CHAPTER 2

LITERATURE REVIEW

2.1 GENERAL

An elaborate discussion on the works carried out so far is made in this chapter as literature review. Geometrical and slenderness effects of composite columns and their behaviour studies are discussed as initial subheadings. Subsequently, works on waste materials and codal provisions are discussed comprehensively.

2.2 HISTORICAL BACKGROUND

With the advent of steel and reinforced concrete, the concepts in construction has changed from one of securing stability to that of stressing the materials to the optimum values. This has resulted in very light structures compared to the pre-19th century constructions. This has been made possible by eliminating in the newer materials, the short comings of poor tensile strength of the traditional materials.

In order to critically evaluate the research works done in the area of concrete filled steel tubular composite columns, a detailed review of literature in the field of CFST column has been undertaken. The state-of-the-art research on CFST column has been critically reviewed and grouped under various categories. They are presented in the following sections.

The history of the first application of composite columns in construction industry dates back to the 1940’s. The year 1970 marked the
evolution of concrete filled steel tubes in Japan and this practice was followed by many countries around the world. On the basis of the research results, many countries have developed their design codes for use by their engineers. The current design standards and specifications have originated either from the steel or concrete design approach of that time.

2.3 REVIEW ON COMPOSITE COLUMNS

A comprehensive review of the international research work covering the period from the early experiments until 1960 was published by Viest (1960). A similar review by Johnson (1970) that covered the period from 1962 to 1969 was also published in an industry not particularly addicted to change the adoption of a new method is likely to be slow, even if the method can be shown to be economical. Only limited attention has been paid to either circular thin walled steel tube with medium-strength concrete or circular thick walled steel tubes with high strength concrete. However it has been indicated that the improved strength of the circular thin-walled tubes filled with concrete is due to the influence of bond between the steel tube and concrete rather than lateral restraint. A significant amount of effort over the past 40 years has been aimed for better understanding of circular concrete filled tubes. The obvious advantages of CFST attracted the attention of research workers all over the world. Research works related to such types of steel-concrete composite columns are presented and discussed below.

Dutta and Bhattacharyya (1995) made experimental study on the behaviour of concrete filled steel tubular columns. They observed that the load carrying capacity of concrete filled steel tubular section is more than that of hollow steel tubular columns. It is reported that this increase in strength is not merely due to the addition of individual capacity, but due to confinement of concrete. The strength increases by a certain factor λ. The strength increase factor λ obtained in that study was 2.206.
O’Shea and Bridge (1995) conducted studies on short CFST columns. The loading conditions examined include axial loading of the steel only, axial loading of the concrete only, and simultaneous loading of the concrete and steel both axially and at small eccentricities. The test specimens were short with a length-to-diameter ratio of 3.5 and a diameter thickness ratio between 60 and 220. The internal concrete had nominal unconfined cylinder strengths of 50, 80 and 120 MPa. It was concluded that the strength of unfilled circular steel tubes have been found to be significantly affected by local buckling. Although the buckling strength of square tubes can be improved by providing internal lateral restraint, this was not observed in the circular steel tubes examined. Instead, the predominantly outward buckle remained unaffected by the internal concrete. For axially loaded thin-walled steel tubes, local buckling of the steel tube does not occur if there is sufficient bond between the steel and concrete. An equation was developed to give a better estimate of the ultimate strength of the thin-walled steel tube based upon an effective area approach.

Claeson and Gylltoft (2000) conducted tests on series the structural behaviour of six-slender reinforced concrete columns that were subjected to short-term loading. The concrete strengths used were 35 and 92 MPa with a load eccentricity of 20 mm. Key parameters such as concrete strength, concrete and steel strains, cracking, mid height deflection, and loading rate were studied. It was observed that the high strength concrete (HSC) columns subjected to short-term loading displayed less ductility and had more sudden failures than the normal strength concrete (NSC) columns. Furthermore, the tests conducted indicated that the structural behaviour of the HSC was favorable under sustained loading i.e., the HSC column exhibited fewer tendencies to creep and could sustain the axial load without much increase in deformation for a longer period of time.
Shanmugam and Lakshmi (2001) presented a state-of-the-art review of the research carried out on composite columns with emphasis on experimental and analytical works. Experimental data were collected and compiled in a comprehensive format, listing the parameters involved in the study. The review also included research works that was carried out to account the effect of local buckling, bond strength, seismic loading, confinement of concrete and secondary stresses on the behaviour of steel-concrete composite columns including CFST columns.

Researchers like Elremaily and Azizinamini (2002) investigated the behavior of concrete-filled steel tube columns under seismic loads were also by testing six columns subjected to an axial load. Test conducted for cyclic lateral loads. An analytical model was developed to predict the capacity of circular CFST beam-columns accounting for the interaction between the steel and concrete. The developed analytical model was compared with the experimental data. Good concurrence was observed between the predicted values using the anticipated model and the experimental output. The CFST columns showed high ductility and maintained their strength till it fails. They concluded that the column capacity had significantly improved due because of the concrete strength gained from the confinement provided by the steel tube.

Morino and Tsuda (2003) introduced the structural system and discussed the advantages, research findings and recent trends of the CFT column system in Japan. Extensive research work has been done in Japan in the last 15 years, including the “New Urban Housing Project” and the “US-Japan Co-operative Earthquake Research Program”, in addition to the work done by individual universities and industries that were presented at the annual meeting of the Architectural Institute of Japan (AIJ). A rational design method for the CFT column system has been established through extensive research by the AIJ. Authors concluded that the characteristics of CFT make
the system especially applicable to high-rise and long-span structures, because the system’s construction efficiency saves construction cost, time, and manpower.

Sakino et al. (2004) tested a total of 114 specimens in the experimental investigations on centrally loaded hollow and CFT short columns. The objectives of these tests were to investigate the confining effect of steel tubes on concrete strength and the restraining effect of the concrete fill on local buckling of the steel tube wall, and also to derive methods to evaluate ultimate load and load - deformation relationships. Parameters for the tests were as follows: (i) tube shapes (circular and square); (ii) tube tensile strength (400, 600 and 800 MPa); (iii) tube diameter (width)-to-thickness (D/t or B/t) ratio; and (iv) design concrete strength (20, 40 and 80 MPa). According to the values of the D/t or B/t ratio, the specimens were classified into three groups. The value of D/t ratio or B/t ratio was controlled by changing the outside diameters of circular tubes (122-450 mm), or the widths of square tubes (120–324 mm). The circular steel tubes were cold formed from a flat plate by press bending and seam welding. Design formula to estimate the ultimate axial compressive load capacities were proposed for CFT columns with both circular and square sections based on tests results was obtained. The difference between the ultimate strength and the nominal squash load of circular CFT columns, which is provided by confining the concrete, can be estimated as a linear function of the tube yield strength. The capacity reduction factor due to local buckling of the square steel tube wall was empirically derived based on the test results of columns.

Hatzigeorgiou and Beskos (2005) studied the minimum cost design of fibre reinforced concrete filled steel tube columns. They took into account the effects of confinement of concrete and its steel fibre reinforcement. The authors considered the constraints of the optimum design, prescribed by the
strength and stability requirements that are adopted from the provisions of modern structural codes. A computer program for the analysis was developed, which emphasizes the dimensioning of the composite column and identification of the optimum quantity of fibres in matrix material. The design variables of the problem were the dimensions of the column (external radius and steel tube thickness) and the percentage of steel fibres. Applications using numerical examples demonstrated that fibre reinforced concrete filled steel tube columns can be designed both economically and effectively using the proposed methodology. The authors concluded that, it was difficult to construct practical rules for the optimum design of composite columns since it was a native market cost dependent procedure.

Another interesting investigation was carried out by Kuranovas and Kvedaras (2007). They used steel circular hollow sections (CHS) for their investigation. Yield and ultimate strength of CHS were determined by standard steel plate coupons and rings tests. Theoretical and experimental investigations showed that behaviour of hollow steel tube elements was more complicated than that of solid ones. Because of complex stress states, none of stresses in hollow concrete core were evenly distributed through the thickness of its cross-sections. They also discussed the Poisson’s ratio of the CFST and concrete columns, and found that the average value of Poisson’s ratio for steel tube was 0.28 and that of the concrete column was noted to be approximately equal to 0.175.

Helena et al. (2007) investigated the load-deformation behaviour of concrete filled rectangular sections subjected to a combination of compression and flexure. Experimental and analytical investigations were carried out to assess the stiffness characteristics and load carrying capacity by varying the strength of the in-filled concrete and also the eccentricity of loading. Two grades of concrete M 20 and M 30 were used in this study. A
total of 32 tests, in each series were carried out applying the load axially, uni-axially along the major axis, uni-axially along the minor axis and also bi-axially. Increase in the strength of in-fill substantially improves the initial stiffness and the ultimate load. Based on the experimental investigations, a non-linear finite element model using the Finite Element package ANSYS was developed to predict the ultimate load and behaviour of cold formed steel concrete filled rectangular columns. The authors concluded that for all the cases the model closely predicted the behaviour on the conservative side. Ultimate loads predicted by AISC-LRFD and EC4 were also compared with the experimental results. The initial stiffness was predicted by the numerical model with a standard deviation of 0.07. The column capacity was predicted well within a margin of 10% on the conservative side. The concrete filled sections, as predicted by AISC-LRFD, showed a variation that was found to be 34 % on the conservative side when the eccentricity was less. The predictions by EC4 was also well within a margin of 10%.

2.4 STUDIES ON GEOMETRICAL EFFECTS

Kvedaras and Sapalas (1996) carried out investigations on hollow and concrete filled steel tubular construction and found that CFST had its efficiency due to the effective shape of cross section of load bearing members. Their field of research was on super-thin and thin walled steel tubular columns and beam-columns. The investigated steel tubular members were supplied with hollow concrete cores formed by centrifugal force. The fundamentals of behavioural and structural analysis with the substantiation of principles of design methods for members and connections were presented. In this study the main attention was paid to projects in concrete filled steel tubular structures, realized in various buildings and that which provided their great technical and economical efficiency, safety and reliability.
Shams and Saadeghvaziri (1999) presented an evaluation of the nonlinear response of concrete filled steel tubular columns that were subjected to axial loading. They developed a three-dimensional finite element model for CFST columns and compared the results against existing experimental values. They indicated that the stress-strain properties of the confined concrete were highly affected by the geometrical configuration of the columns as well as material properties of concrete. It was found that the confinement effect in circular columns was higher than that in square columns due to more uniform stress distribution. Concrete with a lower unconfined compressive strength exhibited higher confinement ratio than higher strength concrete. The amount of increase in the maximum compressive strength of concrete mainly depended on the D/t ratio, unconfined concrete compressive strength and cross-sectional shape. The strain at maximum stress depended on the D/t ratio and cross-sectional shape.

Another interesting investigation was carried out by Zheng et al. (2000) that studied a rational ductility evaluation procedure for thin-walled steel structures. This method involved an elasto-plastic push-over analysis and failure criterion based on the empirical ductility equations proposed for stub-columns. Local buckling was considered as the failure criterion and they suggested that the local buckling could be neglected in the push over analysis, which facilitated practical application. The implementation of the proposed procedure was demonstrated by application to the ductility evaluation of some cantilever columns and one-storey frame. Extensive parametric analysis were carried out to investigate the relation of the stub column ductility to various parameters such as the flange width-thickness ratio, axial force, stiffeners slenderness ratio, cross-sectional shape, and column aspect ratio. An elasto-plastic large deformation FEM analysis was employed and both residual stresses and initial deflections were taken into consideration. Consequently, empirical formulae were proposed.
Dalin Liu (2005) conducted tests using 22 specimens in four series that were fabricated and tested in the research programme. The material properties of steel and concrete were obtained from respective tensile and crushing tests. The ultimate capacities and axial load-shortening relationships of the specimens were recorded for analysis. A steel hollow section was formed by welding four component flat plates together to form the hollow steel section. The specimens were tested 32 days after the concrete was cast. An axial load was applied by a 5000 kN capacity Universal Testing Machine. Four displacement transducers were placed symmetrically around the specimen between the two platens of the testing machine to measure the overall deformation. Four strain gauges were bonded on to the exterior surfaces of the steel section at mid-height to record the longitudinal strain. The author suggested that the rectangular steel hollow sections were generally considered to be less effective than circular ones in terms of offering confinement to the concrete core. This is because the rectangular steel section confined the concrete core by plate bending, while the circular section by hoop stress. Test results manifest the favorable ductility performance of the high-strength composite columns. The strength increase of the concrete resulting from confinement by the steel section was observed. The strength improvement was adversely affected by the cross-sectional aspect ratio. Comparison of failure loads between the tests and the design codes were presented. Results showed that the provisions in EC4, ACI and AISC conservatively estimated the ultimate capacities of the specimens by 1, 9 and 11%, respectively.

Han et al. (2008) experimentally investigated the behaviour of concrete filled steel tubular stub columns that were subjected to axial compression. A total of 32 specimens were tested. The main parameters varied in the tests were: (i) sectional types: circular and square; (ii) local compression area ratio (concrete cross-sectional area to local compression
area): 1.44 and 16; and (iii) thickness of the end plate: from 2 to 12 mm. A finite element analysis modeling was used for the analysis of CFST stub columns subjected to axial local compression. A comparison of results using this modeling showed generally good agreement with the test results. The theoretical modeling was also developed and then used to investigate the mechanism of the composite columns subjected to axial local compression. For convenience of analysis, strength index (SI) and ductility index (DI) for CFST stub columns subjected to axially local compression were calculated. The authors concluded that the bigger the end plate thickness, the higher the SI and the DI.

2.5 STUDIES ON SLENDERNESS EFFECTS

Knowles and Park (1970) studied tubes loaded axially and eccentrically for the effect of slenderness ratios. They adopted tangent modulus approach and found an agreement between theoretical and test results. They found that volume dilation takes place at about 95 % of the maximum load and a strain level beyond 0.002. They stated that the confinement action for square tubes was absent, while they have reported an increase from 55 to 69 % of the corresponding uni-axial strength for circular tubes. They concluded that CFST behaviour was different from what would be expected from classical theory of mechanics, assuming complete interaction and strain compatibility at all levels of loading. They found that concrete suddenly increased in volume beyond a particular strain and caused internal pressure on the steel tube, which in turn exerted confining strength. They further concluded that the possibility of bond failure at the inner surface cannot be ruled out. In their tests the factor of safety was observed to be between 2.75 and 4.0.

Shao - Huai Cai (1987) tested seven phases aimed at the ultimate strength analysis of concrete filled steel tube columns. A working mechanism
for short concrete filled steel tube columns was presented. The limit equilibrium method was used to derive a formula for the ultimate strength of the short columns. They suggested a global strength reduction factor of the standard column expressed as the product of the reduction factors due to slenderness ratio. Empirical formulae for predicting these factors were proposed. They also suggested a method for converting the strength of a non-standard column to that of an equivalent standard column. Empirical formulae for predicting the equivalent length of standard column were also discussed.

Another interesting investigation was carried out by Shan-Tong and Yu (1987) that studied stress-strain relationship and strength of concrete filled tubes experimentally and analytically for the specimens of different L/D values from 2 to 5 under axial compression. They recommended a standard test for determining the basic stress-strain relationship, and approximate procedures for determining ultimate strength of the tubes. In this study, two approaches were taken to determine load carrying capacity. In the first approach the concept of plastic limit analysis was used. In the second approach, it was assumed that both steel and concrete behaved elastically until the limit load was reached. Finally they concluded that the deformation behaviour of a concrete filled tube (with $\alpha$ not less than 0.04) was very much like a plain steel tube with good ductility and energy absorption capacity.

Ramajeyam and Swamidurai (1997) conducted an experimental work on concrete in-filled tube stiffened with mesh of various shapes. They studied the behaviour of hollow tubes, concrete in-filled tubes and concrete in-filled tubes stiffened with mesh. They suggested that research on concrete filled steel tubular columns was restricted to short specimens, and this led to identifying methods for calculating their ultimate loads which might seriously overestimate the load carrying capacity. The authors suggested that a tangent modulus approach which sums the flexural rigidity of the steel tube and the
concrete core. Besides, at higher loads, as in-filled concrete tubes deflected, maximum and minimum longitudinal strains varied considerably, and it was felt that taking the average was not sufficiently accurate. Considering the complexity of the problem, a simplified equation for obtaining the load carrying capacity of concrete in-filled tubular columns was suggested

\[ P_u = 0.67 A_c f_{ck} + 0.87 (A_{s1} f_{y1} + A_{s2} f_{y2}) \]  

where,
- \( P_u \) = Ultimate load carrying capacity
- \( f_{ck} \) = Characteristic strength of concrete
- \( A_c \) = Area of the core
- \( A_{s1} \) = Area of cold formed section
- \( f_{y1} \) = Yield strength of cold formed sheet
- \( A_{s2} \) = Area of welded wire fabric
- \( f_{y2} \) = Yield strength of welded wire fabric

They concluded that concrete in-filled cold formed steel columns stiffened with weld mesh showed large enhancement of load carrying capacity as compared to cold formed hollow steel column without in-fill and could sustain large strains and deformations. Test results were fairly well with predicted loads of column which was based on the above equation. In their study they concluded that hollow steel tubes did not show any local buckling of steel and concrete in-filled tubes showed local buckling of shell. They also concluded that concrete in-filled tubes stiffened with mesh showed a mixed behaviour.

Brain Uy (2000) carried out experimental study on the effect of steel plate slenderness limits. A numerical model developed elsewhere was augmented and calibrated with these results. The author developed a simple
model for the determination of the strength-interaction diagram which was verified against both the test results and the numerical model developed. This model based on the rigid plastic method of analysis, was existent in international codes of practice, but did not account for the effects of local buckling, which were found to be significant with large plate slenderness values, particularly for large values of axial force. Based on the study, the author suggested some modifications for the inclusion of slender plated columns in design.

Brain Uy (2001) also carried out an extensive set of experiments on the strength of short concrete filled high strength steel box columns. In his study a numerical model was presented with these tests. Further more, comparisons with the Eurocode4 for composite columns were also undertaken and this was found to be un-conservative in its prediction of axial and combined strengths. Therefore a mixed analysis technique was presented, which treated concrete as rigid plastic and steel as linear elastic. This model was compared well with the numerical model presented and both these models were found to be conservative in predicting the test results.

Brain Uy (2003) who also investigated three series of experiments undertaken to determine the combined behaviour under compression and bending for high strength steel box columns filled with concrete. Each series had a different plate slenderness limit, however all were considered to be compact in terms of restrained local buckling slenderness limits and thus no reduction due to local buckling of the component plates was expected. In order to ascertain the stress-strain behaviour of the steel in both tension and compression, a series of tensile coupon and stub column tests were conducted. Columns were tested in both pure compression and under combined bending and compression. In order to ensure a uniform loading surface, columns were cast in plates with plaster at either end. The eccentrically loaded columns
were loaded using a knife-edge at both the top and bottom of the column. The test set up included strain gauge and Linear Variable Deformed Transducers (LVDT). The author concluded that the maximum loads were obtained from curves of specimens under pure compression. Furthermore, as the eccentricity was increased the maximum axial load that achieved was reduced. And this was the expected result for a column under combined actions. The load-strain curves for these columns were useful in determining the one set of yield as well as highlighting local buckling on the compression faces which was in elastic in all the columns and beams tested. Note worthy is the fact that all columns behaved in a fairly ductile manner with a considerable plastic plateau. Furthermore, premature fracture of the welds was not evident in any of the columns tested.

Tao et al. (2005) tested nineteen specimens, including thirteen square CFT stub columns, two rectangular CFT stub columns and four empty square steel stub columns for reference. They were tested to failure under concentric compression. All tubes were manufactured from mild steel sheet with a measured thickness of 2.5 mm. A 5000 kN capacity testing machine was used for the compression tests of all specimens. The adjustment was terminated until the difference between the measured strain and the average value was not more than 5%. In addition, two displacement transducers were used to measure the axial shortening during the tests. A load interval of less than one tenth of the estimated load capacity was used. Each load interval was maintained for about 2 to 3 minutes. They concluded that when compared with the steel columns, the ultimate strength of the composite columns was greatly increased because of the in-filled concrete. In the case of un-stiffened composite columns, the load carrying capacity of specimen under estimates could be observed. The sectional capacity of the composite stub columns could be increased when stiffeners were provided. And also, no ductility improvement for stiffened CFT columns was observed in the current test. The
increment of moment of inertia of stiffeners did not significantly influence the ductility of the stiffened CFT specimens

Zeghichea and Chaoui (2005) conducted an experimental study on 27 concrete filled steel tubular columns. The column slenderness, the load eccentricity covering axially and eccentrically loaded columns with single or double curvature bending and the compressive strength of the concrete core were the test parameters. The circular steel tube had an outer diameter of 160 mm with a wall thickness of 5 mm. The length of the columns varied from 2.0 to 4.0 m in increments of 500 mm and they were filled with concrete in the vertical position. Three groups of columns were tested under different loading conditions. Columns of the first group were tested under axial loads, columns of the second group were subjected to equal eccentric loads with $e/D$ ratio varying from 0.05 to 0.20 and columns of the third group were tested in double curvature bending. All the columns were tested in a compressive testing machine with a maximum load capacity of 10000 kN. A set of adapter end plates equipped with half-spherical bearings were manufactured and fixed to both ends of each column to form a simply supported column. The main parameters studied were the length of the composite column and the concrete strength. The $L/D$ ratio varied from 12.5 to 25.0. The author concluded that the increase of the concrete core strength was effective for shorter columns and decreased with the increase of the composite column length. All axially loaded columns failed after having reached the steel yield strain with small lateral mid-length deflections.

Gopal and Manoharan (2006) conducted an experimental study of 12 slender steel tubular columns of circular sections filled with both plain and fibre reinforced concrete. The specimens were tested under eccentric compression to investigate the effects of fibre reinforced concrete on the strength and behaviour of slender composite columns. The slenderness ratio
was considered to be the main test parameter in this study. Hollow steel sections of similar specimens were also tested as reference columns. The test results were illustrated by load-deflection and load-strain curves. Various characteristics such as strength, stiffness, ductility, energy absorption capacity and failure mode were discussed. Interpretation of the experimental results indicated that the use of the fibre reinforced concrete as infill material had a considerable effect on the strength and behaviour of slender composite columns. The authors concluded that the use of FRC filled steel tubular columns have relatively high stiffness compared with plain concrete filled columns. The ductility was found to be almost equal for both plain and FRC filled columns. The use of FRC as a filling material increased the load bearing capacity to a much greater extent compared with that of unfilled columns and reduced the lateral displacements.

2.6 INFLUENCE OF WASTE MATERIALS IN CONCRETE

In big and over populated cities, old and dilapidated structures are demolished for the purpose of building new and high rise structures. As a result, considerably large amounts of debris, waste granite pieces from flooring and rubble get accumulated in cities that pose a serious threat to the environment. Further, this waste material must to be transported for disposal. In a developing country like India, the twin objectives of conservation of natural resources and ensuring a pollution free environment may be achieved if this debris or rubble is effectively utilized, i.e. recycled by using the same in new constructions.

Recycled aggregate concrete utilizes demolition material from concrete and burnt clay brick masonry construction as aggregate. Reuse of demolition waste avoids the problem of waste disposal and is also helpful in reducing the gap between the demand and supply of crushed granite fresh aggregate. While the amount of demolition waste materials generated in India
has not yet been quantified properly, it is thought that presently the yearly rate of demolition of buildings and other structures in the major cities has reached 1 to 2 percent. This is mainly due to the following reasons:

- demolition of structures which have become obsolete either in serving the basic functions or due to structural deterioration.
- demolition of structures for better economic gains (through new construction).
- waste construction material formed due to natural disasters like earthquake, cyclone and flood, and
- war-inflicted damages.

Ramamurthy and Gumaste (1998) studied the properties of recycled aggregate concrete and the authors reported that recycled aggregates possessed relatively lower bulk density and higher water absorption as compared to those of fresh granite aggregates. The compressive strength of recycled aggregate concrete was relatively lower and the variation depends on the strength of original (demolished) concrete from which the aggregate was obtained. This reduction was mainly caused by the bond characteristics of recycled aggregate and the fresh mortar of the recycled concrete. The authors concluded that in the case of concrete with fresh granite and recycled concrete aggregate, the reduction in strength was gradual as the mix a become leaner, whereas this reduction was not pronounced in concrete with both types of recycled brick masonry aggregates. Such a trend may be attributed to the higher crushing value of recycled brick masonry aggregates, that is, crushing of aggregates in concrete governed the failure of cubes, thereby reducing the influence of mix proportion.
A similar study had been conducted by Mandal et al. (2002) reported in his paper elsewhere showed that the strength of recycled aggregate concrete was comparatively lower than that of similar mix of conventional concrete. However, with the use of fly-ash, it might be possible to produce recycled aggregate concrete with an improvement in strength. The results of this investigation also showed that drying shrinkage strain, permeability and water absorption of the recycled aggregate concrete was more when compared to conventional concrete. However, the quality of recycled aggregate concrete was found to improve considerably with the addition of fly-ash. This, in turn, improved the durability of recycled aggregate against sulphate and acid attack. Therefore, the result of that study provided a strong support for the feasibility of using recycled aggregates instead of natural aggregates for the production of concrete. He suggested that more research studies on recycled aggregate concrete were necessary for the practical application of recycled aggregate concrete.

In the attempt of Sahu et al. (2003) crushed stone dust waste as fine aggregate for concrete was assessed by comparing its basic properties with that of conventional concrete. Two basic mixes were chosen for natural sand to achieve M 20 and M 30 grade concrete. The equivalent mixes were obtained by replacing natural sand by stone dust partially and fully. Based on the test results they concluded that crushed stone dust waste could be used effectively to replace natural sand in concrete by 40 percent and sand was replaced by quarry dust in concrete. It not only reduced the cost of the concrete but at the same time saved large quantity of natural sand and also reduced the pollution created due to the disposal of this stone dust on valuable fertile land. There has been inadequate utilization of large quantities of crushed stone as alternative material, left out after crushing of rock to obtain coarse aggregate / ballast for concrete. Crushed stone dust does not satisfy the standard specification of fine aggregate in cement mortar and concrete.
Efforts have been made to replace river sand by rock dust. Based upon the results, the effect of partial replacement of dust on workability, compressive strength, modulus of rupture and splitting tensile strength showed a significant increase.

Some studies have also been conducted by Sanni et al. (2004) and they presented an article that highlighted the use of recycled aggregate concrete both from strength and workability point of view. A study was conducted with nominal mixes, which were traditionally being used in the field. The three mixes chosen were 1:2:4, 1:1.5:3 and 1:1:2 all by volume and with different water-cement ratios. Mechanical behaviour of tests like compressive strength (cube & cylinder) and flexural strength were conducted on specimen of standard size and results were discussed. Based on the results of the investigations, workability, compressive strength and flexural strength of the recycled aggregate concrete was found to be marginally lower than that of the conventional concrete. But the authors concluded that economical and environmental pressures justified consideration of this alternative material source, in places where available sources of new rocks were inaccessible.

2.7 REVIEWS ON CODAL PROVISIONS

The different approaches adopted by various codes on composite construction for the design of CFST columns are given below: The Eurocode4 is based on the rigid plastic method of analysis which assumes fully crushed concrete and fully yielded steel. The code ACI 318 uses the traditional reinforced concrete approach, with a minimum load eccentricity that is used to determine the column strength under nominal axial load. The code DL/T5085-1999 is based on the unified theory that considers the CFST member as a composite member, as opposed to the separate components.
Task Group 20 (1979) of the Structural Stability Research Council (SSRC) proposed specifications for the design of steel-concrete composite columns in 1979, which was subsequently incorporated in the 1986 AISC-LRFD code. These specifications required that steel-encased concrete sections be designed in a way that is similar to the design of steel columns, with modifications to the steel yield strength, modulus of elasticity, and radius of gyration to account for the effect of concrete and longitudinal bars. The specifications also placed limitations on the percentage area of steel, concrete strength and minimum thickness of the steel shell. The minimum thickness for steel shells in circular composite columns was calculated using the equation:

\[ t \leq \left( \frac{f_y}{8 \ E_s} \right)^{1/2} \]  

(2.2)

where, \( f_y \) and \( E_s \) are the steel yield stress and modulus of elasticity respectively.

Some studies have also been conducted by Kamba (1996) who carried out numerical and experimental studies of the high strength Circular Hollow Section (CHS) steel stub columns with material of grade 590 centrifugal steel. Their purpose of research was to obtain some fundamental information about elastic-plastic behaviour of the high strength CHS steel columns with small diameter-to-thickness ratio. The following observations were made by him: (i) The high strength CHS steel columns with D/t ratio < 20 had some excellent characteristics compared with others (D/t > 20) (ii) The effect of the differences between the mild and the high strength steel on the strength and deformation capacity of CHS column was evaluated as the yield ratio of material, \( Y \), being their parameter (iii) Finally, the experimental formulae for predicting the maximum stress index and deformation capacity of CHS columns were proposed from the regression analysis considering the test and numerical results.
O’Shea and Bridge (1998) conducted comprehensive series of tests to examine the behaviour of short thin-wall circular steel tubes with or without internal restraint. The tubes had a D/t ratio ranging from 55-200 and an L/D ratio of 3.5. The experiments included bare steel loaded both axially and at small eccentricities, and axially loaded steel tubes with an internal restraint medium. The material properties were measured, including residual stresses and geometric imperfections. The test strengths were compared to strengthen models in design standards and design recommendations were proposed. The results indicated that local buckling significantly decreased the strength of circular thin-walled bare steel tubes, and the concrete infill for circular steel tubes had little effect on the local buckling strength of steel tubes in axial compression. It was therefore suggested by the authors that the strength of steel tubes in CFST columns be determined by using the design rules in current steel codes for bare steel tubes. However, it was noted by the authors that concrete infill can improve the local buckling strength of rectangular and square steel tubes. The results also suggested that the provisions of current steel codes, which include the effects of local buckling on the section strength, were conservative for thin-walled bare steel tubes with small eccentric loads. This was especially evident when a linear interaction between the axial capacity and moment capacity was used.

Chuang et al. (2000) presented and discussed the experimental behaviour of eighteen large scale reinforced concrete columns, with concrete compressive strength of 55.24 N/mm² or 76.15 N/mm², effective length-to-depth ratio of 26.2, 28.7 or 30.4, load eccentricity-to-depth ratio of 0.25 or 0.50, steel ratio of 3.35 % or 5.24 % and specified steel yield of 452-520 N/mm². From the findings it was concluded that the high strength concrete slender columns were stiffer, thus yielding higher axial load capacity compared with normal strength concrete columns. It was found that an increase in steel ratio from 3.35 to 5.24 % led to more stable columns with
higher axial load capacity. For all the test results, the short-term load predicted by BS 8110 showed good agreement, whereas predictions by Eurocode 2, which were close to the P-δ method values, were found to be conservative.

O’Shea and Bridge (2000) developed several design methods that could be used to conservatively estimate the strength of circular thin walled concrete filled steel tubes under different loading conditions. The conditions examined include axial loading of steel only, axial loading of the concrete only, and monotonous loading of the concrete and steel both axially and at small eccentricities. Recent tests on circular concrete filled steel tubes were used to calibrate and validate the proposed design methods. The test specimens were short with a length-to-diameter ratio of 3.5 and diameter-thickness ratios between 60 and 220. Internal concrete had nominal unconfined cylinder strength of 50, 80 and 120 MPa. They suggested that the bond between the steel and internal concrete was critical in determining the formation of a local buckling. The ultimate loads of the filled and unfilled specimens, normalized with respect to the yield load on the steel, were plotted against the diameter-to-thickness ratio and the same is presented in this paper.

Some studies have also been conducted by Saw and Liew (2000) and they have discussed the design assessment of encased I-sections and concrete filled composite columns based on the approaches given in Eurocode4: Part 1.1, BS 5400: Part 5 and AISC LRFD. This study considered the design parameters and carried out comparison of the nominal strength predicted by the three codes with the available test results. The conclusions arrived at specified that the approach in BS 5400 gave a higher increase in concrete strength due to the confinement effect of concrete at low slenderness ratio as compared to EC4. The authors concluded that in concrete filled circular composite columns, the discrepancies in the axial load capacity were mainly
due to the consideration of the confinement effects only. There is a marked difference between EC4 and BS 5400 in the critical slenderness parameter ($\lambda$), above which the confinement effects were ignored. In EC4, the confinement effects were ignored when $\lambda$ is less than 0.5, whereas in BS 5400 the confinement effects were ignored when $\lambda$ is less than 1.0. Finally they suggested that the method of EC4 was recommended because it covered a wide spectrum of the latest research findings influencing the resistance of composite columns.

Liu et al. (2003) experimentally investigated the ultimate capacity of high-strength rectangular concrete filled steel hollow section stub columns. In the experimental programme, 22 rectangular specimens with cross-sectional aspect ratios of 1.0, 1.5 and 2.0 were tested to failure under axial concentric loading. All the specimens were fabricated from high-strength materials. The average yield stress of the steel hollow sections was 550 MPa while the average compressive strengths of concrete were 70.8 and 82.1 MPa. In the study, the ultimate loads obtained from the experiment were compared with the values calculated from design codes, namely EC4, AISC and ACI. The comparison results showed that EC4 closely predicted with a difference of 6% while AISC and ACI under estimated the critical loads by 16 and 14% respectively. The authors concluded that the strength of specimens decreased with the increase of cross-sectional aspect ratios. Also the authors concluded that the failure behaviour and the confining effect of core concrete of the high-strength rectangular columns under various types of loading were still required to be extensively investigated so that guidelines and recommendations could be developed for design.

Mursi and Uy (2003) in their paper have presented both an experimental and theoretical treatment of coupled local and global buckling of concrete filled steel columns sometimes termed interaction buckling. A series
of three experiments were carried out to consider the effect of a slender cross-section on the overall buckling capacity of a concrete filled steel column. The plate slenderness of the cross-sections was 36.0, 46.4 and 56.8 respectively. The tests were conducted on both hollow and concrete filled steel sections. The compactness criteria for plates with two longitudinal edges simply supported was 35.0 according to Australian Standards (AS 4100-1998) and similar for other international codes of practice. The results produced by the model showed the full load-deflection response of the columns before and after the peak and extremely good agreement was shown with experimental results. Local buckling effects depended on the slenderness of the component plates of the column and this played a larger role in considering the confinement effect provided by the concrete core. However, the column model was unable to capture the spread of plasticity, and so for indeterminate structures such as fixed ended columns or columns as part of rectangular frames, a more rigorous approach was necessary.

Fam et al. (2004) conducted an experimental study to investigate the behaviour of circular CFST beam-columns that were subjected to concentric axial compression loading and combined axial compression and lateral cyclic loading. The effects of different bond and end conditions on the strength and ductility of short CFST beam-columns were studied. Test specimens had an L/D ratio of 3 and a D/t ratio of 49. The concrete infill had unconfined cylinder strength of 60 MPa. Both bonded and unbonded specimens were tested, including the application of the axial load to the CFST section and to the concrete core only. The results indicated that the bond and end loading conditions of a CFST beam-column did not significantly affect its flexural strength. However, the axial strengths of the unbonded columns were slightly greater than those of the bonded specimens due to the confinement effect. The stiffness of the unbonded columns was slightly lower due to the absence of contribution of the steel tube in the axial direction. The behaviour
of CFST columns under combined constant axial compression and lateral cyclic loads was very ductile. Bonded CFST columns exhibited better ductile behaviour than unbonded sections. The authors concluded that current design standards significantly underestimated the maximum axial capacity of short CFST columns, including the flexural strength of CFST beam-columns that were subjected to axial compression and bending. Furthermore, an analytical model capable of predicting the flexural and axial load strength of CFST columns was presented.

Studies have also been conducted by Giakoumelis and Lam (2004) who investigated the behaviour of 15 short circular CFST columns that were subjected to axial compression with various concrete strengths. The effects of tube thickness, bond strength between the steel tube and concrete, and confinement of the concrete were studied. Test specimens had an L/D ratio of 3.5 and D/t ratios ranging from 22.9 to 20.5. The concrete infill had nominal unconfined cylinder strengths of 30, 60 and 100 MPa. The results showed that the peak load was achieved with small displacement for high strength CFST columns and with large displacement for normal strength CFST columns. Based on the results, the effect of the bond between the steel tube and the concrete core becomes more critical as the concrete strength increased. For normal strength concrete, the reduction in the axial capacity of the column due to bonding was negligible. The results were compared with values estimated by Eurocode4, Australian Standards, and American Codes. When the experimental results of Giakoumelis and Lam were compared to Eurocode4, the largest variation between the experimental and calculated values for the axial capacity was 17%. The predicted axial strengths using ACI 318 and AS 4100 were 35% lower than the experimental results. A co-efficient was proposed for the ACI/AS equations to take into account the effect of concrete confinement on the axial load capacity of CFSTs.
\[ N_u = 1.3 \, A_c \, f_c + A_s \, f_y \]  \hspace{1cm} (2.3)

where,  \[ N_u \] = Ultimate squash load  
\[ A_c \] = Cross-sectional area of the concrete  
\[ f_c \] = Compressive strength of concrete  
\[ A_s \] = Cross-sectional area of steel tube  
\[ f_y \] = Yield strength of steel tube

Yu et al. (2007) in their paper studied the behaviour of circular concrete-filled steel tube (CFT) stub columns with self-compacting concrete (SCC) and normal concrete (NC) concentrically loaded in compression to failure. Four measurement methods on the axial deformation of specimens were compared. Seventeen specimens were tested to investigate the effects of concrete strength, notched holes or slots, and different loading conditions on the ultimate capacity and the load-deformation behaviour of the columns. The behaviour of these stub columns in confinement was discussed. All specimens were three times the diameter in length in order to reduce the end effects and also to ensure that the specimens would be stub columns with minimum effect from slenderness. Each tube was welded to a square, steel base plate of 5 mm thick at the bottom. The SCC and NC for filling in the steel tube stub columns were mixed first, and then the CFT stub columns were cast. Meanwhile, the corresponding SCC and NC specimens of nine 150 mm cubes were cast for concrete strength tests. The specimens were compacted with vibration for NC specimens and without vibration for SCC specimens.

It was concluded that by using higher strength concrete, the specimens with the entire section loaded experienced a significant increase in the ultimate capacity, but their residual capacity after failure was almost constant. However, once the steel tube was notched, the axial compressive
stiffness of specimens was reduced; in some cases, the ultimate capacity was also reduced, and the steel tube acted more as a transverse confinement than an axial compression component. Eurocode4 predicted a reasonable capacity for the unnotched CFT stub columns with both SCC and NC if the entire section of the specimen was loaded. The measured load versus strain ratio curves of the steel tubes suggested that a significant confinement effect was present for most specimens after the axial load reached a certain percentage of the ultimate capacity of stub columns. Once a steel tube was notched with small holes in the mid height region, the confinement effect was presented earlier and enhanced. But the axial compressive stiffness got reduced. However, the ultimate capacity and residual capacity were hardly influenced.

2.8 REVIEWS ON FINITE ELEMENT ANALYSIS

Chou et al. (2000) adopted finite element analysis on the post-buckling behaviour of stub columns under axial compression. They have obtained numerical predictions on the load versus end-shortening characteristics and ultimate load capacity of the structures using a non linear finite element analysis. Standard design procedures were developed for post-buckling analysis for stub columns using finite element method. In this study they concluded that the ultimate load obtained using the design procedure consistently under estimated the experimental results and analytical predictions using BS 5950.

Some studies have also been conducted by Liang et al. (2000), as they studied the post-local buckling behaviour of steel plates in thin walled CFST welded box columns using the finite element method. The effects of various geometric imperfections, residual stresses and B/t ratios on the post-local buckling characteristic were investigated. A new method was developed for evaluating the initial local buckling loads and post-local buckling reserve strength of steel plates with imperfections based on the load-transverse
deflection relations associated with the theoretical analysis. The accuracy of the design models were verified by a classical solution and experimental results. The results indicated that the theoretical predictions for the ultimate strength of steel plates and CFST box columns using the proposed design models agree very well with the experimental data. Therefore, the authors proposed that effective width formula be used in the ultimate strength calculation of short thin walled CFST box columns that were subjected to an axial load.

Huang et al. (2002) conducted an experimental study which investigated the axial load behaviour of concrete filled tubular (CFT) columns with the width-to-thickness ratios between 40 and 150 and proposed an effective stiffening scheme to improve the mechanical properties of square cross-sectional CFT columns. Seventeen specimens were tested to examine the effects of cross-sectional shapes, width-to-thickness ratios, and stiffening arrangements on the ultimate strength, stiffness, and ductility of CFT columns. Moreover, nonlinear finite element analysis was also conducted to investigate cross-sectional axial stress distribution at the ultimate strength level. Of the specimens, five were for B/t (or D/t) = 40, eight were for B/t = 70, and four were for B/t = 150. Three of the specimens were for circular cross section and the rest were for square cross section. The square tubes were constructed by seam welding two U-shaped cold-formed steel plates. When stiffening was specified, the tie bars were fillet welded to the U-shaped cold-formed steel plates before making the seam complete penetration groove welds. The compression tests were conducted in a 4900 kN Universal Testing Machine. Axial loads, measured by the test machine load cell, were slowly applied to the specimen. The compression tests stopped at a strain level of 5 %. Comparing the measured ultimate strength with estimates by using some current specifications suggested that current specifications might considerably under estimate the ultimate strength
of circular CFT columns, particularly for columns with a small width-to-thickness ratio. Results in this study demonstrated that the proposed stiffening scheme significantly enhanced the ultimate strength and ductility of square CFT columns.

Hu et al. (2003) investigated the behaviour of CFST columns subjected to axial loads using the non-linear finite element program ABAQUS. The cross-sections in the numerical analysis were categorized into three groups; circular section, square section, and square section stiffened by reinforcement ties. Based on the results for circular CFST columns, the steel tube provided a large confining effect due to the concrete core, especially when the D/t ratio were small (D/t<40), which indicated that local buckling of the steel tube was unlikely to occur. The results for square CFST columns suggested that the steel tube did not provide a large confining effect particularly when the width-to-thickness ratio was large (B/t>30). The results indicated that local buckling of the steel tube was very likely to occur. Based on the analysis results for square CFST columns stiffened by reinforcement ties, the confinement effect was enhanced especially when the tie spacing was small and the tie number or diameter was large. The results showed that local buckling of the steel tube was prevented by the reinforcement tie. Furthermore, the results from the non-linear finite element analysis indicated that the lateral confining pressure decreased with an increase in the B/t ratio due to the decrease in the lateral support for the steel tube.

2.9 SUMMARY OF REVIEW OF LITERATURE

The behaviour of CFST columns and its advantages over the existing conventional construction systems has now gained more importance and has attracted the attentions of researchers all over the world. From the literatures reviewed, it is evident that considerable progress over the last 40 years has been made in the investigation of CFST columns. From the
research works conducted so far, the fundamental knowledge on ultimate strength of the composite construction system is well understood. From the past studies, it is also evident that the load carrying capacities of CFST columns are more than that of hollow steel tubular columns. It has been proved that the CFST columns are applicable to high rise and long span structures because the system’s construction efficiency saves construction cost, time and manpower. For studies in the past waste materials were utilized as a replacement for aggregate in concrete. It not only reduced the cost of construction but also saved large quantity of natural sand used in construction industry. At the same time the effect of pollution due to disposal of the waste materials also saved most valuable fertile land. The behaviour of core concrete with waste materials aggregates in columns under various conditions has been extensively investigated. So, a wide range of research studies has to be conducted in this area to make use of waste materials in core concrete of CFST columns.

But intensive research is required particularly to study the behaviour of CFST columns using waste materials on interaction between steel tube and concrete core. The effect of waste materials interaction with steel and concrete core has to be studied to know its restraining effect over local buckling. Many researchers have arrived at similar conclusions on the behaviour of CFST columns. So, further research is required in the area of CFST column behaviour. Some of the analysis methods, as reviewed in this chapter have been utilized in this dissertation to investigate the buckling of steel tubes in thin walled CFST columns.

Behaviour of circular thin walled steel tube with medium strength concrete or thick walled steel tubes with high strength concrete has been studied. In the past, the researchers have studied the behaviour of CFST columns, which had the value of L/D = 2 to 5 with strength of concrete from
60 to 120 MPa. Some studies have been conducted for CFST columns with L/D ratio varying from 12 to 25. And so, in this study, the L/D ratio of the CFST columns has been varied from 2.5 to 12.5 and its behaviour was studied with M 20 grade of concrete. Fibre Reinforced Concrete (FRC) has been used by some of the researchers instead of plain concrete for the purpose of high stiffness and high ductility than plain concrete filled columns. The lateral displacements of CFST columns were found to be less than the lateral displacements of plain concrete in-filled columns.

From the studies conducted in the past, it was found that many analytical models were developed and compared with experimental results. In addition to this, Finite Element Analysis (FEA) using ANSYS models were developed to predict the ultimate load and behaviour of columns. But so far, no codal provision has been formulated in India to guide the designer. The international codes like ACI 318, AISC-LRFD, BS 5400 and AS 4100 were taken into consideration in the present study and these codes were found to underestimate the critical loads when compared with the test results. Eurocode 4 was found to closely predict the behaviour of CFST columns and also found to treat the effect of long term loading separately.

The reports of earlier research work on composite columns shows that widely varying and often contradictory assumptions were made by researchers. One of the reasons for the large deviations between theoretical and experimental strengths reported by researchers could be due to an enhanced load carrying capacity. The earlier researches did not give any clear design method that truly reflected the strength and behaviour of axially loaded concrete filled steel tubular columns with utilization of waste materials. Hence there is a need to study the behaviour of in-filled CFST columns using waste and recycled materials.