CHAPTER 7

SUMMARY AND CONCLUSIONS

7.1 SUMMARY

The entire study was divided into 5 distinct phases. In the first phase, the performance of Reinforced Concrete columns subjected to cyclic loading is studied to determine the desirable percentage of longitudinal reinforcement. The percentage of longitudinal reinforcement was varied as1.13%, 2.01%, 3.14% in order to study the performance of column.

In the second phase, six experiments were conducted to find out the effectiveness of using Fibre reinforced polymer jackets for enhancing the seismic shear strength and ductility of column. The specimens were subjected to reverse cyclic loading under constant axial load to address the use of the specimens in seismic regions. Four Reinforced concrete columns with and without GFRP jacketing were tested. One specimen was tested without GFRP jacketing and other three specimens were tested with 2 layers, 4 layers and 6 layers of GFRP wrapping. Three Reinforced concrete columns with and without CFRP jacketing were tested. One specimen was tested without CFRP jacketing and other two specimens were tested with CFRP wrapping.

In the third phase, nine experiments were conducted to find out the effectiveness of using Reinforced concrete jacketing. The specimens were designed and detailed as per IS 456-2000. The variable in the test specimen is the amount of longitudinal reinforcement in the column. Analytical modeling of column specimen with varied percentage of reinforcement was carried out using the finite element software package ANSYS and the experimental results were validated with the result obtained from the finite element models.

In the fourth phase, seven experiments were conducted to find out the effectiveness of using steel plate, steel strip and corrugated steel jacketing of column for enhancing the seismic shear strength and ductility. The variable in the test specimen is the type of steel jacketing. One specimen was tested up to failure without any jacketing and three specimens were tested by jacketing with steel plate, steel strip and corrugated sheet. In order to find the effect of steel jacketing on the damaged column, another three specimens were retrofitted with steel plate, steel strip and corrugated sheet after the formation of first crack by subjecting the specimens under reversed cyclic loading at constant axial loading.

In the fifth phase, four experiments were conducted to find out the effectiveness of Ferro cement jacketing of column for enhancing the seismic shear strength and ductility. Experiments were conducted on four columns. One specimen was tested without Ferro cement jacketing and other three specimens were tested with one, two and three layers of Ferro cement jacketing.

7.2 CONCLUSIONS

7.2.1 Optimum Percentage of Longitudinal Reinforcement in Column

As the first part of the investigation, the effect of percentage of longitudinal reinforcement on the performance of the column has been investigated and it is found that the column with 2.01% of longitudinal reinforcement performed well compared to the columns with 1.13%, 3.14% of longitudinal reinforcement.

Column with 2.01% longitudinal reinforcement exhibited 63% and 52% higher ductility than that of the columns with 1.13% and 3.14% longitudinal reinforcement, respectively. Similarly, the energy dissipation capacity of the column with 2.01% longitudinal reinforcement is 72% higher than that of the column with 1.13% longitudinal reinforcement and 64% higher than that of the column with 3.14% longitudinal reinforcement. Considering the lateral load carrying capacity, the column with 2.01% longitudinal reinforcement exhibited 76% and 12% higher capacity than that of the columns with 1.13% and 3.14% longitudinal reinforcement, respectively.

7.2.2 Performance of Retrofitted Columns

In the second part of the investigation, the performance of various specimens retrofitted with GFRP, CFRP, RC, Ferro cement and Steel jacketing were studied and the results were compared. All the specimens were initially loaded up to the development of first crack and then retrofitted. The various parameters considered for the comparative study are (i) lateral load carrying capacity, (ii) energy dissipation capacity and (iii) ductility.

(a) Columns Retrofitted with Glass Fibre Reinforced Polymer (GFRP) Jacketing

Specimens retrofitted with different layers, 2, 4and 6 of GFRP wrapping were considered for the investigation. All the specimens were subjected to lateral cyclic loading and constant axial loading and compared their performance. It is observed that the specimens with 6 layers of wrapping performed well compared to the specimens with 2 and 4 layers of wrapping. The specimen with 6 layers of wrapping exhibited 27% and 7% increase in lateral load carrying capacity compared to that of the specimens with 2 and 4 layers of wrapping as well as 32% higher than the specimen without GFRP wrapping.

Similarly, the specimen with 6 layers of wrapping exhibited 36% and 10% increase in ductility compared to specimens with 2 and 4 layers of wrapping as well as 70% higher than the specimen without GFRP wrapping. At higher levels of lateral displacement, the energy absorbed by the column wrapped with GFRP was 43% higher than the column without GFRP wrapping.

(b) Columns Retrofitted with Carbon Fibre Reinforced Polymer (CFRP) Jacketing

The column retrofitted with single layer of CFRP exhibited 98% higher lateral load carrying capacity compared to the unwrapped column. Similarly, these specimens exhibited 33% increase in ductility and 98% increase in energy dissipation capacity. The failure of these specimens was due to the rupture of the CFRP from the surface of the column. The specimens wrapped with CFRP failed due to the brittle failure of the fibers due to the stress concentration. The CFRP wrapped columns were less ductile than the GFRP wrapped columns.

(c) Columns Retrofitted with RC Jacketing

The parameter considered in this investigation is the variation in percentage of additional longitudinal reinforcement, 0.18%, 0.32%, 0.50% and 0.72%. The RC jacketed specimens were subjected to lateral cyclic loading and the performance were observed and compared.

The specimen jacketed with 0.32% longitudinal reinforcement has shown better performance in all aspects such as; lateral load carrying capacity, ductility and energy dissipation capacity. It was observed that the specimens with 0.32% additional reinforcement exhibited 7 times higher load carrying capacity, 1.25 times higher ductility and 7 times higher energy dissipation capacity compared to the control specimen.

Further increase in percentage of longitudinal reinforcement has not improved the lateral load carrying capacity, ductility and energy dissipation capacity of the jacketed specimens. Hence, it is suggested that 0.32% of additional longitudinal reinforcement is optimum for column of size 100mm x 100mm.

(e) Columns Retrofitted with Ferro Cement Jacketing

The column wrapped with one layer of Ferro cement has the highest load carrying capacity, ductility and energy dissipation capacity compared to the columns with two layers and three layers of wrapping**.** The one layered Ferro cement jacketed column exhibited 57% higher lateral loading capacity, 86% higher ductility and 7.5 times higher energy dissipation capacity compared to the column without jacketing.

(d) Columns Retrofitted with Steel Jacketing

Columns were retrofitted with steel strip (2mm thick), steel plate (2mm thick) and corrugated sheet (2mm thick). Among the steel jacketed specimens, the specimen with steel strip jacketing has the maximum energy dissipation capacity, ductility and energy dissipation capacity. The steel strip jacketed specimen exhibited 43% higher lateral load carrying capacity, 32% higher ductility and 3.5 times higher energy dissipation capacity compared to the un-retrofitted column.

7.3 DISCUSSION

The investigations on the performance of the retrofitted columns is summarized as shown in Table.7.1. The cost comparison of various retrofitting strategies is shown in Table 7.2.

Table 7.1 Comparison of the performance of retrofitted columns

Sl. No.	Type of Jacketing	Percentage increase in various performance of retrofitted columns compared to the un-retrofitted columns			Mode of Failure	Merit	Demerit
		Lateral Load Carrying Capacity	Ductility	Energy Dissipation			
1	GRFP Jacketing	32%	70%	43%	Rupture of GFRP	Higher ductility. Ease of fabrication and bonding. Corrosion resistance, Light weight	Failure was due to rupture of GFRP jacket due to stress concentration. Failure of jacket was observed when subjected to reverse lateral cyclic loading.
2	CFRP Jacketing	98%	33%	98%	Sudden Brittle failure due to Rupture of CFRP	Higher lateral load carrying capacity compared to all other types of jacketing.	Increase in ductility is less compared to GFRP jacketed specimen. Brittle failure of jacket due to stress concentration. CFRP is the most expensive material.
3	RC Jacketing	7 times	1.25 times	7times	Failures of RC jacketed columns were mainly due to the crushing of cover concrete in the plastic hinge region	RC jacketing is a very effective strengthening technique with respect to strength, stiffness and economy. The energy dissipation capacity is high.	Labour intensive.
4	Ferrocement Jacketing	57%	86%	7.5 times	The failure was mainly due to the delaminating of the Ferro cement jacket at the beam column junction.	Better lateral load carrying capacity and good ductility compared to steel jacketing. Less expensive compared to all other types of jacketing except RC jacketing. Light weight compared to steel and RC jacketing.	Corrosion may be possible if air voids are present in the original column.
5	Steel Jacketing	43%	32%	3.5 times	Failure is due to the concrete crushing at the point of termination of the jacketing.	The steel jacketing is effective in passive confinement, ie, confining stress is induced in the concrete as it expands laterally. The jacket can be considered equivalent to continuous hoop reinforcement. Steel jacket is effective in upgrading the lateral strength and ductility of columns.	Corrosion of external plate, Transporting, handling and installation is difficult. Cost of the steel plates is high

Table 7.2 Cost comparison of Jacketed specimens

Sl. No.	Retrofitting technique	Jacketing cost per specimen for 1000mm height of column (Rs.)
1	R.C Jacketing	**950**
2	C.F.R.P Wrapping	12,675
3	G.F.R.P Wrapping	8,850
4	Steel plate jacketing	17,500
5	Steel strip jacketing	5,000
6	Corrugated sheet jacketing	12,500
7	Ferro Cement Jacketing	2,500

From Table 7.1 pertaining to the results on the performance of the retrofitted columns, it is noticed that RC jacketed and Ferro-cement jacketed columns performed much better than the columns jacketed with CFRP, GFRP and Steel jacketed columns. In case of Ferro-cement jacketed columns, the columns failed due to the delamination of the Ferro – cement jacket. As mentioned in Table.7.1, the possibility of corrosion is higher in case of Ferro-cement jacketed specimen compared to the RC jacketed columns. From Table.7.2, it is observed that, the cost of retrofitting with RC jacketing is less compared to all other types of Jacketing. Considering the level of performance and less cost of construction, the RC jacketing can be adopted as the better retrofitting method for the Reinforced Concrete Columns.

7.4 CONTRIBUTIONS

The aim of the present investigation was to arrive at an optimum method of retrofitting of columns. The research outcome of the present work has been presented in Table.7.1 and Table.7.2. The performance, merits and demerits of various retrofitting schemes has been presented. This summary of work is highly useful for the practicing engineers.

7.5 SCOPE FOR FUTURE WORK

- Due to the limitations imposed by the infrastructural facilities, only scaled models of specimens could be included in the present work. This work can be extended to testing full scale specimens of columns and joints.

- In the present study, all the specimens were tested under constant axial load. The study may be extended to specimens for varying axial loads.

- In the present work, the effect of longitudinal reinforcement on Reinforced Concrete jacketing has been studied. The work may be extended to study the effect of transverse reinforcement