CHAPTER 8

SUMMARY AND CONCLUSION

8.1 GENERAL

Reinforced cement concrete wall panels are load bearing integral structural elements of a building system. The conventional wall panels are heavy, reinforced at least with minimum percentage of compression steel and possess handling and erection problems. Thin-walled reinforced concrete wall panels may eliminate the above short comings of the conventional wall panels. They are also highly suitable for modern construction as well as economical.

A thin-walled open section compression member may be a suitable alternative to the rectangular thin wall panels to overcome the stability problems. Various geometrical sections like channel, trapezoidal and curved sections can be used in place of conventional wall panels. By virtue of their geometrical shape, the slenderness effect, hence the stability problem can be minimised if not completely eliminated.

The main objective of the investigation is to study the behaviour of thin-walled reinforced concrete compression members with web stiffener in terms of load bearing capacity, lateral deflection and failure mode and formulate suitable design equations if the existing equations referred in literature are not compatible. Regression analysis based on experimental data is carried out to suggest minimal changes in the existing design equations of
IS 456 – 2000 and ACI 318 – 2008. The entire study is carried out in four phases.

In the first phase of investigation, literature survey was carried out covering the analytical and experimental works so far conducted in the area of the research. A critical review of the published literature indicates that research work available on thin-walled compression members is only related to steel and research on reinforced concrete thin-walled compression members is few. Moreover no literature is available on reinforced concrete thin-walled compression members with web stiffener. However, review of published literature in the area of the investigation either in reinforced concrete or otherwise was taken up to identify the parameters of investigation.

In the second phase of investigation, test specimens were cast. Forty-eighty numbers of channel section test specimens and thirty-six numbers of trapezoidal section specimens were cast. The height, wall thickness, flange width and web width of the test specimens were varied to effect the change in the behaviour and load bearing capacity. All the test specimens were tested to failure in a loading frame. First crack load, lateral deflection, failure load and failure mode were obtained. The modes of failure were identified as torsional-flexural buckling failure and flexural buckling failure.

In the third phase, analysis of experimental results were carried out to study the effect of vertical web stiffener, increase in wall thickness, slenderness ratio and height to flange width ratio were examined and quantified in terms of lateral deflection, first crack load, failure load, stiffness and ductility factors. A series of graphs were drawn to illustrate the influence of above parameters. It is observed that torsional-flexural failure takes place in channel specimens with slenderness ratio less than 40 and beyond which flexural failure takes place. The same limit in case of trapezoidal specimens
found to be 30. The above limit in case of height to flange width ratio is 12 and 10 for channel and trapezoidal specimens respectively. The web stiffener provided has significantly enhanced the ultimate load in all the four series of test specimens, but its contribution is influenced by the slenderness ratio. The contribution of web stiffener in reducing the ultimate lateral deflection is quite effective but again highly influenced by the slenderness ratio. The experimental data of one third number of specimens were used for validation purpose.

In the fourth phase, comparison of the experimental failure load was made with the existing equations of concrete wall design. Their compatibility to the types of open sections tested has been evaluated. Due to lack of compatibility and inconsistent estimation of failure load in different ranges of slenderness ratio, it was decided to formulate an empirical expression for open section compression members in the same form of referred equations. The strength ratio degradation of test specimens with increase in slenderness ratio is the basis on which the empirical equation is formulated. The validity of the proposed empirical equation for other type of specimens has been established using validation tests data. In the second stage of this phase, regression analyses of channel and trapezoidal specimens have been carried out using two exclusive Particle Swarm Optimisation technique programmes written in MATLAB to suggest minimal modification to the existing IS 456 – 2000 and ACI – 318 concrete column/wall formulae. Suitable slenderness and buckling factors were identified, optimised and incorporated in the above formulae without altering the present basic form of equations. The compatibility of the modified IS and ACI expressions has been tested for channel and trapezoidal specimens and found to be satisfactory. Finally comparison of theoretical ultimate loads of empirical equation, modified ACI – 318 concrete walls and IS 456 – 2000 short column equations were made. In order to make the existing IS 456 short column and ACI – 318
concrete wall equations applicable to the type of open section thin-walled specimens tested, suitable buckling coefficients for channel and trapezoidal sections have been computed. All the three proposed equations are simple to use and yield reliable estimation of ultimate load.

8.2 MAJOR FINDINGS

The following are the major findings of the present investigation made on the basis of the experimental observations, interpretation of results and regression analysis.

1. Torsional-flexural buckling failure takes place in channel section specimens with slenderness ratio less than 40, beyond which the specimens suffered flexural buckling failure.

2. The limit of slenderness ratio for torsional-flexural buckling failure in case of trapezoidal section specimens is 30. Trapezoidal section specimens with slenderness ratio more than 30 suffered flexural buckling failure.

3. The limit of height to flange width ratio for torsional-flexural buckling failure to take place in channel section specimens is 12 and beyond this limit flexural buckling governs the mode of failure.

4. Torsional-flexural buckling failure occurred in trapezoidal sections specimens with height to flange ratio less than 10, beyond which flexural buckling mode of failure takes place.

5. No specimen failed due to local buckling like conventional thin-walled steel compression members.
6. The C₃₀ specimens with λ less than 40 on average carried 58.2% more load at ultimate stage than C₀ specimens due to the provision of vertical web stiffener. The same increase in load bearing capacity for specimens with λ greater than 40 is 25.6%.

7. The C₃₀ specimens with λ less than 40 on average carried 43.2% more load at first crack than C₀ specimens due to the provision of vertical web stiffener. The same for specimens with λ greater than 40 is 28.7%.

8. The beneficial effect of web stiffener in enhancing the load bearing capacity at first crack remains uninfluenced by the slenderness ratio. But the beneficial effect gradually reduces with increase in λ in case of ultimate load capacity.

9. The T₃₀ specimens with λ less than 30 on average carried 28.83% and 37.04% more load at ultimate and first crack respectively than T₀ specimens. The same for specimens with λ greater than 30 is 31.39% and 42.26% respectively, indicating that the contribution of web stiffener is nearly constant and uninfluenced by λ of the specimens.

10. The influence of web stiffener on the strength ratio at first crack and ultimate load remains nearly at constant level over the entire range of λ considered for channel and trapezoidal specimens. The strength of the section utilised in supporting the load rapidly decreases with increase in λ at ultimate stage for both series of specimens.
11. The strength ratio degradation with increase in λ can be taken as a measure to predict the load capacity of thin-walled compression members.

12. The web stiffener provided has reduced the ultimate lateral deflection of C_{30} specimens with λ less than 40 by 34.20% than that of C_{0} specimens. The same for specimens with λ more than 40 is only 8.22%, indicating the adverse effect of slenderness ratio in curtailing the beneficial contribution of web stiffener.

13. The lateral deflection at first crack of C_{30} specimens with λ less than 40 is 28.29% more than that of C_{0} specimens. The same for specimens with λ more than 40 is 18.28%, indicating higher resistance to first crack due to the stiffness infused by the web stiffener.

14. The lateral deflections suffered by T series specimens are also similar to that of C series specimens indicating that the effect of web stiffener is same for both series of specimens.

15. The vertical web stiffener provided has significantly enhanced the initial stiffness and ultimate stiffness of torsional-flexural buckling failure specimens of C and T series. The same in case of flexural buckling mode failure specimens is less than one third of the above increase.

16. The ductility factor possessed by C and T series torsional-flexural buckling failure specimens is less than that possessed by flexural buckling failure specimens.
17. The web stiffener has reduced the ductility factor of web stiffened C and T series torsional-flexural buckling failure specimens by nearly 50% than that of unstiffened specimens. The same for flexural buckling failure specimens is about 25%, indicating loss of stiffness with increase in slenderness ratio.

18. The web stiffened specimens become moderately ductile at higher ranges of $\lambda$ without any major compromise on the stiffness and strength.

19. The ratio of ultimate to first crack load of specimens with $\lambda$ more than 40 is in the range of 1 to 1.2, indicating that the failure takes place soon after the formation of first crack.

20. The ratio of ultimate to first crack load of specimens with $\lambda$ less than 40 is in the range of 1.2 to 1.5, indicating that even after the formation of cracks, significant resistance to failure is offered by the specimens by the virtue of web stiffener.

21. The increase in wall thickness of $C_{30}$ series specimens with $h/b_f$ ratio less than 12 has increased the strength ratio nominally by 6.7% than that of $C_{25}$ series. The same in specimens with $h/b_f$ ratio greater than 12 is insignificantly at 1.6%, indicating that nominal increase in wall thickness will not contribute much in enhancing the strength ratio.

22. The increase in wall thickness has contributed a corresponding increase in first crack and ultimate load supported by the C and T series specimens for the entire range of $\lambda$ due to increase in cross sectional area and not due to increase in section efficiency.
23. The increase in wall thickness has contributed a corresponding increase in first crack stiffness by 41.33% for specimens with h/b\(_f\) ratio less than 12. The same is 24.49% for specimens with h/b\(_f\) ratio more than 12.

24. The increase in wall thickness has contributed a corresponding increase in ductility factor by 11.37% for the entire range of h/b\(_f\) ratio.

25. Any increase or decrease in percentage reinforcement provided in single layer in thin-walled compression members of C and T series has negligible effect or contribution to the ultimate strength of the section.

26. The empirical expression formulated for channel specimens on the basis of strength ratio degradation agrees well with the experimental ultimate loads of both C and T series specimens.

27. The value of shape factor used in the empirical expression to predict the ultimate load is rounded off, so that it is simple to use.

28. The empirical equation suggested in the present investigation and modified IS 456-2000 and ACI 318-2008 equations obtained using the programmes written in MATLAB for regression analysis of experimental data by Particle Swarm Optimisation technique; show good correlation with experimental ultimate load and can be used to predict the ultimate load of thin-walled C and T series compression members.
29. Out of the three equations suggested the empirical equation (Equation 6.7) obtained in the present investigation is most reliable, safe and nominally conservative in estimation of ultimate load.

30. Buckling coefficients are calculated so as to make the existing equations of IS 456 short columns and ACI 318 concrete walls applicable to the type of thin-walled open section members tested.

31. For optimum exploitation of section efficiency, material strength and effectiveness of stiffener, the \(\lambda\) shall be limited to 40 and 30 for C and T series specimens respectively. The same limits in terms of \(h/b_t\) ratio are 12 and 10. The above limits for \(b_w/b_t\) ratio are 2 and 1.71. The limits for \(h/t_e\) ratio are 36 and 30 for C and T series specimens respectively.

### 8.3 CONCLUSIONS

The following are the generalised important conclusions obtained in the present investigation done by carrying out an extensive experimental programme on thin-walled RC open section compression members with vertical stiffeners, detailed and systematic analysis of the results obtained aided by regression analysis using MATLAB during different phases of the research programme.

1. Torsional-flexural buckling governs the ultimate failure of all thin walled web stiffened RC channel section members with slenderness ratio \(\lambda\) less than 40. The governing mode of failure for these members with slenderness ratio greater than 40 is flexural buckling.
2. The limit of slenderness ratio for governing mode of failure in case of thin walled RC trapezoidal section members is found to be 30.

3. Similarly torsional-flexural buckling governs the failure mode of all thin walled channels with height to flange width ratio (h/bf) less than 12 and beyond these limiting ratio, the channels suffers flexural buckling mode of failure.

4. For trapezoidal section members the limiting ratio of height to flange width ratio which governs the mode of failure is observed to be 10.

5. The conventional local buckling failure associated with thin-walled steel compression members is not applicable to thin-walled RC compression members.

6. The presence of vertical web stiffener is not only very effective in enhancing the initial and ultimate stiffness but also contributes towards; reduction in lateral deflections, improvement in strength ratio and finally results in increase in load carrying capacity of these open sections thin- walled RC members.

7. The contribution of vertical web stiffener in enhancing load carrying capacity remains unaffected by the influence of slenderness ratio as long as the specimens are crack free.

8. The ultimate load capacity of the section is not influenced by variations in percentage of reinforcement provided in single layer in the vertical direction.
9. It is also observed that the small increase in wall thickness contributes corresponding increase in load capacity.

10. The empirical equation formulated in the present investigation to predict the ultimate load carrying capacity of thin-walled RC members on the basis of strength ratio degradation correlates well with the experimentally observed ultimate loads. The same is also vindicated by the test results of the validation specimens.

11. The above proposed empirical equations can be used to predict the ultimate load capacity of thin-walled open section RC compression members in a safe and nominally conservative manner.

12. The modified IS 456-2000 and ACI 318-2008 equations also show good correlation with experimental results and can be used in the design process.

13. The thin-walled open section RC compression members with vertical stiffeners studied in the present investigation will serve as a suitable alternative to the conventional rectangular thin wall. They are also highly suitable for modern construction as well as economical.

8.4 Scope for Further Work

- Experimental study similar to the one conducted can be undertaken on different geometrical profiles such as curved shell, angular, corrugated open sections.
• Analytical studies, stress – strain based investigation and numerical analysis can be conducted on the type of members tested in this thesis.

• The behaviour of open section compression members with slenderness ratio less than 12 and more than 70 can be studied.

• The grade of steel reinforcement and concrete, \( h/t_e \) ratio, \( b_o/b_f \) ratio, \( h/b_f \) ratio, type of stiffener and support conditions can be varied for further study.

• Experimental investigation can be conducted to study the performance, interaction and behaviour of these elements when assembled in groups forming load bearing straight wall, wall junction, wall with door and window openings and return (corner) wall.