Effect of Different Strengthening Ways on Rc Beams Using Gfrp, Cfrp and Ultra High Strength Concrete

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Abstract. A new type of cement mix called Ultra High Strength Concrete (UHSC) was employed for making weak RC beams stronger. Other retrofitting methods like GFRP and CFRP were also tried, and each one has its own good and bad sides. To keep the study fair, same ingredients and same process were followed for all the beams. The behavior of the beams after strengthening was also checked using finite element analysis (FEA). The results from computer model matched well with the lab test results. The cracks, damaged areas and crushing of concrete shown in simulation were almost same as what happened during testing, so the FEA model was quite accurate. It was seen that the main failure of retrofitted beams was still like normal RC beams, mainly flexural failure where steel starts yielding first and then concrete crushes. So the way of failure did not change much, but the strength and ductility improved clearly. From the whole study it can be said that UHSC is a very good method to retrofit damaged RC beams. It avoids many problems that come with steel plates or FRP laminates. Beams retrofitted with UHSC not only become stronger but also show more ductility and better performance in long run.

Keywords: Reinforced concrete beams, Retrofitting, Ultra High Strength Concrete (UHSC), GFRP, CFRP, Flexural strengthening, Finite Element Analysis (FEA), Structural performance, Ductility, Crack behavior

1. Introduction

Taking care, repairing and retrofitting of structures is one of big issues in building technology work. Many buildings and bridges made in past with old design codes are not safe as per new standards [1]. Fully replacing them needs huge money and time, so strengthening is the better and practical option to improve load carrying and also to increase service life [2]. Because of early damage and deterioration in many structures, different strengthening methods have been studied [3]. The main challenge is to pick a method that not only makes the structure stronger but also easy to construct, does not disturb building use too much, and stays in budget [4]. Strengthening may be needed for many reasons like poor design, material aging, more load demand etc. Among different methods, FRP systems are now popular since they

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can be used even in places where normal strengthening methods are not possible or practical [5].

1.1 Objectives Of Research

The central intent is to check how effective FRP laminates and Ultra High Strength Concrete (UHSC) strips are when used for strengthening the bending and shear performance of concrete beams. To reach this aim, the work was carried out in following steps

- Checking and evaluating the load-deformation behavior of concrete
- Testing of normal RC beams without strengthening (both flexural and shear weak)
- Testing of RC beams that were undamaged but strengthened for flexural deficiency
- Structural performance evaluation of unblemished RC members augmented via hybrid laminar composites
- Testing of already damaged RC beams (flexural and shear weak) after strengthening
- Doing numerical analysis on strengthened beams

2. Materials And Methods

In this study, both Normal Strength Concrete (NSC) and Ultra High Strength Concrete (UHSC) were manufactured, and their mix proportions were determined after following suitable procedures and conducting several experiments [6]. For NSC the mix was designed using IS code, while for UHSC the design was done based on limited literatures available and repeated trial mixes. The NSC mix had the usual materials like Ordinary Portland cement (OPC), granular coarse aggregates, fine granular aggregates, and mixing water [7]. One important point is that UHSC does not use coarse aggregate, which makes big difference in its micro structure and performance [8]. The steel fibres in the mix give extra strength and also make the concrete more ductile, sometimes even working as replacement of normal mild steel reinforcement. The details of material properties and the exact mix proportions are given in this chapter [9]. From the sustainability point of view, it is also seen in studies that making FRP materials needs less energy compared to many traditional materials Table 1. Also, because FRP is light in weight, transporting it has very small effect on environment [10,11].

2.1 MIX PROPORTION

Table 1. Mix proportions for M20 grade concrete as per IS 10262 -2009

Description	Water	Cement	Fine Aggregate	Coarse Aggregate
Quantity (kg/m^3)	186	413.3	666.17	1138.6
Ratio	0.45	1	1.61	2.755

REINFORCEMENT DETAILS OF BEAM

The reinforcement details of a typical under reinforced RC beam (flexure) are depicted in the Fig.1, 2 and Table 2 below.

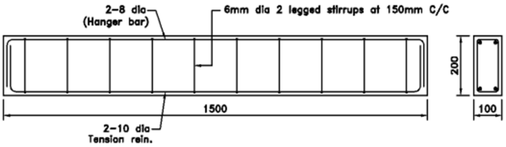

Fig.1. Reinforcement Details of Beam (Flexure)

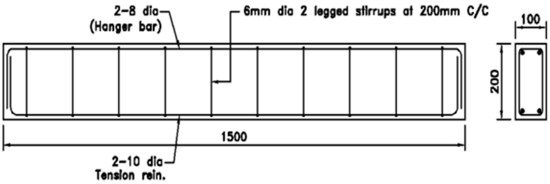

Fig.2. Reinforcement Details of Beam (Shear)

Table 2 Tests made on Concrete specimens

Specimen	7 days Test Result	28 days Test Result
Cube compressive strength	9.46 N/mm^2	27.6 N/mm^2
Prism flexural strength	2.83 N/mm^2	6.2 N/mm^2
Cylinder split tensile strength	1.02 N/mm^2	2.4 N/mm^2

2.2 Experimental Investigation

In this study, experimental work was done to check the mechanical load-transfer behavior under bending moments and shear stresses in RC beams. The program was planned carefully to understand how retrofitted beams behave compared to normal onesSome RC beams have been tested to failure and are referred to as control beams. Other beams were either pre-damaged to varying degrees or left unharmed before reinforcement.

Fig.3. Casting RC beams

Loading pre-damaged beams was done up to 70%, 80%, and 90% of the average failure load of control beams, respectively. This was done to create flexural and shear cracks. Following that, these beams were strengthened with GFRP and CFRP laminates in various wrapping methods, as well as UHSC strips inserted at the tension face.They were then tested under four-point bending. For undamaged beams, strengthening was done using GFRP and CFRP laminates at the tension zone. Some beams were also strengthened with hybrid laminates (one layer GFRP and one layer CFRP) with different wrapping patterns, and then tested again under four-point bending.The process of typical casting of RC beams used in this work is shown in Fig.3.

2.3 Preparation of UHSC Wrap Sheet

The UHSC retrofitting strips were made by casting them in steel moulds of size 1000 mm long and 100 mm wide, with a 10 mm raised edge and an oiled base. After casting, the strips were kept in the moulds for about 48 hours for curing before they were removed.

To ensure a strong adhesion between the UHSC strips and the damaged beams, all contact surfaces were thoroughly cleaned and roughened. An angle grinder was used to carve a grid of grooves about 3 mm deep at 50 mm intervals on the surface of damaged beams. The UHSC strips were then fixed to these prepared surfaces using a thixotropic epoxy adhesive (BASF-Master Brace ADH 2200). The materials used and the steps in making UHSC sheets are shown in Fig.4.

Fig.4. Preparation of UHSC wrap sheet

Testing of Control Beam (Flexure)

In this investigation, Fig.5 shows, three normal strength concrete beams were evaluated till failure and preserved as control beams. These were utilized to compare the findings to beams modified with GFRP, CFRP, and UHSC strips.

It was seen that the beam behaved almost linear elastic until the first crack appeared, which happened at around 35 kN load. After this point, several cracks started to form until the steel began to yield at about 70 kN. The final failure took place when the concrete got crushed under the load, at nearly 80 kN.

At failure, all beams had a maximum crack depth of about 170 mm. Almost all of the control beams failed in flexure. A few shear cracks were discovered during loading, but they had no bearing on the beams' eventual failure.

Fig.5 Control beam (flexure) testing under four-point bending

2.4 TESTING OF CONTROL BEAM (SHEAR)

Three conventional-grade concrete (NSC) beams were subjected to monotonic loading as control specimens for comparison with GFRP- and CFRP-retrofitted beams Fig.6. Linear-elastic response prevailed up to the first flexural-shear crack at ~30 kN, followed by progressive micro-cracking. Ultimate failure occurred due to concrete crushing at ~65 kN. All control beams exhibited shear-dominated failure, with inclined cracks governing structural collapse, highlighting the critical role of shear stress redistribution in unstrengthened members.

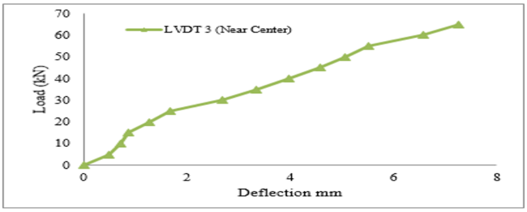

Fig.6. Approximate average load versus deflection (Shear)

3. Discussion Of Results On Strengthened Undamaged Beams (Flexure)

Three of the six intact beams were strengthened by wrapping GFRP laminates in the tension zone, while the other three were strengthened with CFRP laminates. The beams were tested for ultimate load-carrying capacity after being wrapped in carbon fiber reinforced polymer and glass fiber reinforced polymer along their bottom length.

Although the major goal of this study is to repair and rehabilitate RC beams, tests on undamaged beams were conducted to examine the behavior of the FRP laminates. It was observed that no debonding of the laminates occurred until the specimens failed. Test results indicate that all strengthened undamaged beams exhibited higher strength compared to control beams. At lower loads, the beams behaved in a quasi-linear elastic manner, with no development of microcracks.

Fig.7,8 show approximate average deflections of the reinforced beams. Also shows a comparison of the ultimate loads of enhanced undamaged beams against control beams.

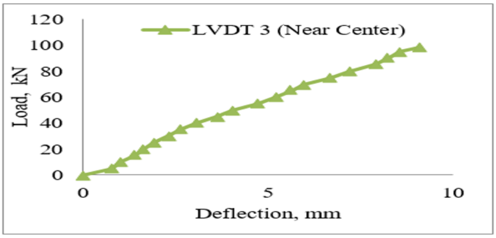

Fig.7. Approximate average load versus deflection

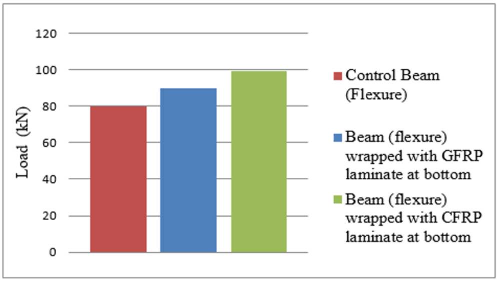

Fig.8. Ultimate loads of strengthened undamaged beams were compared to control beams (flexure).

The control beam had an ultimate load of 80 kN. The beams that were strengthened directly without any pre-damage with CFRP laminates had an ultimate load of 99 kN. Thus, the increase in load carrying capability is around 19%.Also the beams strengthened directly with GFRP laminates, they carried load of 90 kN, which is about 11% more than control beam. Nine beams were tested after being strengthened with hybrid FRP layers, first layer being GFRP and then CFRP laminates on top in three different wrapping ways. Three beams had wrapping at the bottom (tension zone), three beams had sides only wrapped, and the last three beams had ‘U’ shaped wrapping. It was discovered that the 'U' design produced more strength than the other two methods. In general, hybrid beams were stronger than control beams. They behaved almost linear elastic at first. As the load went up, major flexural cracks started going towards the top (compression side) and the crack widths got bigger. No de-bonding was seen between the RC beam and the laminates. The adhesive used to stick the laminates helped a lot to avoid de-bonding, also the careful wrapping work played a part. The thickness of the laminates was determined by previous research and literature Fig.9,10 shows a comparison of ultimate loads for hybrid laminate-strengthened beams and control beams.

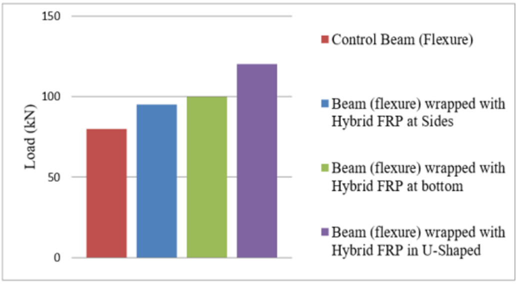

Fig.9. Comparison of the ultimate loads of undamaged beams enhanced utilizing hybrid laminates with the control beam (flexure).

3.1 Pre-Damaging The Beam (Flexure) Up To 70% Of Pmax

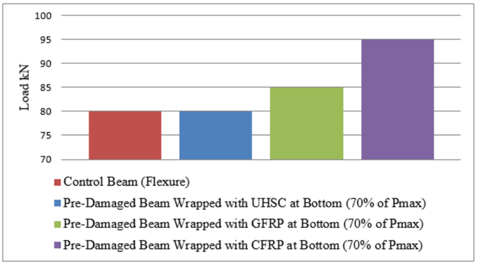

Fig.10. Ultimate loads of pre-damaged strengthened beams (flexure) and control beam (flexure)

3.2 PRELOADING (70%) OF SHEAR DEFICIENT BEAMS

Shear deficient beams were preloaded up to 70% and then strengthened using GFRP with different wrapping patterns. Fig.11, 12 shows a comparison of ultimate loads for strengthened beams wrapped in different styles.

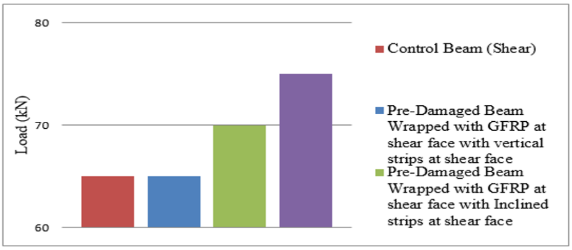

Fig.11. Comparison of Ultimate Beam Loads (Shear). Pre-damaged beam (flexure) encased in GFRP with a control beam (shear) (70% of Pmax)

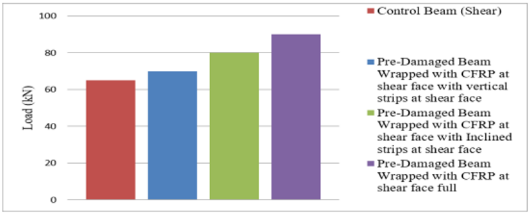

Fig.12. Comparison of ultimate loads of beams (shear). Pre-damaged beam (flexure) encased in CFRP with a control beam (shear) (70% of Pmax)

3.3 TESTING FOR 80% OF ULTIMATE LOAD CARRYING CAPACITY (Pmax)

Nine beams were pre-damaged to 70% Pmax and then reinforced using various laminates. In the tension zone, three beams were strengthened using GFRP laminates, three with CFRP laminates, and three with UHSC laminates. The GFRP beams exhibited only a slight gain in strength, however the CFRP beams had a significant increase of approximately 15 kN over the control beam. The UHSC strengthened beams reached the needed strength and also behaved ductile before failing. No peeling of laminates was seen while loading. The UHSC layer broke along with the beam at the failure line. The main failure mode of the retrofitted beams was like normal RC beams – flexural failure with steel yielding first and then concrete crushing. The pre-loaded and strengthened beams had stiffer load-deflection curves than the control beams. The thickness of UHSC strip used was enough for the beams to get back their original behavior. Fig 13,14,15 shows a comparison of beams' ultimate loads. A clear increase in strength was seen in the beams wrapped in ‘U’ pattern. These beams behaved more ductile compared to control beams. UHSC laminates of 10 mm thickness gave good improvement in strength and also showed strong bond with the concrete surface. All preloaded and retrofitted beams showed essentially identical inelastic deformation to control beams, with no significant loss of ductility. The maximum load carrying capacity of preloaded and retrofitted beams was somewhat greater than the average maximum load of control beams. No failure of sheets or delamination was seen, which shows that the member behaved as one single unit.

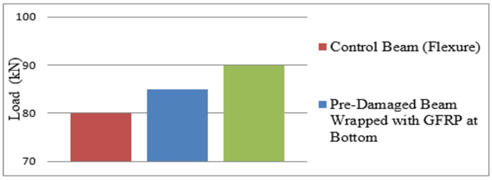

Fig.13 Comparison of Maximum loads of Beam (flexure) before damaged Beam wrapped with the GFRP with CB(flexure) - (80% of Pmax)

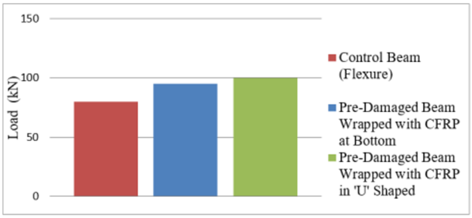

Fig.14 Comparison of Maximum loads of Beam (flexure) Pre-Damaged Beam wrapped using CFRP with CB (flexure) - (80% of Pmax)

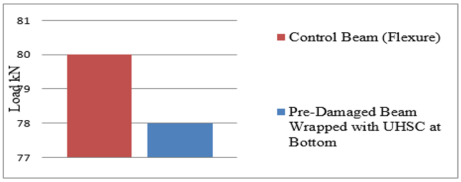

Fig.15 Comparison of Maximum loads of Beam (flexure) Pre-Damaged Beam wrapped using UHSC with CB (flexure) - (80% of Pmax)

3.4 TEST RESULT OF 80% PRELOADED SHEAR BEAMS

Six shear deficient beams were taken for the study. After pre-damaging up to 80% of Pmax they were strengthened at the sides with GFRP laminates and CFRP laminates. The pre-damaging made the beams crack and also disturbed the internal bond of the material. Many visible cracks were formed because of the pre-loading. After strengthening, both sets of beams showed improvement in strength. The beams with GFRP laminates reached almost the same strength as control beams, while the beams with CFRP laminates showed about 7% more strength compared to the control beams. Fig .16 illustrates that the average ultimate loads of retrofitted beams compared to control beams.

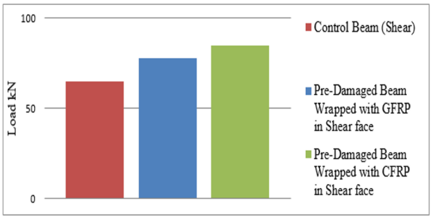

Fig.16 Comparison of Ultimate loads of Beam (Shear) Pre-Damaged Beam wrapped with GFRP with Control beam (Shear)- (80% of Pmax)

3.5 TESTING 90% OF ULTIMATE LOAD CARRYING CAPACITY (Pmax)

A study was done on nine beams after pre-damaging up to 90% of Pmax. Out of these, three beams were ‘U’ wrapped with GFRP laminates, another three beams were ‘U’ wrapped with CFRP sheets, and the remaining were strengthened with UHSC layer at the bottom. After loading the beams close to failure, it was seen that strengthening with both GFRP and CFRP was satisfactory. All preloaded and retrofitted beams have a slightly higher maximum load carrying capacity than control beams Fig. 17. The beams with UHSC also reached almost the same strength as control beams and then failed.

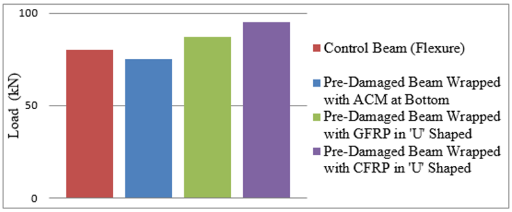

Fig.17 Comparison of Maximum loads of Beam (flexure) Pre-Damaged Beam with CB (flexure)- (90% of Pmax)

3.6 TEST RESULT OF 90% PRELOADED SHEAR BEAMS

The adhesive used was very effective and proper application helped to get a good bond with the concrete surface. At 90% of Pmax almost full damage was done, and then strengthening was carried out by ‘U’ wrapping with GFRP and CFRP. Both types of sheets helped the beams to gain good load carrying capacity. Fig 18 compares the ultimate loads of the strengthened beams to the average ultimate loads of the control beams.

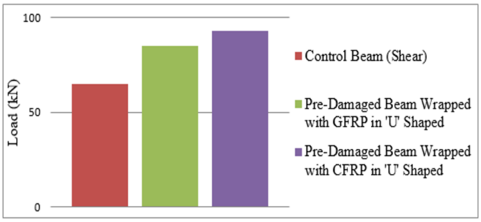

Fig. 18 Comparison of Final maximum loads of Beam (Shear) Pre-Damaged Beam with CB - (90% of Pmax)

4. Finite Element Analysis Of Rc Beams Fortified With Gfrp, Cfrp, And Uhsc

Modeling the behavior of reinforced concrete is always difficult in structural engineering due to the complicated nature of concrete and steel. The aim of this numerical study is to use nonlinear finite element analysis (FEA) to see how close we can get to the experimental results. In this, concrete and steel are taken as separate materials with their own models and then combined together to behave like a single RC beam.

Concrete Beam

In ABAQUS, the geometry of the beam was created and material properties were given. The beam was modeled to same size as in the lab test – 1500 mm length, 200 mm depth and 100 mm width. The input units were kept uniform, like length in mm, density in N/mm^3, modulus in N/mm^2, yield stress in N/mm^2, strain in mm/mm and so on. A typical model of concrete beam in ABAQUS is shown in Fig. 5.7.

Load and Boundary Condition

Loading was given as pressure load and downward displacement using four-point bending set-up with steel loading plate. Simply supported boundary condition was used, with supports kept at 150 mm away from both ends of the beam. One end was taken as hinge (U1=0, U2=0) and the other end as roller (U2=0), so that it behaves like a simply supported beam.

Analysis, Result and Discussion

The following situations were investigated:

- Controlled RC and shear beams.
- • U-shaped GFRP strengthened the RC beam (flexure) by up to 80% after preloading.

- Strengthened RC beam (flexure) with bottom GFRP after preloading up to 80%
- Strengthened shear deficient RC beam with side GFRP after preloading up to 80%
- U-shaped CFRP was used to strengthen the RC beam (flexure) after up to 80% preload.
- Used bottom CFRP to strengthen RC beam (flexure) after up to 80% preload.
- Strengthened shear deficient RC beam with side CFRP after preloading up to 80%
- Strengthened RC beam (flexure) with bottom UHSC after preloading up to 80%

For each of these, nonlinear finite element analysis was done. For strengthened beams, two steps were taken – first simulating pre-damage by loading beams of about 80% of average ultimate load of CB, and second analyzing the same beams after strengthening with GFRP, CFRP or UHSC. The models considered nonlinear behavior of concrete, steel and UHSC, along with damage parameters and failure conditions.

5. Load-Deflection Behavior

The predicted load–deflection curves were compared with the experimental results and are shown in the figures below. Table 3 includes a further comparison of the expected load and deflection values to the test findings.

Table 3 Comparison of load deflection responses

Specimen	**Finite element analysis**		**Experimental**	
	Maximum Load (kN)	**Deflection, mm**	**Maximum Load (kN)**	**Deflection, mm**
Control flexure	**75**	**7.98**	**80**	**6.81**
Shear deficient	**62.2**	**6.59**	**65**	**7.24**
Flexure strengthened with U-shaped GFRP	**96**	**7.61**	**100**	**8.47**
Flexure strengthened with U-shaped CFRP	**109**	**8.46**	**100**	**8.47**
Flexure strengthened with GFRP at bottom	**99**	**6.5**	**85**	**7.3**
Flexure strengthened with CFRP at bottom	**84.35**	**8.06**	**95**	**8.49**
Flexure strengthened with UHSC at bottom	**77**	**11.2**	**78**	**15.1**
Shear deficient strengthened with GFRP at sides	**78**	**6.94**	**75**	**6.61**
Shear deficient strengthened with CFRP at sides	**89**	**9.01**	**85**	**7.86**

The max percentage difference between predicted and experimental values came around ±15%. For example, in the case of control flexure beam, the predicted max load was 75 kN with deflection 7.98 mm, while the experimental result showed 80 kN load and 6.81 mm deflection. These findings demonstrate that numerical simulations of RC beams may reproduce the behavior observed in tests and the same are illustrated below from Fig .19,20.

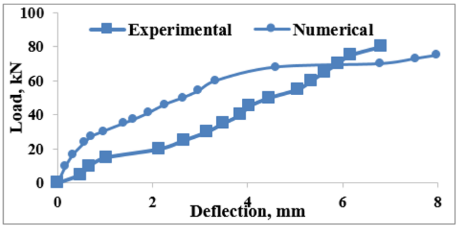

Fig .19 Load – deflection (control beam – flexure)

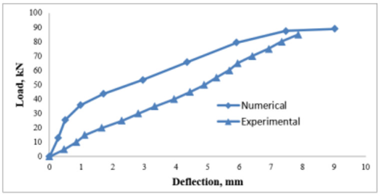

Fig 20 Load – deflection (strengthened beam shear deficient with CFRP – sides)

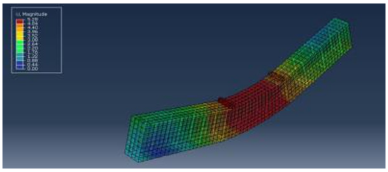

Fig. 21 Deformed shape of the Beam – control flexure

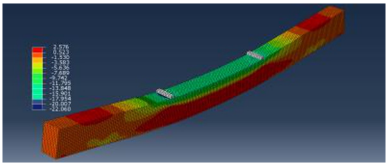

Fig. 22 Stress direction along S33 - control flexure

Meshing of Assemble

After making the beam, the RC assembly was meshed with a seed size chosen as per requirement Fig 21,22. In FE analysis, more refined mesh gives more accurate result but also takes more time to solve. Based on earlier experience and problem type, the mesh size of 10 mm was taken for concrete beam (brick elements) and rebar (truss elements). So the element length in the beam is 10 mm. The total number of elements for concrete, main reinforcement, hanger reinforcement and stirrups are taken accordingly Fig 23.

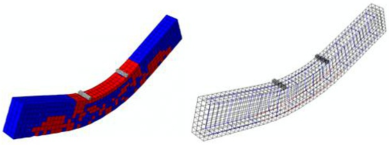

Fig.23 Steel yielding and concrete cracking

6. Summary

Nonlinear finite element analysis (FEA) was performed on RC beams both with and without strengthening. The simulation took into account the nonlinear behavior of concrete and steel. Modeling and analysis were carried out using the ABAQUS software. The concrete damage model in ABAQUS was developed to depict concrete's nonlinear behavior. Proper constraints were applied so that steel and concrete worked together as a single unit. Static nonlinear analysis was done and the results like peak load and deflection were compared with experiments. The FE results were found to be compatible with experimental data, indicating that the FE models developed are robust and reliable.

7. Conclusion

This work presented the experimental and numerical study on retrofitted RC beams using GFRP, CFRP and UHSC overlays. For the control RC flexural beams, behavior was almost elastic up to first crack at around 35 kN. Then many cracks formed, causing the steel to give at around 70 kN. The last failure occurred when concrete was crushed at 80 kN, with a maximum deflection of 6.84 mm. The crack depth at failure was approximately 170 mm. Control shear beams failed with an average load of 65 kN and maximum deflection of 7.3 mm. Strengthening with hybrid laminates (GFRP + CFRP) was done on 9 undamaged beams with three wrapping styles – bottom, sides, and U pattern. Beams strengthened at bottom reached 100 kN with deflection 9.26 mm (about 25% more than control). Beams with U wrapping failed at 120 kN with deflection 10.84 mm, and beams with side wrapping carried 95 kN with deflection 8.75 mm (about 20% gain). control, while GFRP wrapping gave about 10 kN gain. UHSC performed same as control beams but failed along the crack line. Failure mode stayed flexural – yielding of steel then concrete crushing. For shear beams pre-damaged to 70% Pmax, different wrapping patterns with GFRP and CFRP were studied.

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