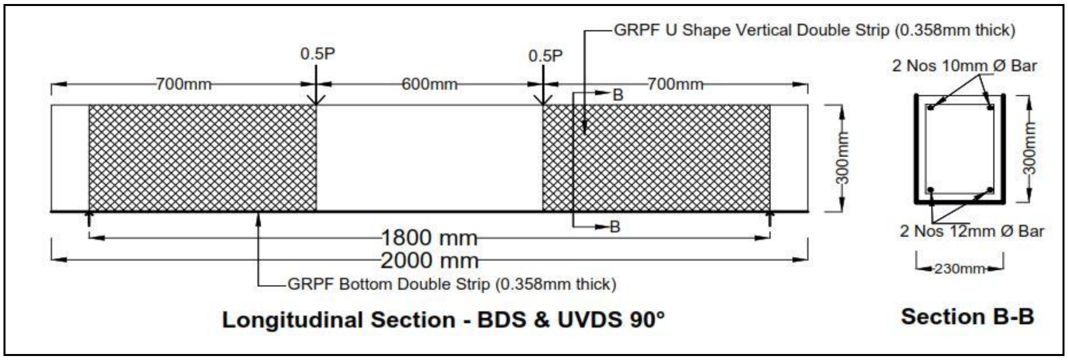
Volume of Concrete	Cement	Water	Fine Aggregate	Coarse Aggregate
By Weight (kg/m^3)	425	170	635.62	1160.41
By Volume	1.00	0.40	1.49	2.73

3.3 Test Set Up

The flexure strength of the concrete is determined according to Indian Standard 516:1959. The beam is 2000 mm long, with a cross-section of 230mm x 300mm. The bottom reinforcement of the beam is 2-12 mm diameter and 2-10 mm diameter bars are provided at top, while 8 mm diameter stirrups @ 250 mm c/c are provided as shown in Figure 1. Conceptual two point load loading pattern and support condition for the beam is shown in figure 2.



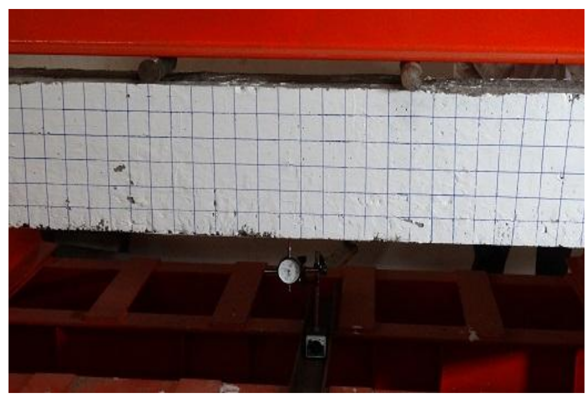
"Figure 1. Typical Details of Test Beam"



"Figure 2. Details of Loading and Support Condition"

The tests are carried out at room temperature in concrete laboratory with the loading frame of capacity 50 tons. The testing arrangement is shown in figure 3. Two point loads are applied on all beams of span 2m through hydraulic jack. The beams are suitably instrumented for measuring mid span deflection with dial gauge as shown in figure 4.

"Figure 3. Experimental Setup"



"Figure 4. Arrangement of Dial Gauge at Mid-span"

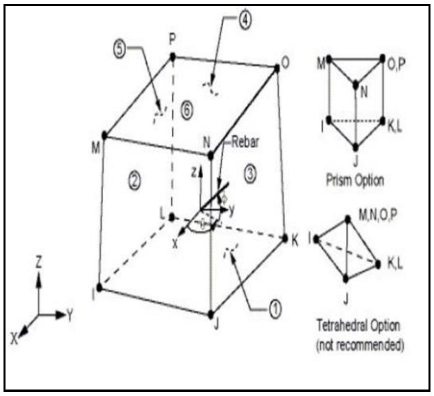
IV. ANALYTICAL INVESTIGATION

All the proposed six beams are modelled and analyzed using ANSYS software. In the software unique element needs to be used for the particular physical property and its material type. The physical properties are characterized by assigning the real constants and material type through the material property module. Different elements their real constants and material properties used in developing the model are given in table 6, 7 and 8 respectively. The conceptual type of elements for concrete, steel and FRP composites of the software are shown in figure 5, 6 and 7 respectively.

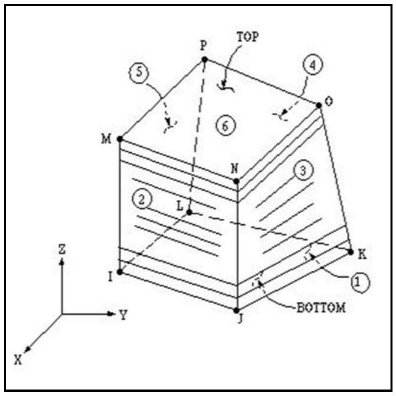
"Table 6. Material and Element Types in ANSYS"

Element Type	ANSYS Element
Concrete	Solid 65

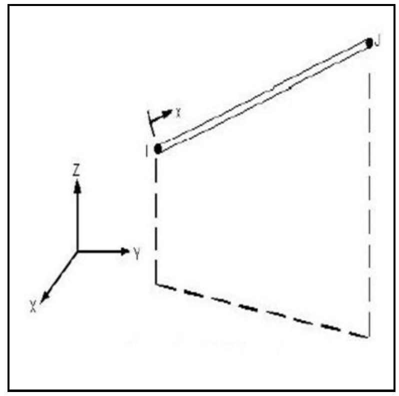
Steel Reinforcement	Link 8
FRP Composites	Solid 46



"Figure 5. Solid 65 Element"



"Figure 6. Solid 46 Element"



"Figure 7. Link 8 Element"

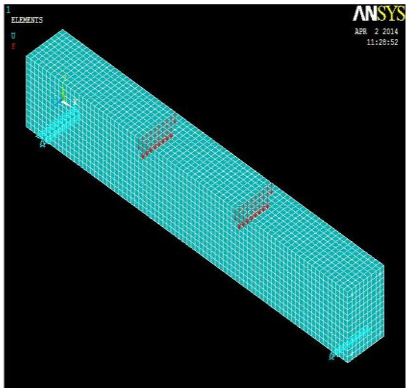
"Table 7. Real constant for beam model"

Set No	Element Type	Constants			
		Properties	Real Constants		
			Rebar 1	Rebar 2	Rebar 3
1	Solid 65	Material Number	0	0	0
		Volume Ratio	0	0	0
		Orientation Angle	0	0	0
		Orientation Angle	0	0	0
2	Solid 46	Number of Layers	1		
		Layer Symmetry Key	0		
		First Layer for Output	0		
		Second Layer for Output	0		
		Location of Reference Plane	0	1	2
			Midplane	Bottom	Top
2	Link 8	Cross section area (mm^2)	113.09		
		Initial Strain	0		
3	Link 8	Cross section area (mm^2)	78.540		
		Initial Strain	0		
4	Link8	Cross section area (mm^2)	50.265		
		Initial Strain	0		

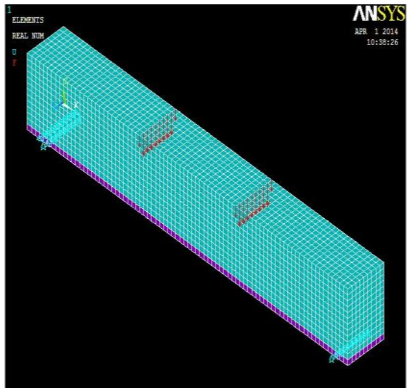
"Table 8. Material Properties for Reinforced Concrete Beam"

Material Model Number	Element Type	Material Properties					
		M – 25 Grade Concrete			**M – 40 Grade Concrete**		
1	Solid 65	Linear Isotropic			Linear Isotropic		
		EX	25000	N/mm^2	EX	31630	N/mm^2
		PRXY	0.2		PRXY	0.2	
		Multilinear Isotropics			Multilinear Isotropics		
		Point	Strain (mm/mm)	Stress (N/mm^2)	Point	Strain (mm/mm)	Stress (N/mm^2)
		1	0.0003	7.5	1	0.00038	12
		2	0.00054	12.58	2	0.0006	17.94
		3	0.00124	22.39	3	0.0013	32.36
		4	0.00184	24.91	4	0.0019	38.08
		5	0.00237	25	5	0.00243	40
		Concrete			Concrete		
		Open Shear Transfer Coef.		0.3	Open Shear Transfer Coef.		0.3
		Close Shear Transfer Coef.		1	Close Shear Transfer Coef.		1
		Uniaxial Cracking Stress		3.58	Uniaxial Cracking Stress		3.58
		Uniaxial Crushing Stress		-1	Uniaxial Crushing Stress		-1
2	Solid 46	Linear Isotropic			Linear Isotropic		
		EX	76000	N/mm^2	EX	76000	N/mm^2
		PRXY	0.28		PRXY	0.28	
3	Link 8	Linear Isotropic			Linear Isotropic		
		EX	200000	N/mm^2	EX	200000	N/mm^2
		PRXY	0.3		PRXY	0.3	
		Bilinear Isotropics			Bilinear Isotropics		
		Yield Stress	415	N/mm^2	Yield Stress	415	N/mm^2
		Tung modulus	25	N/mm^2	Tung modulus	40	N/mm^2

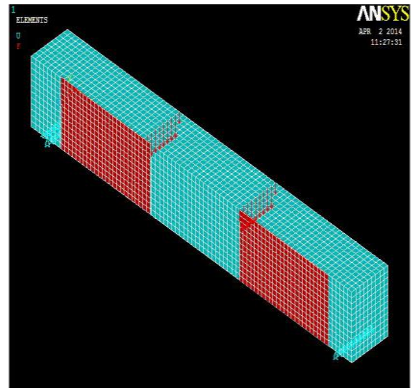
A finite element analysis requires meshing of the model. In other words, the model is divided into a number of small elements. The bond strength between the concrete and steel reinforcement should be considered. To provide the perfect bond, the link element for the steel reinforcing is connected between nodes of each adjacent concrete solid element, so the two materials shared the same nodes. The same approach is adopted for Fiber Reinforced Polymer composites. Meshing, Load and boundary conditions for control beam (CB), Bottom Single Strip beam (BSS) and Bottom Double Strip with U Shaped Vertical Double Strip Beam (BDS & UVDS 90^0) are shown in figure 8, figure 9 and figure 10 respectively.



"Figure 8. CB"



"Figure 9. BSS Beam"



"Figure 10. BDS & UVDS 90º Beam"

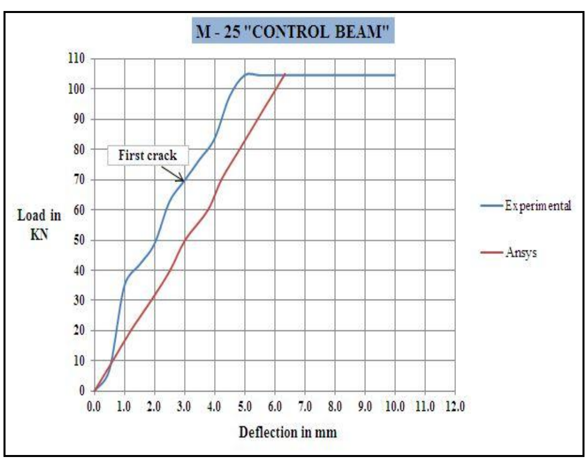
The Finite Element analysis of the model is set up to examine the behavior of load vs deflection and crack pattern of the beam. The Solution Controls command dictates the use of a linear or non-linear solution for the finite element model. The tolerance value of 0.001 is used for both force and displacement during the nonlinear solution for convergence. A small criterion must be used to capture correct response. This criterion is used for the remainder of the analysis.

V. RESULTS AND DISCUSSIONS

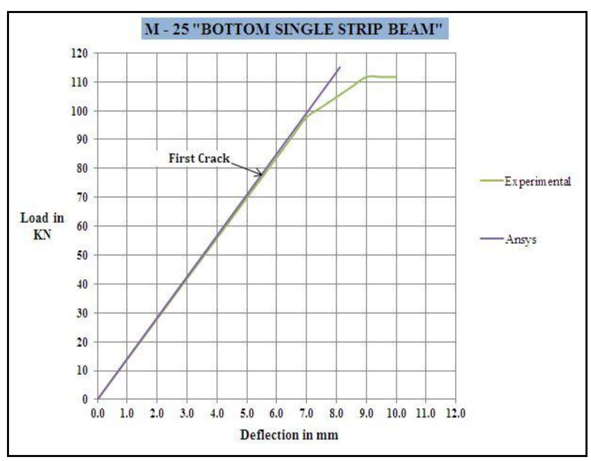
The objective was to get the load vs deflection behavior and crack pattern from the experimental work and to model same in the finite element software. Experimental and analytical results of both the observational parameters are compared in the following sections.

5.1 Load Deflection Curves:

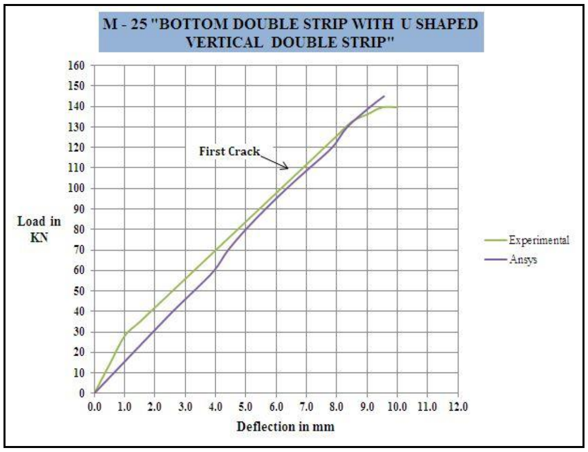
Similar pattern of the Load-deflection behavior is observed in the experimental and analytical approach. The results are overlapped in the graphical form as shown in Figure 11 to 16.



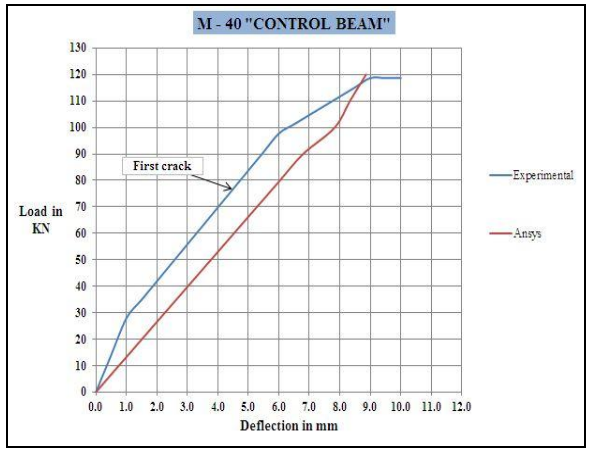
"Figure 11. Load vs Deflection curve for CB - M25"



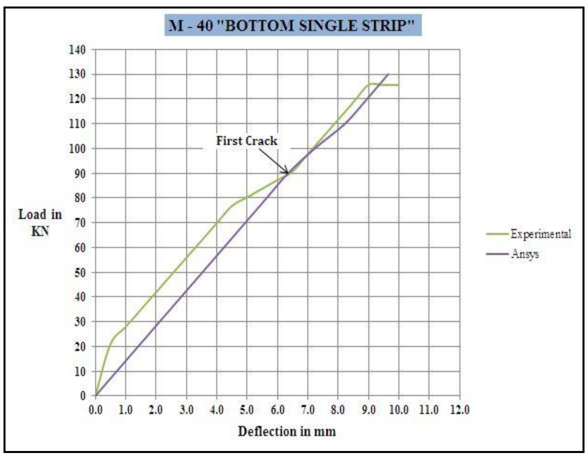
"Figure 12. Load vs Deflection curve for BSS Beam - M25"



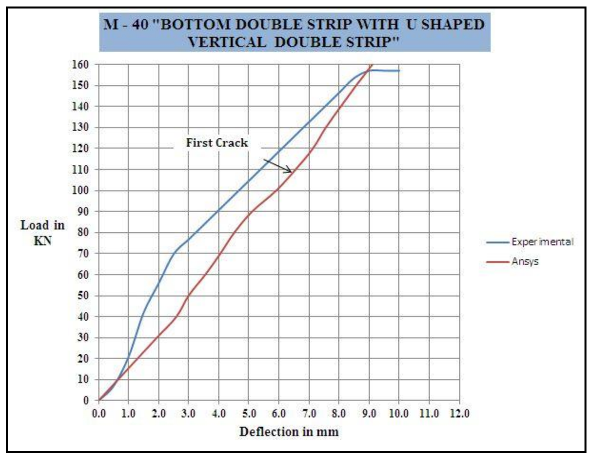
"Figure 13. Load vs Deflection curve for BDS & UVDS 90º Beam - M25"



"Figure 14. Load vs Deflection curve for Control Beam - M40"



"Figure 15. Load vs Deflection curve for BSS Beam - M40"

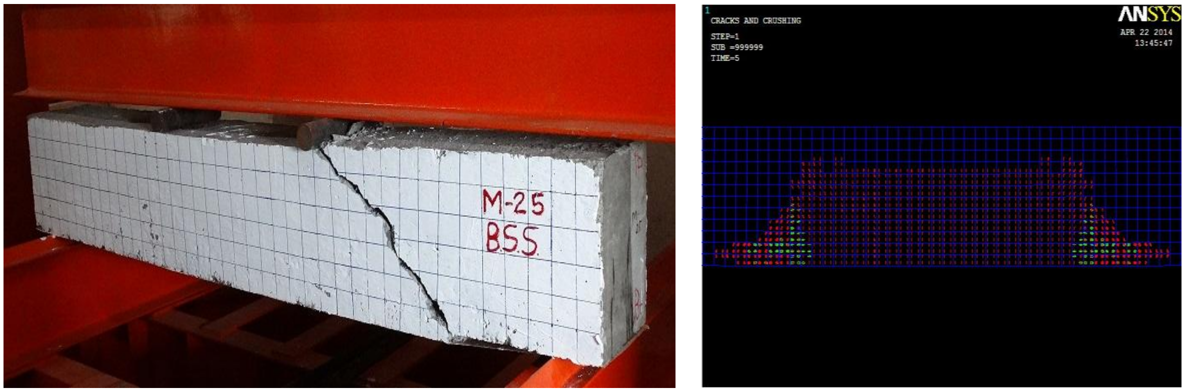


"Figure 16. Load vs Deflection curve for BDS & UVDS 90º Beam - M40"

5.2 Crack Pattern:

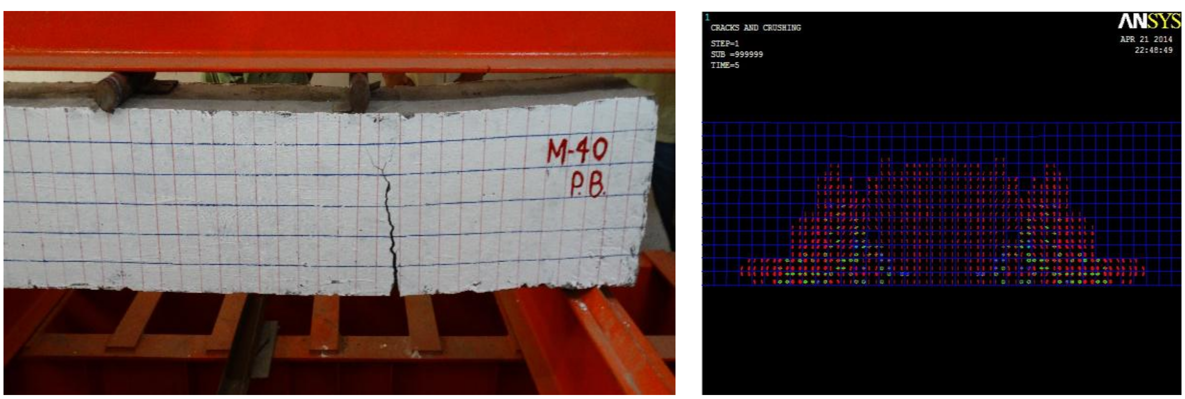
The crack patterns developed in the finite element model have shown good agreement with the actual patterns observed in the experimental investigation for all the beams. All the experimental and analytical crack patterns are shown in figure 17 to 22.

"Figure 17. Experimental and Analytical Crack pattern in Control Beam - M25"

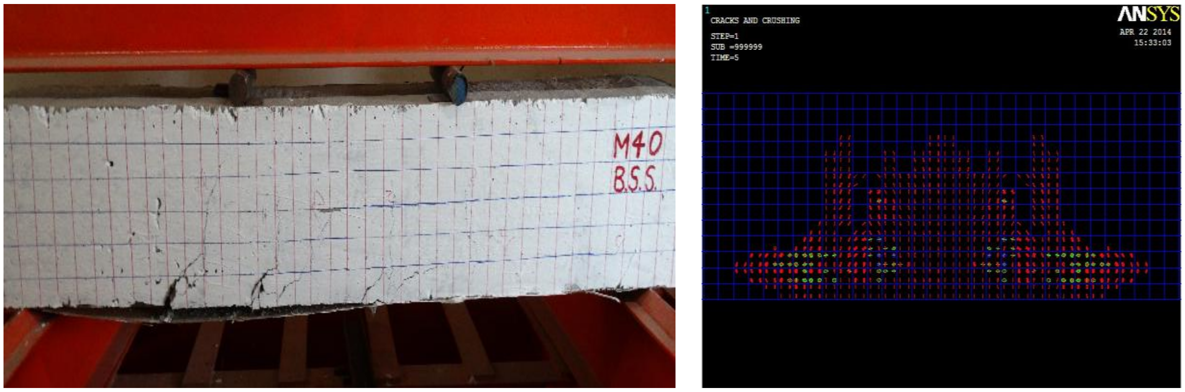


"Figure 18. Experimental and Analytical Crack pattern in Bottom Single Strip Beam - M25"

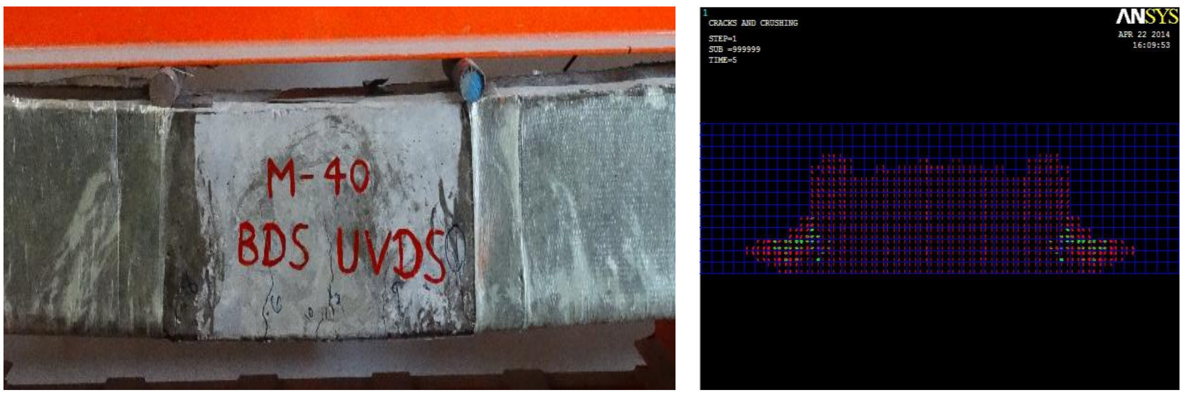
"Figure 19. Experimental and Analytical Crack pattern in Bottom Double Strip U Shaped Vertical Double Strip Beam - M25"



"Figure 20. Experimental and Analytical Crack pattern in Control Beam – M40"



"Figure 21. Experimental and Analytical Crack pattern in Bottom Single Strip Beam – M40"



"Figure 22. Experimental and Analytical Crack pattern in Bottom Double Strip U Shaped Vertical Double Strip Beam – M40"

5.3 Ultimate Load:

The flexural strength of the control beam is improved by strengthening pattern in two stages in the form of BSS and BDS & UVDS 90°. The ultimate load and accordingly percentage increase in flexural capacity are tabulated in below Table 7 for experimental and analytical investigations.

"Table 9. Comparison of Ultimate Loads for all Beams"

Sr. No.	Grade of Concrete	Strengthening Scheme	Ultimate load (kN)		Percentage Increase in Flexural Capacity	
			Experimental	Analytical (ANSYS)	Experimental	Analytical (ANSYS)
1	M25	Control Beam	104.55	105	-	-
2		BSS Beam	111.68	115	6.82	9.52
3		BDS & UVDS 90° Beam	139.60	145	33.52	38.09
4	M40	Control Beam	118.66	120	-	-
5		BSS Beam	125.64	130	5.88	8.33

6		BDS & UVDS 90° Beam	157.05	165	32.35	37.50

VI. CONCLUSION

The types of failure of CB, BSS and BDS & UVDS 90° occurred as per planned approach only those are flexural, shear and again flexural. This provides the confidence over the material as well as strengthening pattern. The experimental failure load is 20.75% and 16.26% higher than the design load in case of Control beam, 13.42% and 9.32% in case of Bottom single strip beam and 12.80% and 16.08% in case of Bottom Double Strip Beam with U Shaped Vertical Double Strip Beam for M 25 and M40 grade of concrete respectively. Load vs. Deflection behavior is almost similar in experimentally & analytically for all beams. Crack pattern developed in the analytical models are also similar to the experimental. The final loads from the finite element analysis are higher than the ultimate loads from the experimental results.

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