CHAPTER-5

ANALYSIS OF RESULTS AND DISCUSSION

5.1. GENERAL

The study of the Structural Health Monitoring and Retrofitting of Reinforced Cement Concrete (RC) rectangular Slabs was the main objective of this research work. Therefore, to meet the Objectives set out in *Chapter-1,* an extensive experimental programme outlined in *Chapter-3* was planned. In total, eighteen slabs were cast and tested using Non-Destructive Tests (NDT) such as Rebound Hammer (RH) tests and Ultrasonic Pulse Velocity (UPV) tests were conducted. These slabs specimens were subsequently tested, retrofitted and retested to achieve the Objectives of this investigation. Retrofitting of slabs was carried out using different materials such as Glass Fibre Reinforced Polymer (GFRP), Ferrocement and Mild Steel plates. The test data so obtained had been analyzed to establish the damage index; examine the crack patterns; estimate the degree of deterioration, and to develop the load- midspan deflection curves for virgin slabs and retrofitted slabs.

The analysis of the test data for control and retrofitted slabs obtained in this investigation was compared with numerical investigation done on model slabs by using ATENA 3D software. For this purpose, the modelling of the slabs was done as per the procedure laid down in *Chapter-4* on *'Finite Element Modeling '.* The data obtained from analytical investigation was used to produce load-deflection curves. These curves have been compared with the experimental results to make the interpretations and conclusions.

5.2. NON-DESTRUCTIVE TESTING ON SLABS BEFORE LOADING

Firstly, the virgin slabs specimens S1 (2.35 x 1.75) m x 75 mm were examined by NDT methods of RH and UPV and the corresponding readings were recorded and shown in Tables 5.1.- 5.3. for the virgin slabs S11, S12 and S13 (where S11, S12 and S13 stands for slabs specimens of size S1 and that are to be retrofitted with GFRP, Ferrocement and Mild Steel plate).

Similarly the virgin slabs specimens S2 (2.35 x 1.566) m x 75 mm were examined by NDT and the corresponding readings for the virgin slabs S2 1, S22 and S23 are listed in Tables 5.4-5.6 (where S11, S12 and S13 stands for slabs specimens of size S1 and that are to be retrofitted with GFRP, Ferrocement and Mild Steel plate).

Table 5.1: Rebound Hammer and Ultrasonic Pulse Velocity values at marked points of virgin slabs S11

Points	Average Rebound Hammer Number	Equivalent cube compressive strength (N/mm^2)	Ultrasonic Pulse Velocity (km/s)	Concrete quality grading
0	26	22.5	4.05	Good
1	29	27.0	3.75	Good
2	28	25.5	3.84	Good
3	28	25.5	4.16	Good
4	33	33.0	4.54	Excellent
5	30	28.5	3.65	Good
6	31	30.0	3.65	Good
7	28	25.5	4.28	Good
8	31	30.0	4.16	Good
9	32	31.5	3.94	Good
10	33	33.0	3.50	Good
11	27	24.0	4.54	Excellent
12	33	33.0	3.75	Good
13	30	28.5	4.05	Good
14	27	24.0	4.54	Excellent
15	27	24.0	3.84	Good
16	26	22.5	4.68	Excellent
17	33	33.0	4.68	Excellent
18	30	28.5	3.50	Good

Table 5.2: Rebound Hammer and Ultrasonic Pulse Velocity values at marked points of virgin slabs S12

Points	Average Rebound Hammer Number	Equivalent cube compressive strength (N/mm^2)	Ultrasonic Pulse Velocity (km/s)	Concrete quality grading
0	32	31.5	3.94	Good
1	28	25.5	3.57	Good
2	30	28.5	4.54	Excellent
3	29	27.0	4.41	Good
4	30	28.5	3.65	Good
5	27	24.0	3.57	Good
6	33	33.0	4.68	Excellent
7	27	24.0	4.28	Good
8	27	24.0	3.57	Good
9	26	22.5	4.54	Excellent
10	31	30.0	4.28	Good
11	33	33.0	3.69	Good
12	31	30.0	3.50	Good
13	32	31.5	4.00	Good
14	29	27.0	3.65	Good
15	29	27.0	3.75	Good
16	28	25.5	3.50	Good
17	26	22.5	3.57	Good
18	27	24.0	3.65	Good

Table 5.3: Rebound Hammer and Ultrasonic Pulse Velocity values at marked points of virgin slabs S13

Points	Average Rebound Hammer Number	Equivalent cube compressive strength (N/mm^2)	Ultrasonic Pulse Velocity (km/s)	Concrete quality grading
0	33	33.0	3.69	Good
1	28	25.5	3.94	Good
2	32	31.5	4.12	Good
3	27	24.0	3.93	Good
4	27	24.0	3.50	Good
5	26	22.5	3.50	Good
6	30	28.5	4.17	Good
7	30	28.5	3.43	Good
8	28	25.5	3.67	Good
9	28	25.5	4.26	Good
10	32	31.5	4.26	Good
11	32	31.5	3.50	Good
12	29	27.0	3.64	Good
13	26	22.5	3.62	Good
14	32	31.5	3.86	Good
15	26	22.5	3.61	Good
16	27	24.0	4.28	Good
17	27	24.0	3.50	Good
18	31	30.0	3.69	Good

Table 5.4: Rebound Hammer and Ultrasonic Pulse Velocity values at marked points of virgin slabs S21

Points	Average Rebound Hammer Number	Equivalent cube compressive strength (N/mm^2)	Ultrasonic Pulse Velocity (km/s)	Concrete quality grading
0	30	28.5	4.00	Good
1	28	25.5	3.50	Good
2	32	31.5	4.05	Good
3	26	22.5	3.75	Good
4	29	27.0	4.28	Good
5	29	27.0	3.75	Good
6	33	33.0	4.68	Excellent
7	31	30.0	4.54	Excellent
8	26	22.5	4.05	Good
9	26	22.5	3.50	Medium
10	26	22.5	3.65	Good
11	33	33.0	4.68	Excellent
12	28	25.5	4.28	Good
13	32	31.5	5.17	Excellent
14	28	25.5	3.50	Good
15	28	25.5	4.28	Good
16	29	27.0	3.94	Good
17	26	22.5	4.68	Good
18	31	30.0	3.75	Good

Table 5.5: Rebound Hammer and Ultrasonic Pulse Velocity values at marked points of virgin slabs S22

Points	Average Rebound Hammer Number	Equivalent cube compressive strength (N/mm^2)	Ultrasonic Pulse Velocity (km/s)	Concrete quality grading
0	33	33.0	4.28	Good
1	29	27.0	3.65	Good
2	31	30.0	4.62	Excellent
3	32	31.5	4.65	Excellent
4	30	28.5	4.05	Good
5	28	25.5	3.75	Good
6	29	27.0	3.84	Good
7	29	27.0	3.75	Good
8	33	33.0	4.05	Good
9	28	25.5	3.69	Good
10	30	28.5	3.69	Good
11	32	31.5	3.98	Good
12	33	33.0	3.50	Good
13	28	25.5	3.69	Good
14	33	33.0	3.67	Good
15	31	30.0	3.96	Good
16	28	25.5	3.50	Good
17	26	22.5	3.65	Good
18	32	31.5	3.75	Good

Table 5.6: Rebound Hammer and Ultrasonic Pulse Velocity values at marked points of virgin slabs S23

Points	Average Rebound Hammer Number	Equivalent cube compressive strength (N/mm^2)	Ultrasonic Pulse Velocity (km/s)	Concrete quality grading
0	28	25.5	4.12	Good
1	31	30.0	3.94	Good
2	28	25.5	3.50	Good
3	30	28.5	4.26	Good
4	32	31.5	4.07	Good
5	26	22.5	4.09	Good
6	26	22.5	3.60	Good
7	32	31.5	3.64	Good
8	31	30.0	3.53	Good
9	28	25.5	3.71	Good
10	30	28.5	3.53	Good
11	28	25.5	3.57	Good
12	29	27.0	3.88	Good
13	26	22.5	4.12	Good
14	29	27.0	3.64	Good
15	33	33.0	4.31	Excellent
16	32	31.5	3.53	Good
17	26	22.5	3.57	Good
18	28	25.5	4.12	Good

From the Tables 5.1-5.6, it was observed that the minimum equivalent compressive cube strength was 22.5 N/mm^2 against the Rebound Hammer Number 26 and the maximum equivalent compressive cube strength was 33.0 N/mm^2 against the Rebound Hammer Number 33. This indicated the sufficiently hard condition of the surface of the slab.

The dense and homogeneous stateddxc of the slabs was exhibited by the ultrasonic pulse velocity tests results. The higher velocity values of UPV tests showed that the condition of the concrete quality grading was good when the velocity was in the range of 3.5 km/s to 4.5 km/s and excellent when the velocity was more than 4.5 km/s.

5.3. LOADING TEST RESULTS BEFORE RETROFITTING

Subsequently, the slabs were intentionally damaged under uniformly distributed load in the loading arrangement of the heavy testing laboratory of Civil Engineering Department of Guru Nanak Dev Engineering College. The load was applied and the corresponding central deflection was observed at each 5 kN interval (equivalent to 1.21 kN/mm^2 for S1 slabs specimens and 1.35 kN/mm^2 for S2 slabs specimens). In all the slabs, almost uniform crack patters were observed. Some typical crack patterns obtained are shown in Fig. 5.1-5.4.

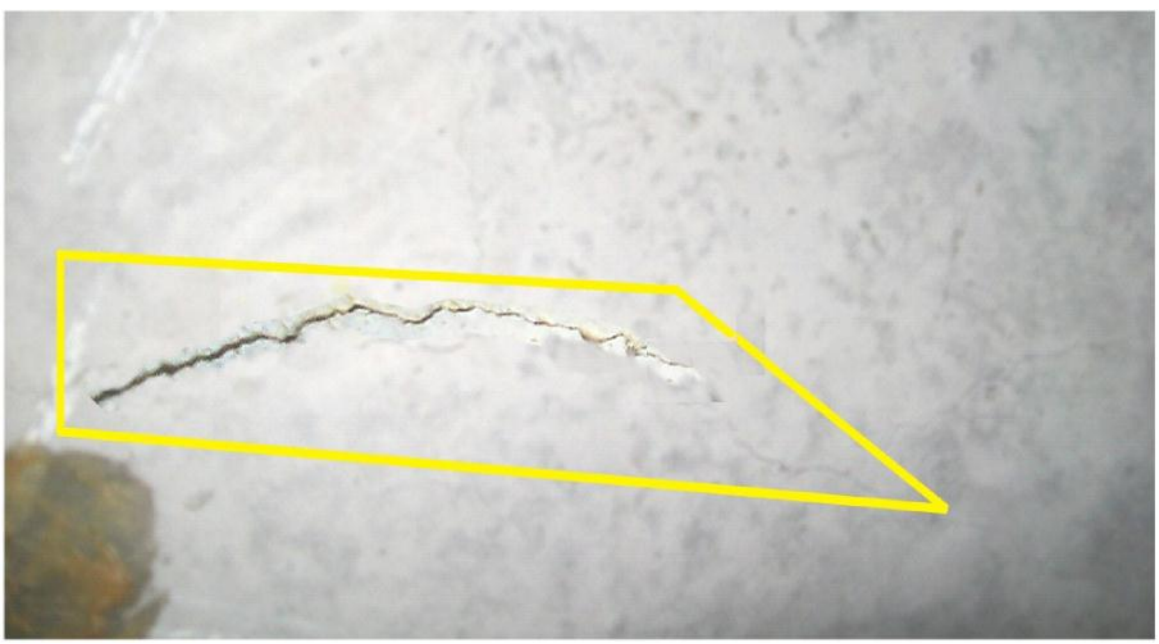

Fig. 5.1: Initiation of cracks in slabs (typical)

Fig. 5.2: Cracks in slabs (typical)

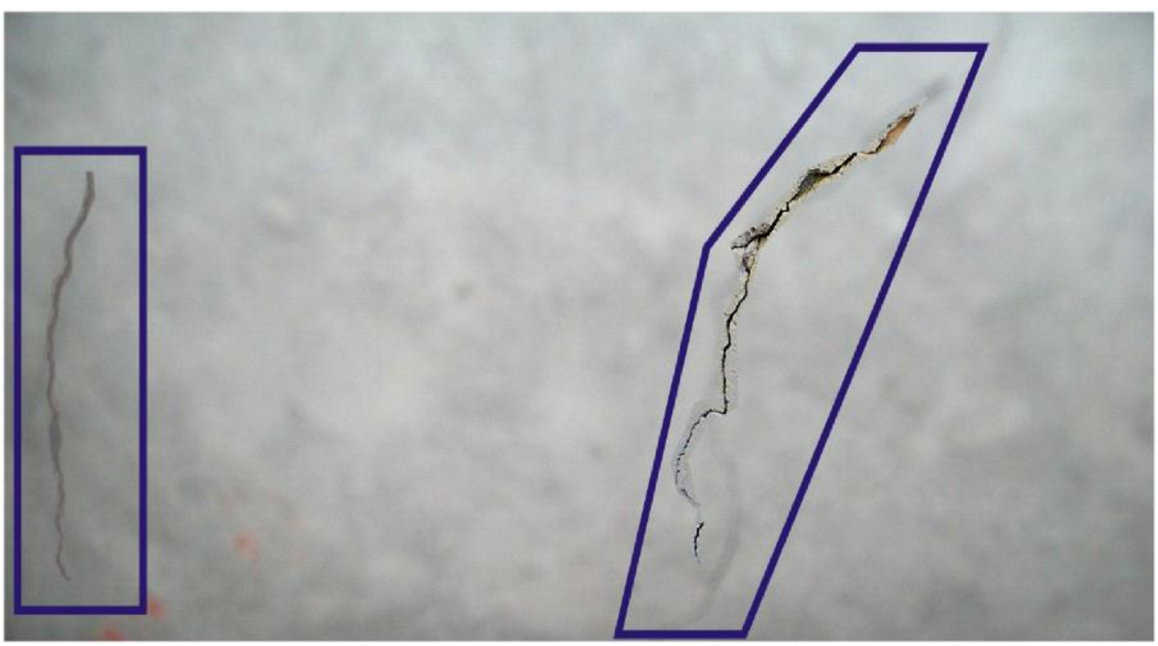

Fig.5.3: Development of cracks (typical)

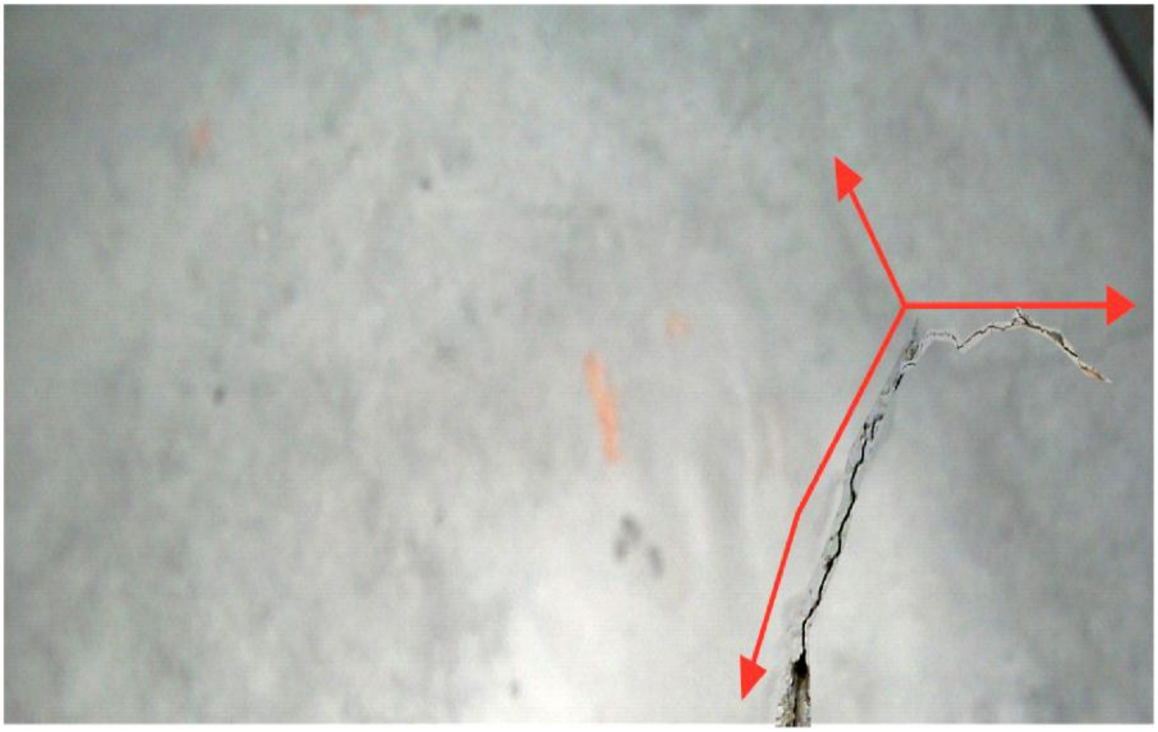

Fig.5.4: Propagation of cracks (typical)

It was found that for the virgin slabs S11 (3 No's); where S11 stands for the slabs of S1 size (2350 x 1750 x 75) mm that were to be retrofitted with Glass Fibre Reinforced Polymer (GFRP); that the value of average midspan deflection was 3.89 mm against the load 6.07 kN/m^2 when the minor cracks started forming. At the load 8.51 kN/m^2 the major cracks propagated and at the load 14.58 kN/m^2 when the deflection was 8.22 mm, the cracks started spreading throughout the slab. The deflection reached up to 14.36 mm against the load 21.88 kN/m^2 after which the value followed slower rise and the cracks spread all over when the deflection reached 17.37 mm against the load 23.10 kN/m^2. The ductility of 21% was observed for virgin slabs S11 as against initiation of nonlinear range at 14.36 mm and the final deflection 17.37 mm.

For the virgin slabs S12 (3 No's); where S12 depicts for the slabs of S1 size that were to be retrofitted with Ferrocement; that the value of average mid span deflection was 5.51 mm against the load 6.07 kN/m^2 when the cracks started forming. The deflection reached up to 15.40 mm against the load 21.88 kN/m^2 when there was a small increase in value and it reached to 18.48 mm against the load 23.10 kN/m^2 and ductility of 20% for these virgin slabs as against initiation of nonlinear range at 15.40 mm and the final deflection 18.48 mm.

The slabs S13 (3 No's) of size S1 that were to be retrofitted with Mild Steel plate were observed and it was seen that the cracks were initiated at the deflection of 5.33 mm at load 4.86 kN/m^2. The value of deflection 15.11 mm occurred at load 21.88 kN/m^2 leading to 20% ductility when compared with the final deflection 1 8.13 mm at load 23.10 kN/m^2.

The trend for virgin slabs S21 (3 No's); where S21 stands for slabs of size S2 (2350 x 1566 x 75) mm that were to be retrofitted with GFRP; showed that minor cracks were formed at load 6.80 kN/m^2 at the deflection 4.27 mm. The major cracks were formed at deflection 5.51 mm at load 9.51 kN/m^2. The deflection reached at 16.83 mm at load 24.45 kN/m^2. The deflection reached up to 20.19 mm at load 25.81 kN/m^2 and resulting in increase in ductility of 20%.

The virgin slabs S22 (3 No's) that were to be retrofitted with Ferrocement indicate that the deflection 13.24 mm was at the load 24.45 kN/m^2. The value followed slower rise up to 15.88 mm for load 25.81 kN/m^2. The ductility was observed to be 20% for these slabs specimens when the final deflection 15.88 mm was compared with the initiation of nonlinear deflection 13.24 mm.

The value of virgin slabs S23 (3 No's) that were to be retrofitted with Mild Steel plate indicates that the deflection 13.57 mm was at the load 24.45 kN/m^2. Thereafter, the value followed slower escalation up to 16.28 mm at load 25.81 kN/m^2 leading to 20% ductility.

5.4. NON DESTRUCTIVE TEST RESULTS AFTER LOADING TEST

After the loading test on slabs, the NDT was again carried out. The respective readings of non-destructive testing are listed in the Tables 5.7-5.12.

From the Tables 5.7-5.12, it was observed that the minimum equivalent compressive cube strength was 14.0 N/mm^2 against the Rebound Hammer Number 20 and the maximum equivalent compressive cube strength was 21.0 N/mm2 against the Rebound Hammer Number 25. This indicated that the presence of cracks due to the flexural or loading test carried out on slabs.

The state of the slabs was exhibited by the ultrasonic pulse velocity tests. The low velocity values of ultrasonic pulse velocity test showed that the condition of the concrete quality grading was doubtful when the velocity was less than 3 km/s. This indicated that the time taken by the waves to travel through cracks was sufficiently high that resulted in the reduction in the velocity.

Table 5.7: Rebound Hammer Number and Ultrasonic Pulse Velocity values after loading test at marked points of virgin slabs S11

Points	Average Rebound Hammer Number	Equivalent cube compressive strength (N/mm^2)	Ultrasonic Pulse Velocity (km/s)	Concrete quality grading
0	21	15.5	1.93	Doubtful
1	20	14.0	1.36	Doubtful
2	23	18.0	1.70	Doubtful
3	23	18.0	1.72	Doubtful
4	22	17.0	1.10	Doubtful
5	25	21.0	1.81	Doubtful
6	20	14.0	1.94	Doubtful
7	21	15.5	1.23	Doubtful
8	21	15.5	1.33	Doubtful
9	23	18.0	1.50	Doubtful
10	20	14.0	1.83	Doubtful
11	21	15.5	1.80	Doubtful
12	20	14.0	1.71	Doubtful
13	22	17.0	1.54	Doubtful
14	25	21.0	1.81	Doubtful
15	23	18.0	1.50	Doubtful
16	24	19.5	1.57	Doubtful
17	25	21.0	1.19	Doubtful
18	25	21.0	1.63	Doubtful

From UPV test, Damage Index = 0.609

Table 5.8: Rebound Hammer and Ultrasonic Pulse Velocity values after loading test at marked points of slab S12

Points	Average Rebound Hammer Number	Equivalent cube compressive strength (N/mm^2)	Ultrasonic Pulse Velocity (km/s)	Concrete quality grading
0	21	15.5	1.79	Doubtful
1	25	21.0	1.54	Doubtful
2	23	18.0	1.41	Doubtful
3	26	22.5	1.74	Doubtful
4	22	17.0	1.88	Doubtful
5	25	21.0	1.83	Doubtful
6	25	21.0	1.83	Doubtful
7	26	22.5	1.89	Doubtful
8	25	21.0	1.95	Doubtful
9	26	22.5	1.89	Doubtful
10	25	21.0	1.90	Doubtful
11	23	18.0	1.72	Doubtful
12	23	18.0	1.37	Doubtful
13	21	15.5.	1.36	Doubtful
14	21	15.5	1.39	Doubtful
15	20	14.0	1.34	Doubtful
16	20	14.0	1.59	Doubtful
17	23	18.0	1.41	Doubtful
18	23	18.0	1.39	Doubtful

From UPV test, Damage Index = 0.62

Table 5.9: Rebound Hammer and Ultrasonic Pulse Velocity values after loading test at marked points of slab S13

Points	Average Rebound Hammer Number	Equivalent cube compressive strength (N/mm^2)	Ultrasonic Pulse Velocity (km/s)	Concrete quality grading
0	21	15.5	1.96	Doubtful
1	25	21.0	1.50	Doubtful
2	23	18.0	1.04	Doubtful
3	24	19.5	1.39	Doubtful
4	24	19.5	1.19	Doubtful
5	22	17.0	1.36	Doubtful
6	20	14.0	1.46	Doubtful
7	21	15.5	1.04	Doubtful
8	22	17.0	1.79	Doubtful
9	23	18.0	1.44	Doubtful
10	22	17.0	1.26	Doubtful
11	21	15.5	1.72	Doubtful
12	20	14.0	1.78	Doubtful
13	20	14.0	1.20	Doubtful
14	25	21.0	1.39	Doubtful
15	22	17.0	1.18	Doubtful
16	21	15.5	1.71	Doubtful
17	21	15.5	1.91	Doubtful
18	23	18.0	1.36	Doubtful

From UPV test, Damage Index = 0.61

Table 5.10: Rebound Hammer and Ultrasonic Pulse Velocity values after loading test at marked points of slab S21

Points	Average Rebound Hammer Number	Equivalent cube compressive strength (N/mm^2)	Ultrasonic Pulse Velocity (km/s)	Concrete quality grading
0	23	18.0	1.88	Doubtful
1	20	14.0	1.65	Doubtful
2	20	14.0	1.33	Doubtful
3	21	15.5	1.53	Doubtful
4	23	18.0	1.80	Doubtful
5	25	21.0	1.47	Doubtful
6	22	17.0	1.54	Doubtful
7	24	19.5	1.50	Doubtful
8	23	18.0	1.28	Doubtful
9	21	15.5	1.18	Doubtful
10	20	14.0	1.32	Doubtful
11	25	21.0	1.81	Doubtful
12	24	19.5	1.94	Doubtful
13	23	18.0	1.93	Doubtful
14	20	14.0	1.36	Doubtful
15	21	15.5	1.81	Doubtful
16	23	18.0	1.50	Doubtful
17	20	14.0	1.33	Doubtful
18	24	19.5	1.52	Doubtful

From UPV test, Damage Index = 0.61

Table 5.11: Rebound Hammer and Ultrasonic Pulse Velocity values at marked points of slab S22

Points	Average Rebound Hammer reading	Equivalent cube compressive strength (N/mm^2)	Ultrasonic Pulse Velocity (km/s)	Concrete quality grading
0	25	21.0	1.63	Doubtful
1	23	18.0	1.96	Doubtful
2	23	18.0	1.93	Doubtful
3	24	19.5	1.80	Doubtful
4	20	14.0	1.39	Doubtful
5	20	14.0	1.88	Doubtful
6	21	15.5	1.70	Doubtful
7	21	15.5	1.44	Doubtful
8	22	17.0	1.25	Doubtful
9	26	22.5	1.70	Doubtful
10	23	18.0	1.79	Doubtful
11	22	17.0	1.42	Doubtful
12	20	14.0	1.94	Doubtful
13	21	15.5	1.86	Doubtful
14	21	15.5	1.94	Doubtful
15	25	21.0	1.52	Doubtful
16	25	21.0	1.45	Doubtful
17	23	18.0	1.27	Doubtful
18	22	17.0	1.30	Doubtful

From UPV test, Damage Index = 0.63

Table 5.12: Rebound Hammer and Ultrasonic Pulse Velocity values at marked points of slab S23

Points	Average Rebound Hammer reading	Equivalent cube compressive strength (N/mm^2)	Ultrasonic Pulse Velocity (km/s)	Concrete quality grading
0	21	15.5	1.88	Doubtful
1	22	17.0	1.81	Doubtful
2	23	18.0	1.64	Doubtful
3	20	14.0	1.54	Doubtful
4	20	14.0	1.59	Doubtful
5	25	21.0	1.69	Doubtful
6	23	18.0	1.36	Doubtful
7	25	21.0	1.39	Doubtful
8	21	15.5	1.54	Doubtful
9	21	15.5	1.34	Doubtful
10	20	14.0	1.25	Doubtful
11	24	19.5	1.29	Doubtful
12	24	19.5	1.56	Doubtful
13	22	17.0	1.55	Doubtful
14	25	21.0	1.52	Doubtful
15	26	22.5	1.46	Doubtful
16	20	14.0	1.48	Doubtful
17	21	15.5	1.54	Doubtful
18	22	17.0	1.46	Doubtful

From UPV test, Damage Index = 0.61

It was observed that in every case, the damage index was in the range between 0.6 and 0.7. This clearly indicated that the slabs were severely damaged which necessitated the retrofitting practice to restore the strength.

So the slabs were retrofitted with Glass Fibre Reinforced Polymer, Ferrocement and Mild Steel plate as laminates. The loading tests were again carried out to see the extent of restoration of strength.

5.5. LOADING TEST RESULTS AFTER RETROFITTING

After retrofitting, the slabs were tested under uniformly distributed load. The load-deflection curves obtained for retrofitted and control slabs are presented in Fig. 5.5-5.10. Their combined load deflection results for S1 and S2 slabs have been shown in the Fig. 5.11 and Fig. 5.12.

For GFRP retrofitted slab S11, minor cracks were observed to develop parallel to long side of the slab at 40 kN. As load reached 50 kN, the cracks were initiated at edges of slab and developed towards centre under increasing load. Then the cracks started joining each other at 70 kN. Major cracking was observed at 95 kN. Average value of final deflection at the centre was 7.40 mm. For Slab S21, minor cracks were observed at 35 kN and cracks were visible at edges at 50 kN. The major cracking was observed at load 75kN. Average value of final deflection at the centre was 9.89 mm at load of 90kN. GFRP retrofitted slab developed less cracks as compared to non-retrofitted or virgin slabs. The ductility was 43% for GFRP retrofitted slabs S11 when the deflection 7.40 mm at the initiation of nonlinear range was compared with the final deflection 10.58 mm. The ductility was 36% when the deflection 9.89 mm at the initiation of nonlinear range was compared with the final deflection 13.45 mm.

It was also observed that the percentage decrease in deflection for virgin and GFRP retrofitted slabs was 50% for S11 and 42 % for S21 when the deflection values against the nonlinear range were compared.

Similarly for Ferrocement retrofitted slabs S12 and S22 of size S1 and S2, the percentage decrease in deflection for control and Ferrocement retrofitted slabs was found to be 23 % for S1 and 17 % for S2 slabs.

In case of Mild Steel retrofitted slabs S13 and S23 of size S1 and S2, it was observed that the percentage decrease in the deflection was 22% for S13 and 12 % for S23 when the virgin slabs before retrofitting and Mild Steel plate retrofitted slabs were compared

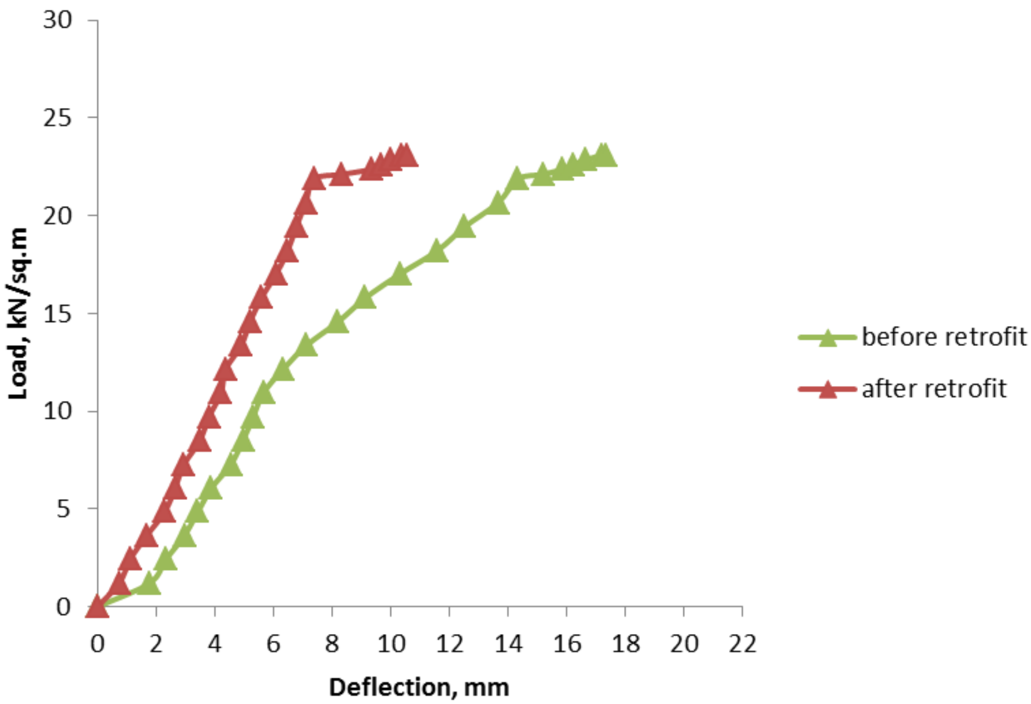

Fig. 5.5: Load-Deflection curve of slab S11 (before and after GFRP retrofitting)

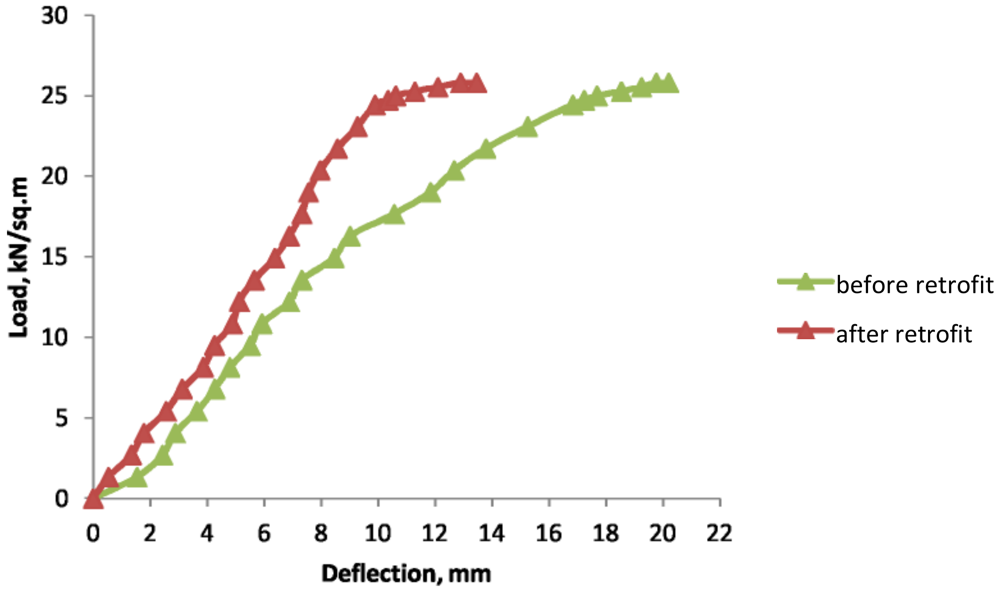

Fig. 5.6: Load-Deflection curve of slab S21 (before and after GFRP retrofitting)

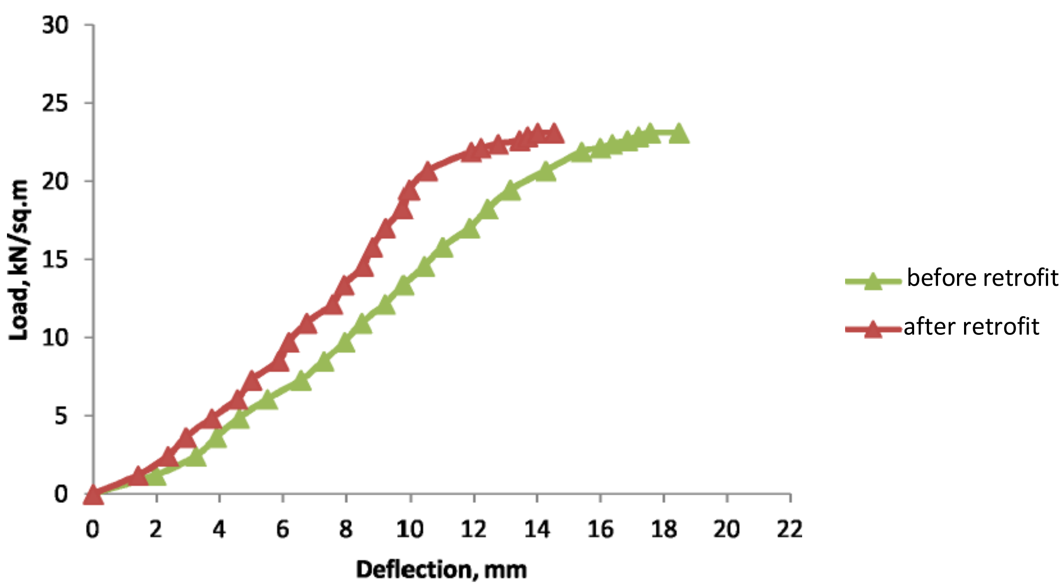

Fig. 5.7: Load-Deflection curve of slab S12 (before and after Ferrocement retrofitting)

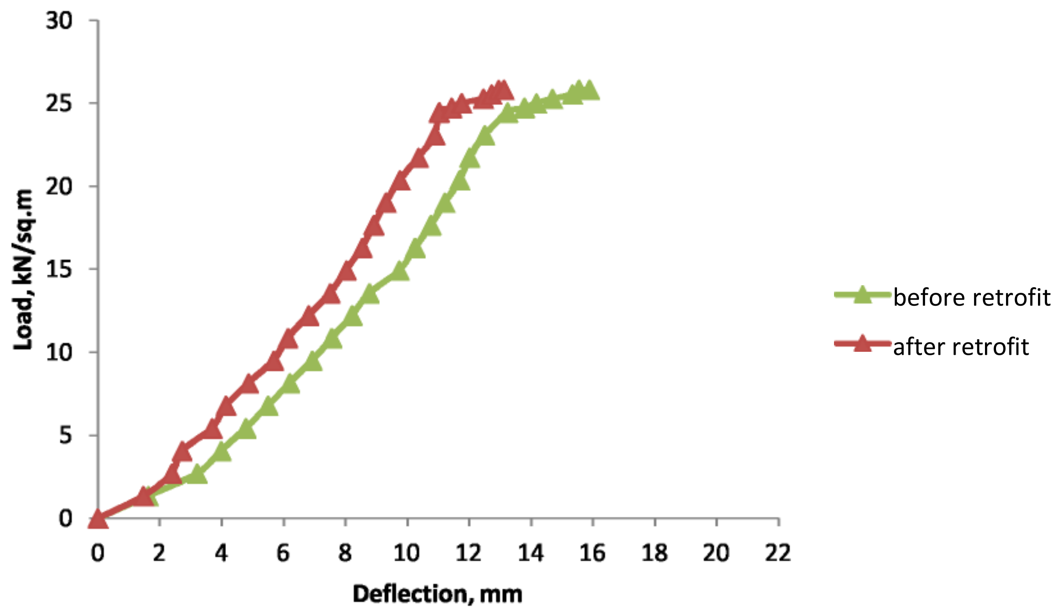

Fig. 5.8: Load-Deflection curve of slab S22 (before and after retrofitting with Ferrocement)

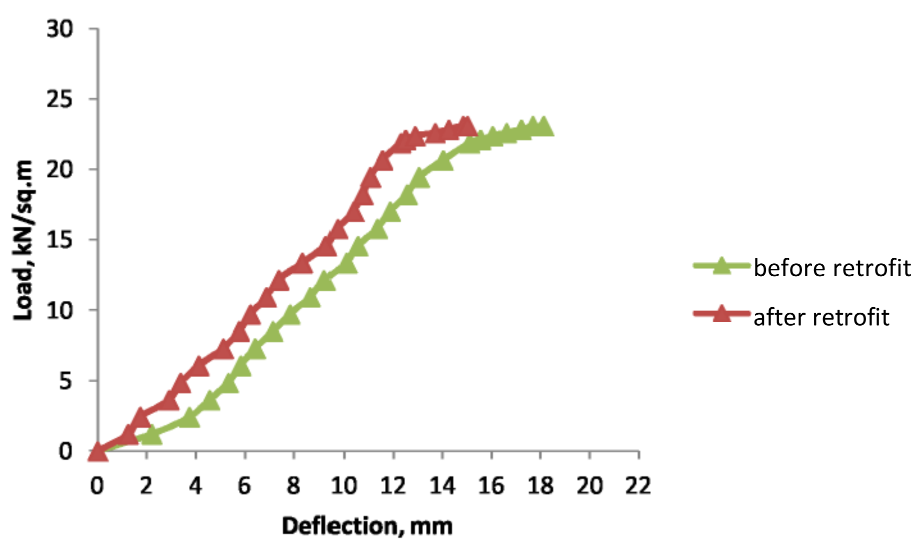

Fig. 5.9: Load-Deflection curve of slab S13 (before and after MS Plate retrofitting)

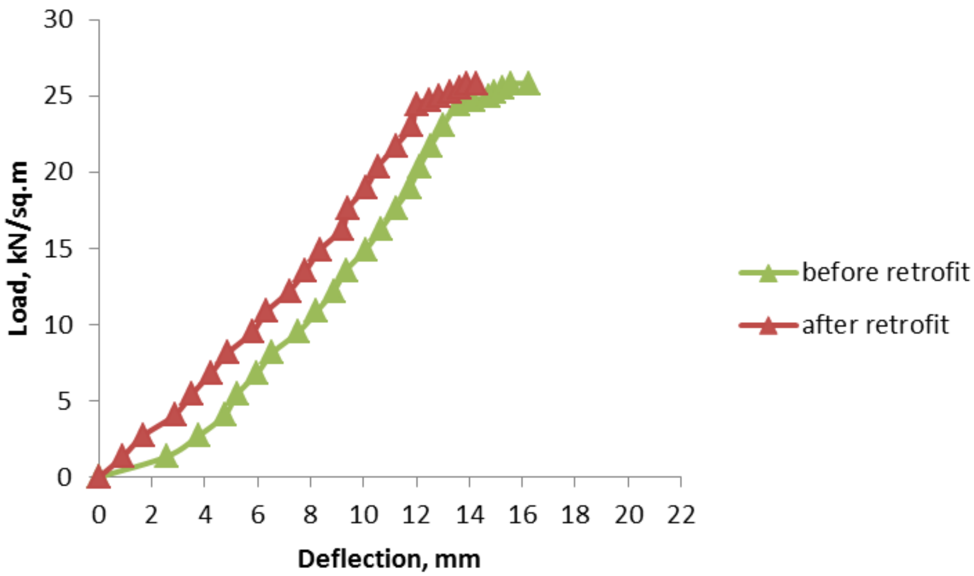

Fig. 5.10: Load-Deflection curve of slab S23 (before and after MS Plate retrofitting)

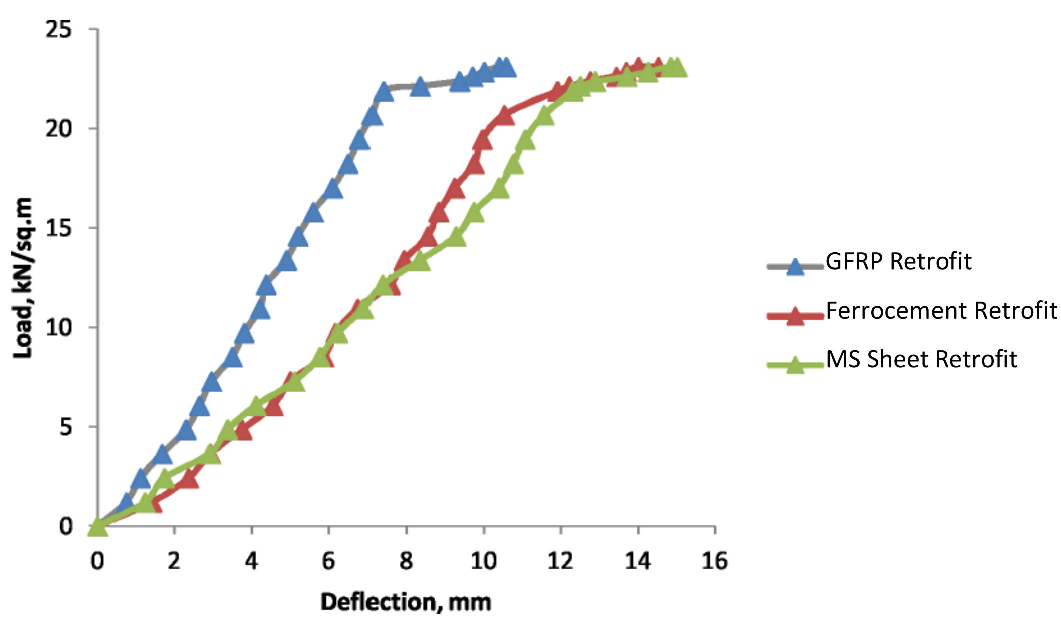

Fig. 5.11: Load-Deflection curve of S1 slabs retrofitted with different materials

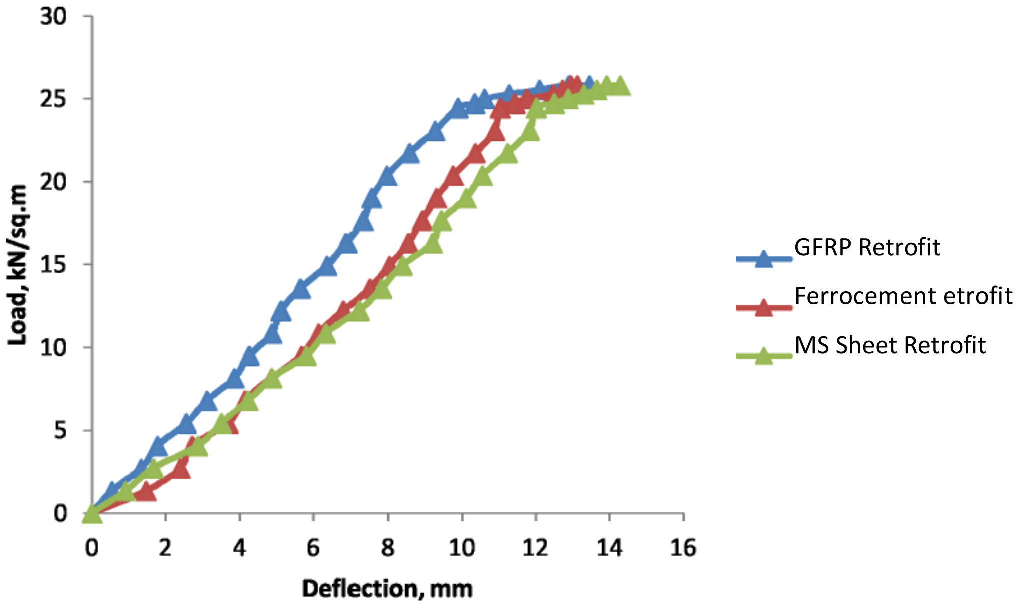

Fig. 5.12: Load-Deflection curve of S2 slabs retrofitted with different materials

5.6. FINITE ELEMENT MODELING RESULTS

The slabs were then investigated for finite element analysis using ATENA 3D package. The modeling of the slabs has been discussed extensively in *Chapter-4* on *'Finite Element Modeling'*. Both the slabs S1 and S2 before retrofitting (virgin slabs) well as the retrofitted slabs were modeled.

Thus, the two slabs S1 and S2 were modeled as virgin slabs as well as retrofitted slabs. The data so obtained was compared with experimental results.

As seen from analytical results for control and retrofitted slabs, it was found that the experimental and analytical results were in close agreement with each other.

These analytical values were then compared with experimental values obtained as discussed in detail in *Chapter-3* on *'Experimental Programme'*. The comparison indicated that the analytical values as seen from Fig. 5.13 to 5.22 were in good agreement with the numerical values (within ± 5%). This confirmed the numerical validation on the slabs.

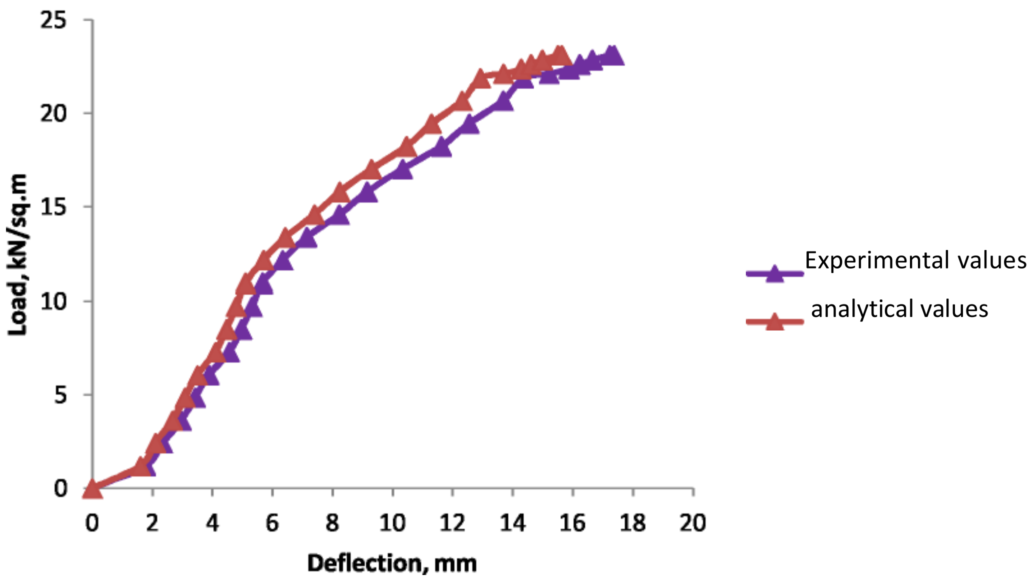

Fig. 5.13: Analytical and Experimental Load-Deflection values of virgin Slabs S1

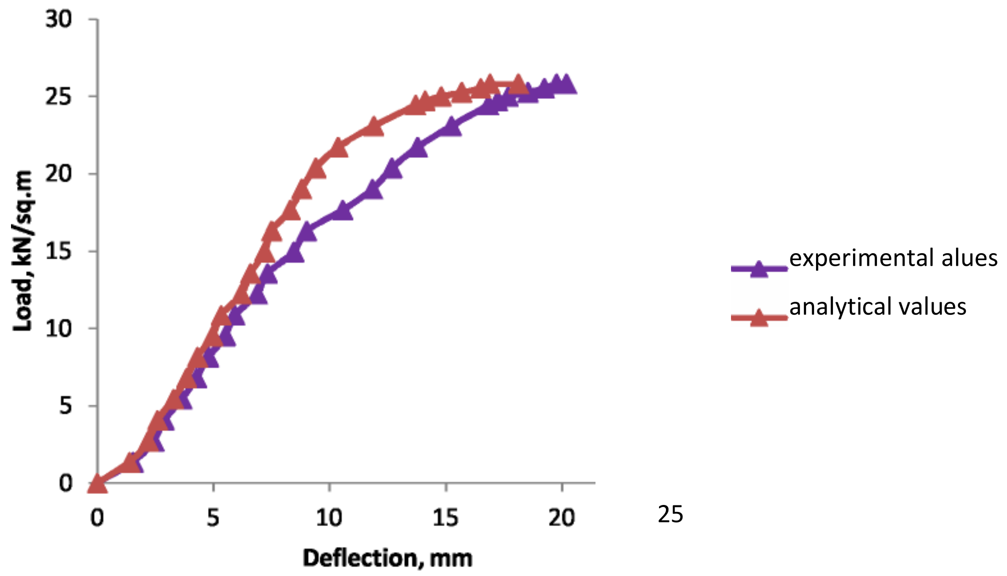

Fig. 5.14: Analytical and Experimental Load-Deflection values of virgin slabs S2

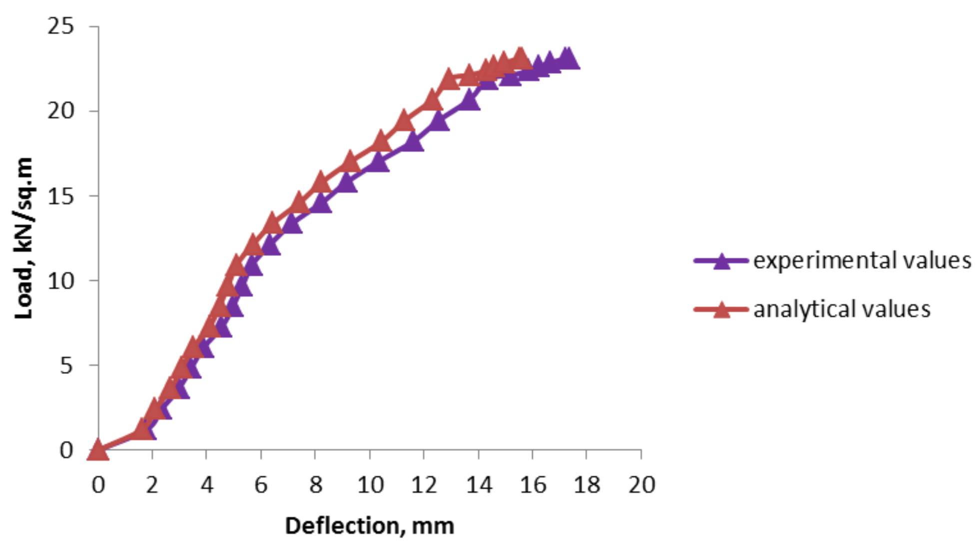

Fig. 5.15: Analytical and Experimental Load-Deflection values of GFRP retrofit slab S11

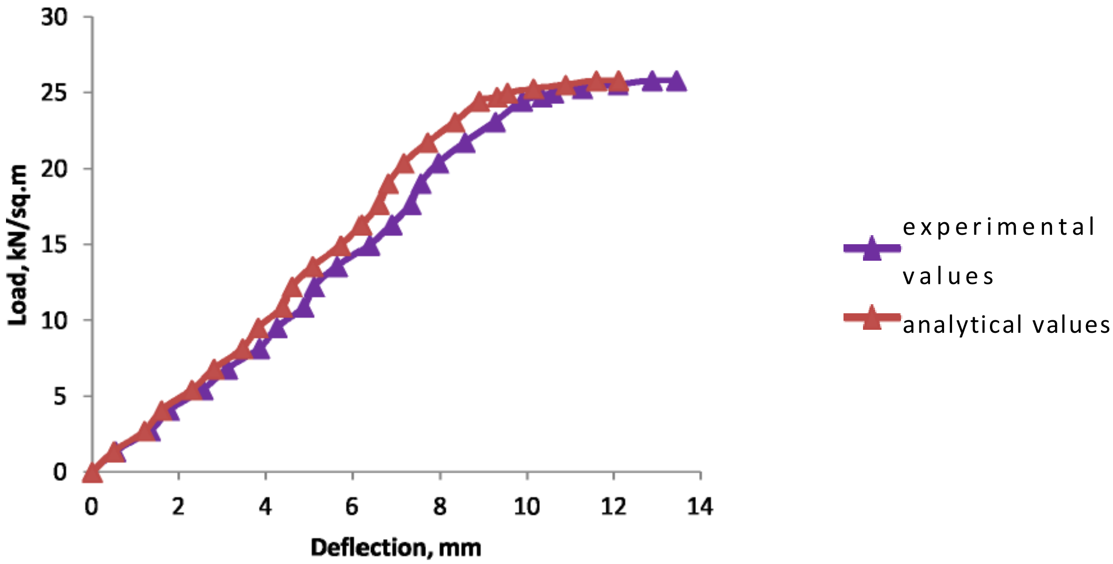

Fig. 5.16: Analytical and Experimental Load-Deflection values of GFRP retrofit slab S21

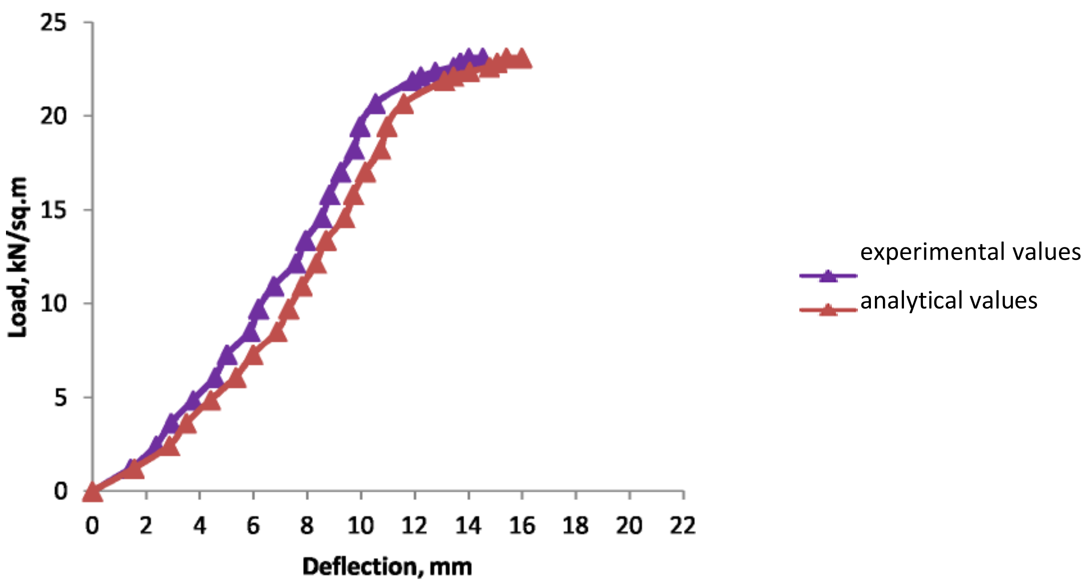

Fig. 5.17 Analytical and Experimental Load-Deflection values of Ferrocement retrofit Slab S12

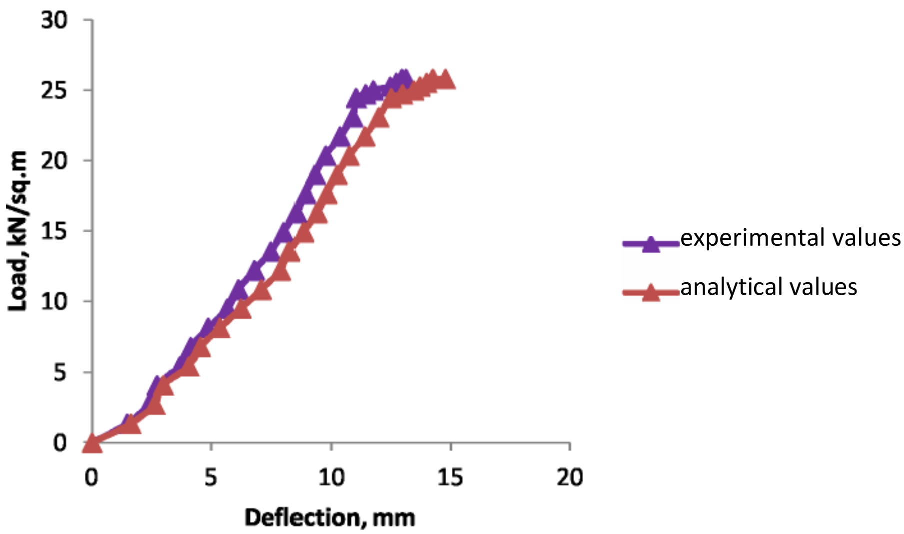

Fig. 5.18: Analytical and Experimental Load-Deflection values of Ferrocement retrofit slab S22

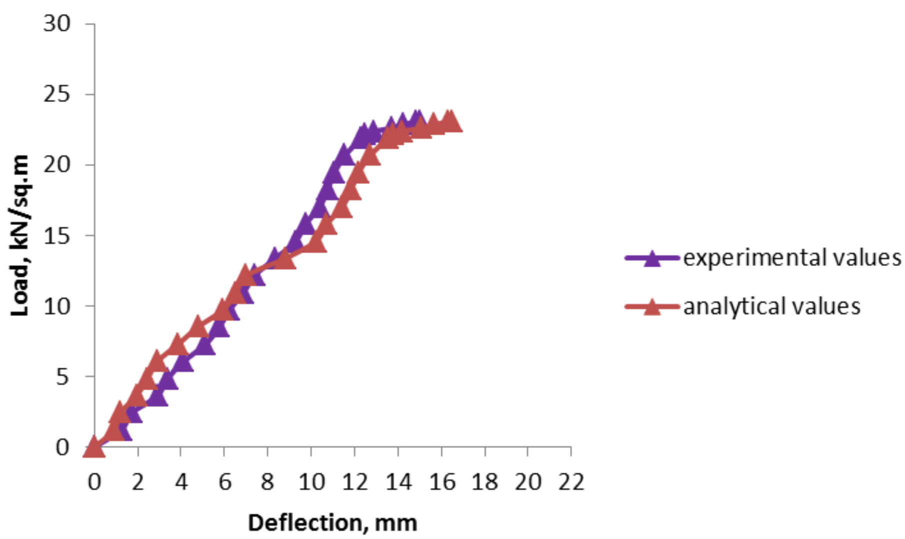

Fig. 5.19: Analytical and Experimental Load-Deflection values of MS Plate retrofit slab S13

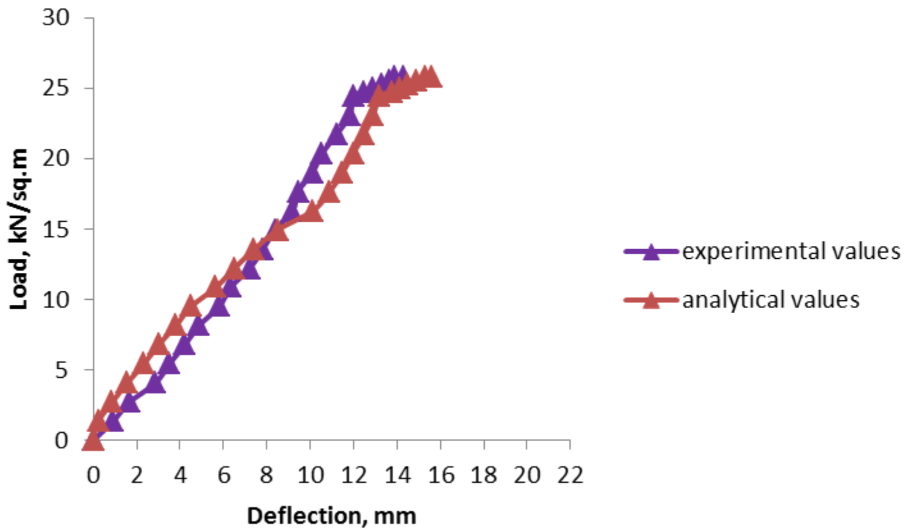

Fig. 5.20: Analytical and Experimental Load-Deflection values of MS Plate retrofit slab S23

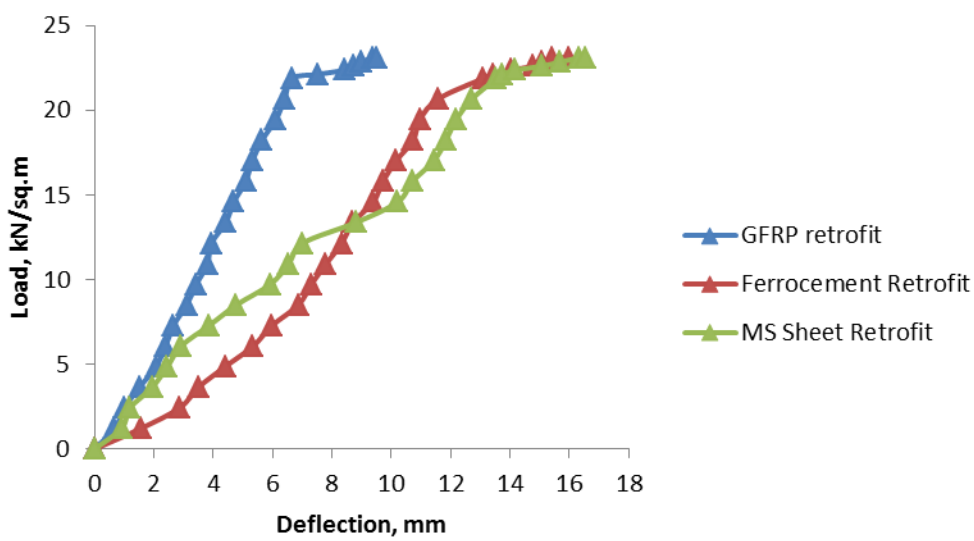

Fig. 5.21: Analytical Load-Deflection curve of S1 slab retrofitted with different material

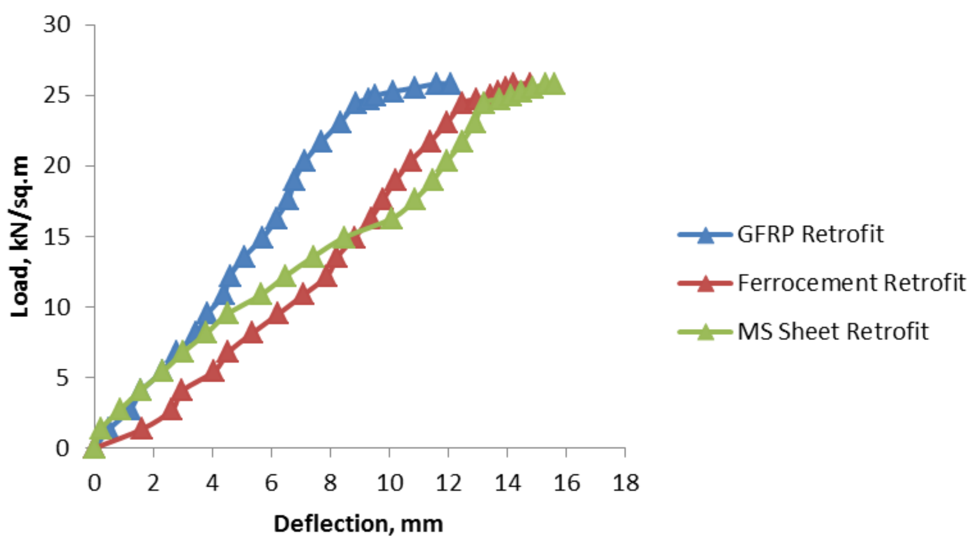

Fig. 5.22: Analytical Load-Deflection curve of S2 slab retrofitted with different materials

5.7. POST CRACKING BEHAVIOUR OF RETROFITTED SLABS

It was observed that the major failure through which the slabs underwent was the debonding failure. In all the retrofitted slabs, almost uniform crack patterns and failure patterns were observed. Some typical crack and failure patterns obtained are shown in Fig. 5.23-5.29.

(a)

(b)

Fig.5.23: Debonding of GFRP in Slab (typical).

Fig.5.24: Debonding of GFRP at Corners (typical).

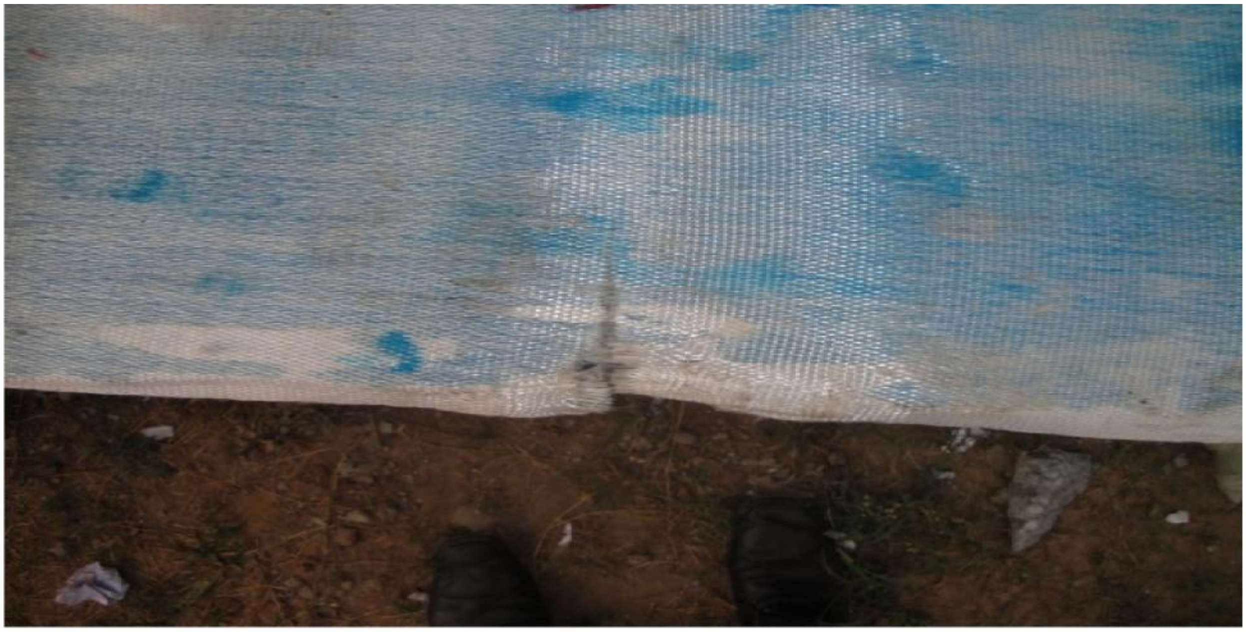

Fig. 5.25: GFRP failure pattern followed similar trend on other side of the slab (typical)

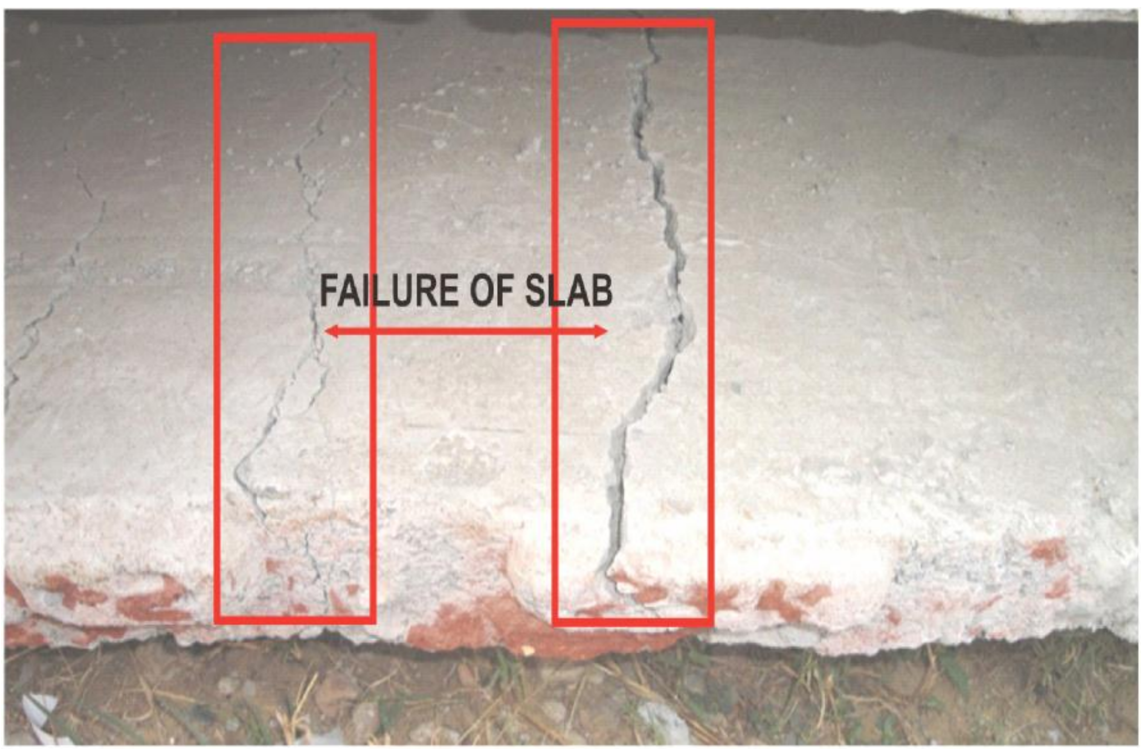

Fig.5.26: Failure pattern of slab retrofitted with Ferrocement (typical)

Fig.5.27: Debonding of MS Plate (typical)

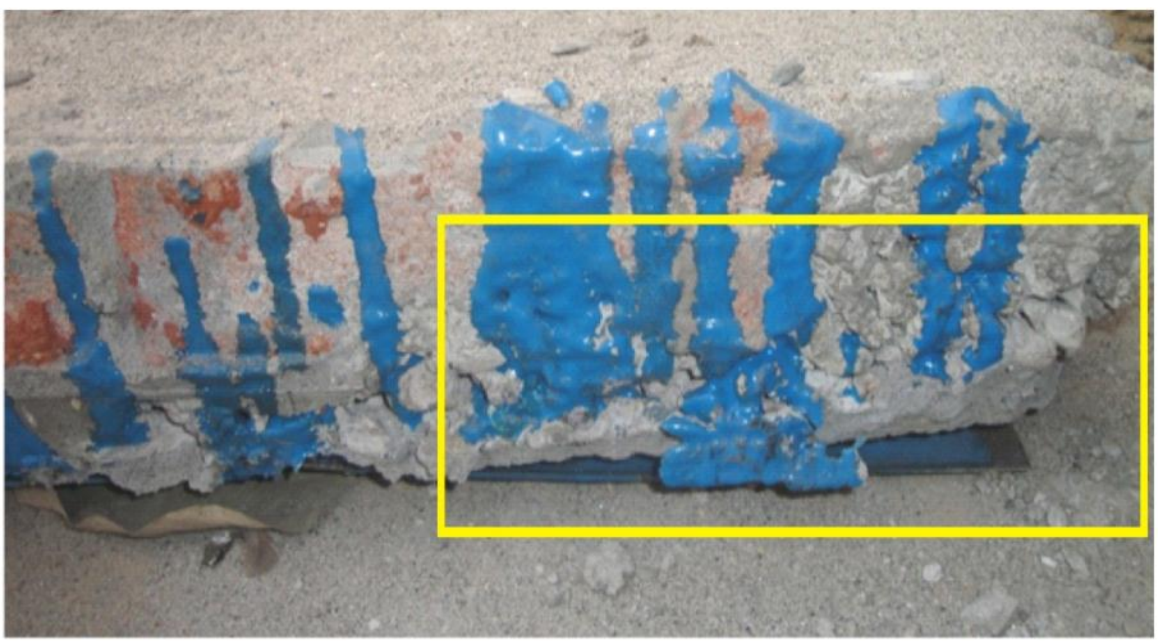

Fig.5.28: Debonding of MS Plate at Corners (typical)

Fig.5.29: Complete Split-up of MS Plate (typical)

The various stages of crack development in the slabs retrofitted with GFRP, Ferrocement and Mild Steel Plate are shown in Fig. 5.30 and the values are given in Table 5.13.

Table 5.13: Value of Load (A, B, C and D) at various stages of Crack Development

S.No.	GFRP Retrofitted Slab (kN/m^2)		Ferrocement Retrofitted Slab (kN/m^2)		Mild Steel Retrofitted Slab (kN/m^2)	
	S11	S12	S12	S22	S13	S23
A	9.72	9.51	8.51	8.15	7.29	6.80
B	12.15	13.56	10.94	12.22	9.72	9.51
C	17.02	16.30	14.58	13.50	12.15	16.30
D	20.67	20.37	18.23	19.02	17.02	17.66

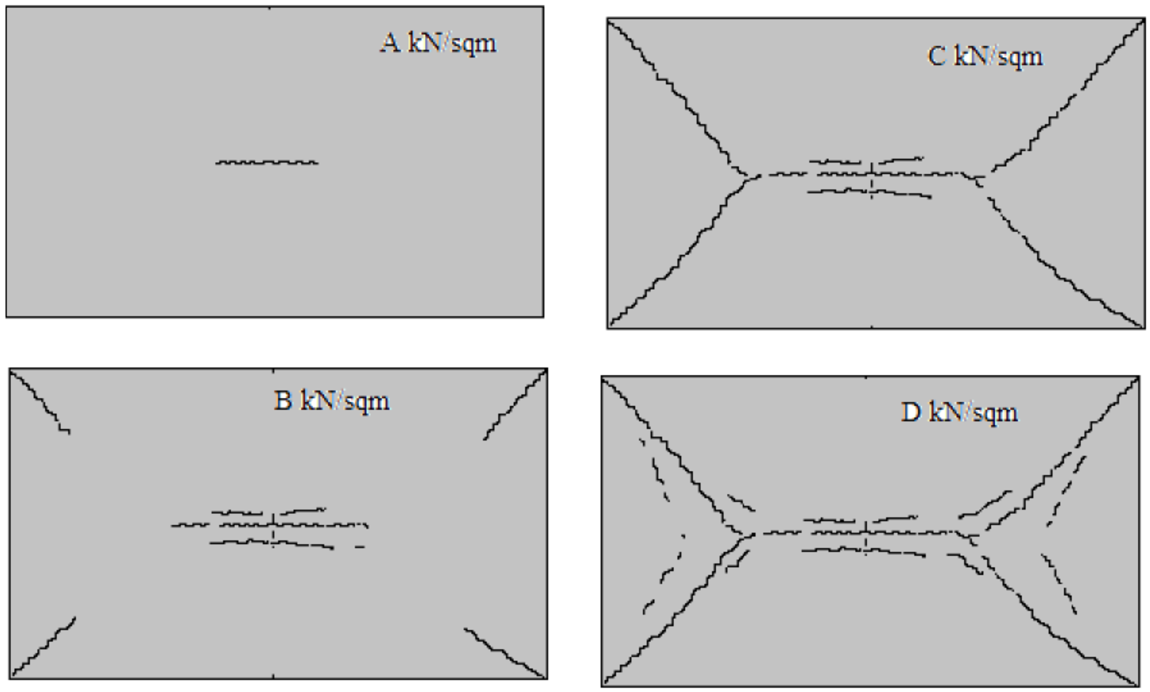

Fig.5.30: Generalised crack pattern at various stages of loading

5.8. DISCUSSION

Present investigation described the performance of two-way RCC slabs specimens under uniformly distributed load. The study investigated the restoration of load carrying capacity of damaged reinforced concrete slabs retrofitted with laminates and its failure pattern. It was found that a single layer of laminates at the tensile face of the slabs restored the load carrying capacity to more than 100 per cent of original strength and its easy fixation made it very convenient to use it in field. GFRP retrofit material surpassed the other laminates and showed better performance.

First the non-destructive testing was carried out to see the extent of deterioration. The results of ultrasonic pulse velocity test conducted before and after loading test indicated that the quality of concrete at the marked points was good to excellent before loading and it was doubtful after the loading test. The Rebound Hammer tests and Ultrasonic Pulse Velocity tests assessed the degree of deterioration and were used to determine the damage index. In each case the damage index showed that the slabs were severely damaged. Keeping this in mind, the retrofitting was done and the extent of restoration was observed. The loading test results are presented in the form of load-deflection curves of the slabs along with crack pattern of the slab. Experimental results were found to be in well agreement (within ± 5%) with those obtained from analytical investigations.

For retrofitting, GFRP having width of 500 mm and in running length 50 m was used. The plate used was bidirectional for two-way strengthening. Under stress due to loading, fibres resulted in high strength of retrofitted slab. Main function of fibre matrix comprised the combination and the protection of the fibres against external environment into which the composite was placed.

As seen from the results, the virgin slabs underwent more deflection as compared to the retrofitted slabs.

The GFRP retrofitted slabs were observed to be the most effective of all the materials as the glass fibres have very high tensile strength that helped in the restoration of the strength. The ductility of the GFRP retrofitted slabs was highest being 43% for S1 slabs and 36% for S2 slabs. The major failure pattern of the fibres was the debonding failure.

The material after GFRP that proved advantageous was ferrocement. The ferrocement retrofitted slabs exhibited sufficient decrease in the deflection, that is, 23% for S1 slabs and 17% for S2 slabs. The ferrocement material indicated 22% ductility value for S1 slabs and 19% for S2 slabs.

The material after ferrocement was Mild Steel plate. The MS plate retrofitted slabs showed the least value of restoration of strength that was 18% for S1 slabs and 12% for S2 slabs.

The small difference in the size of the slabs was made to see the effect of decrease in the size of the slab on the deflection and ductility. It was seen that the deflection in the small size slabs was lesser than the bigger size slabs. The ductility also followed same pattern as of deflection. This was attributed to more stiffness of the small size slabs.

Also, if the equation for flexural Moment of Resistance is assumed to be of the form:

$M_u = A+B$

Where A = Moment of slab without retrofitting

B = Moment of the slab taking into account the retrofitting material

Where A and B are diferent for GFRP, ferrocement and Mild steel

Then, as explained in detail in *Annexure-1,* the equation for Flexural moment of resistance for slab with GFRP retrofitting material,

$$M_u = 0.87\, f_y\, A_{st}\, (d - 0.42\, x_u) + 0.765\, A_f\, E_f\, H_{fe}\, (d_1 - 0.42\, x_u)$$

(The detailed explanation is given in *Annexure-1)*

Here $A = 0.87\, f_y\, A_{st}\, (d - 0.42\, x_u)$

$B = 0.765\, A_f\, E_f\, H_{fe}\, (d_1 - 0.42\, x_u)$

Then extent of damage or Damage Index (D.I) $\dfrac{(M_u - A)}{A} = \dfrac{B}{A}$

Solving the above equation, we get

$$\frac{A_f}{A_{st}} = \frac{(D.I)}{305.8}$$

As the damage index range between 0 and 1, substituting the values of D.I in equal increment of 0.1 from 0 up to 1, we get the curve as shown in Fig. 5.31. From this curve, the area of fibres can be found out from the already known value area of reinforcement and the design of the retrofit system can be made.

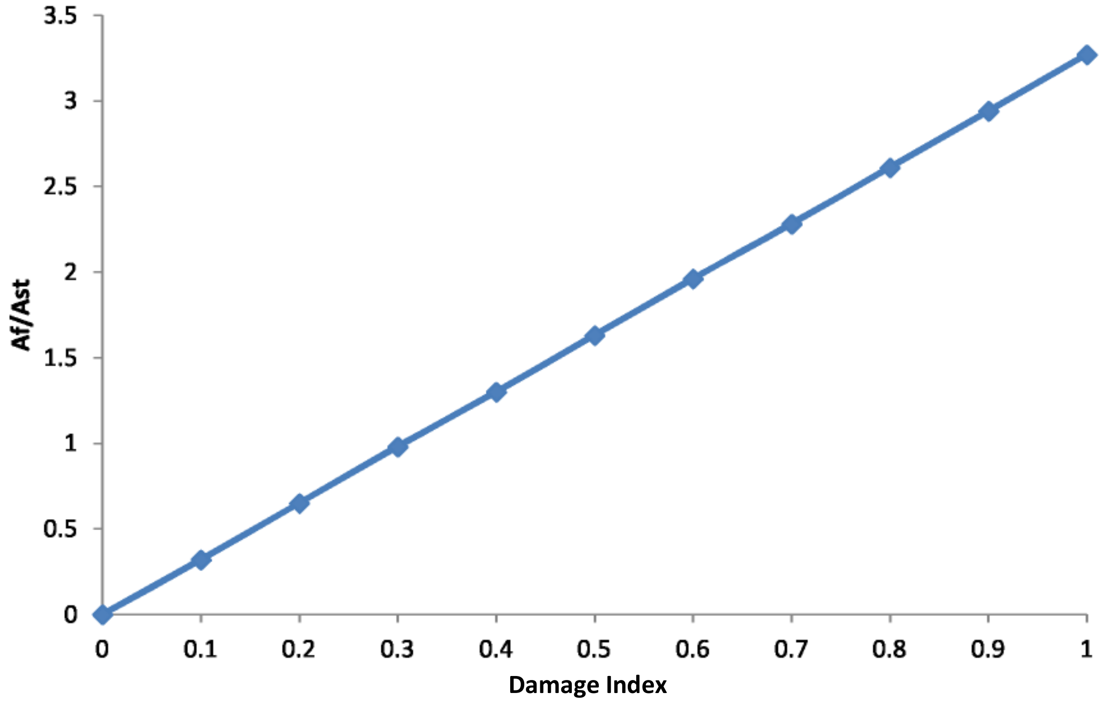

Fig. 5.31: Relation between damage index and ratio of areas for GFRP retrofitted slab

Similarly, the design of Ferrocement as a retrofitting material can be understood from the Fig. 5.32 between (σ_m k h) and Damage Index for different values of d_1/d (The detailed explanation is given in *Annexure-1)*.

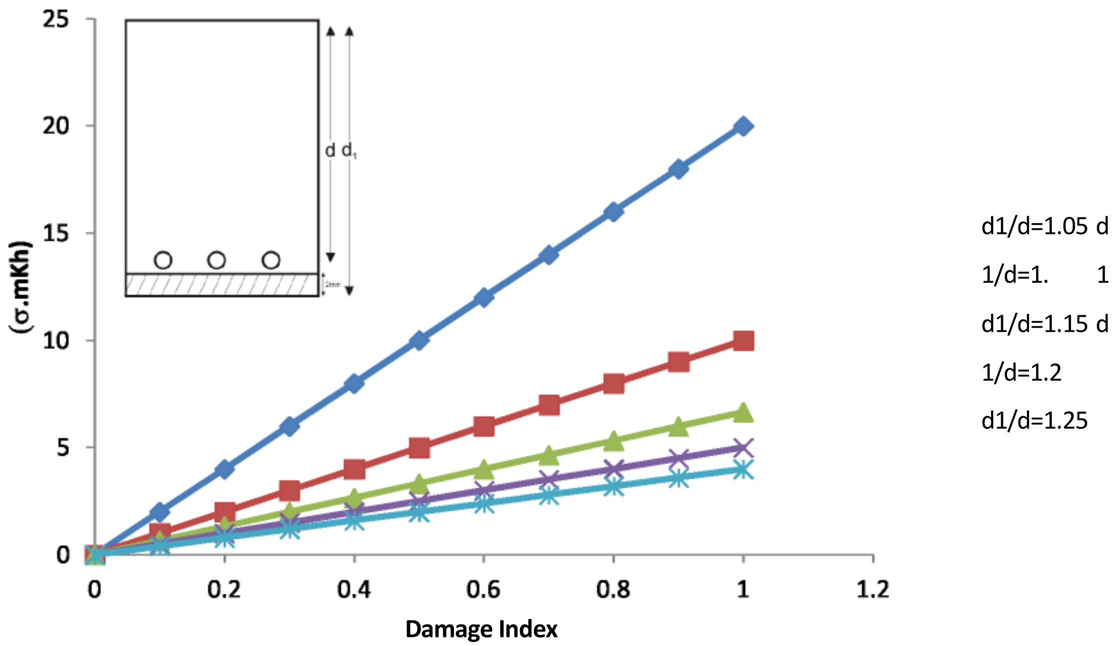

Fig. 5.32: Relation between Damage Index and (σ_m k h) for Ferrocement for different values of d_1/d

Likewise, the design of slab with Mild Steel as a retrofitting material can be made from the Fig. 5.33 between thickness of Mild Steel Plate (t) and Damage Index (The detailed explanation is given in *Annexure-1)*.

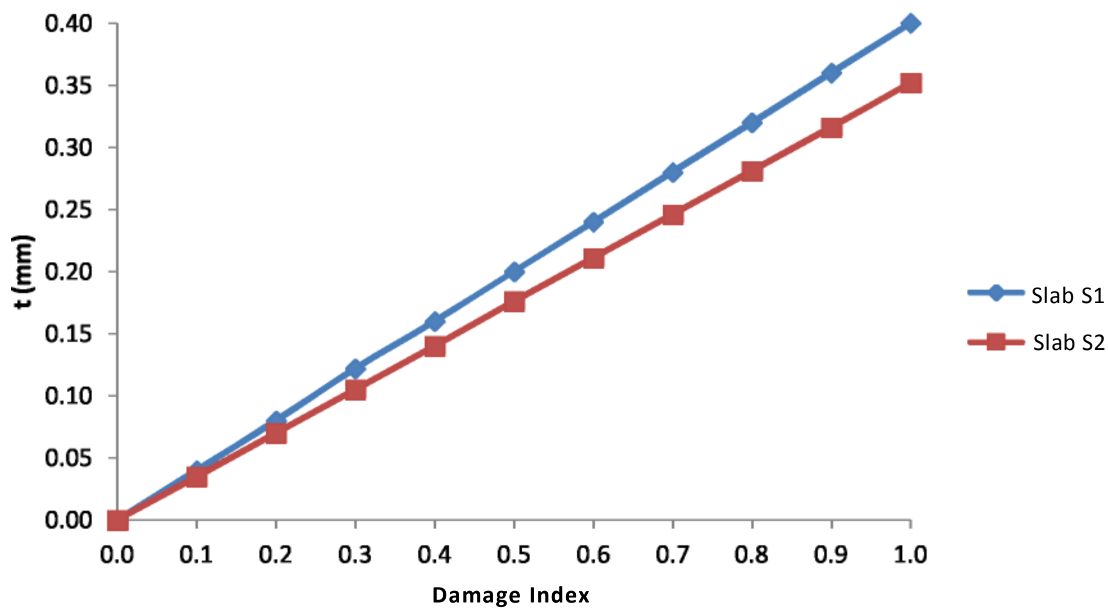

Fig. 5.33: Relation between Damage Index and Thickness (t) of Mild Steel Plate.

The economic comparison was made and it was found that the cost of GFRP retrofitted slabs was the highest and ferrocement slabs being the lowest. As discussed in the *Annexure-2,* the GFRP slabs were found to be the costliest of all the retrofitted slabs after Mild Steel and Ferrocement. The strength restoration and ductility enhancement outshined the construction cost.

5.9. CLOSURE

Present investigation described the performance of two-way RCC slab specimens under uniformly distributed load. The study investigated the restoration of load carrying capacity of damaged reinforced concrete slabs retrofitted with laminates and its failure pattern. It was found that a single layer of laminates at the tensile face of the investigated slab restored the load carrying capacity to more than 100 per cent of original strength and its easy fixation made it very convenient to use it in field. GFRP retrofit material surpassed the other laminates and showed better performance.

Rebound hammer and ultrasonic pulse velocity tests were conducted to assess the degree of deterioration and was used to determine the damage index. Based on the degree of deterioration, it was intended to undergo retrofitting of the slabs. Loading test results are presented in the form of load-deflection curve of the slabs. Experimental results were found to be in well agreement (within ± 5%) with those obtained from analytical investigations.

5.10. CONTRIBUTIONS OF PRESENT INVESTIGATION

In case the slabs were accidentally overloaded due to any unavoidable reasons and got damaged thereby made the slab unfit to serve the job; then the job to make it fit for the purpose may be fulfilled by the use of laminates.

It is possible to design the slab system by taking full advantage of laminates on its tensile face. According to the load level and strength contribution from laminates, conventional reinforcement can be determined. This may or may not be zero. An illustrative example is given in Annexure-1 of the thesis.