INVESTIGATIONS ON STRENGTH OF COMPOSITE CONCRETE FILLED STEEL COLUMNS FOR BRIDGES AND OTHER STRUCTURES

Thesis

Of

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By

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This is to certify that the

Thesis entitled

INVESTIGATIONS ON STRENGTH OF COMPOSITE CONCRETE FILLED STEEL COLUMNS FOR BRIDGES AND OTHER STRUCTURES

Submitted By

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Has been accepted towards the partial fulfillment

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For

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Dedicated

To

My Parents

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SYNOPSIS

The tests were carried out on a total of 28 samples, 12 hollow, 12 filled and 4 filled and welded tubular columns. All thes were short columns havind l/d ratios less than 10. Initial tests on materials were carried out in MCE laboratory and Subsequent testing was carried out in UET Peshawar concrete laboratories. All columns were concentrically loaded and tested upto failure.

Load-deformation characteristics of all the specimens were studied well beyond the ultimate stage. Failure modes were different for hollow, filled and welded columns.

The ultimate capacities of the tested columns specimens have also been compared with those of ACI Code. The relationships of these columns have also been plotted which can be used to predict the ultimate capacity of a column.

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LIST OF SYMBOLS/ABBREVIATIONS

Ser	**Symbol/ abbreviation**	**Meaning**
1.	Ac	Area of concrete cross section
2.	As	Area of steel cross section
3.	Ag	Gross cross sectional area of any member
4.	ACI	American concrete institute
5.	B and b	Width of member
6.	CFT	Concrete filled tubular
7.	CRSI	Concrete reinforcing steel institute
8.	D and d	Diameter of a circular member
9.	Ec	Modulus of elasticity of concrete
10.	Es	Modulus of elasticity of steel
11.	.fc	Specified compressive strength of concrete psi
12.	.ft	feet
13.	Fig	Figure
14.	.fy	Specified yield strength of steel psi
15.	.h	Overall thickness of a member
16.	.hr	hour
17.	.in	inch
18.	.ksi	Kips per square inch
19.	L	Length of member

Contd-

Ser	**Symbol/ abbreviation**	**Meaning**
20.	LRFD	Load resistance factored design
21.	MCE	Military college of engineering
22.	Mpa	Mega pascals
23.	.mm	Milli meter
24.	NIT	National institute of transportation
25.	Psi	Pounds per square inch
26.	P	Designed axial loads
27.	Pn	Nominal strength of cross section under compression
28.	Po	Nominal axial load strength at zero eccentricity
29.	RCC	Reinforced cement concrete
30.	.r	Radius of cross section
31.	.t	Thickness of walls of hollow sections
32.	UET	University of engineering and technology
33.	.yd	Yard
34.	Φ	Strength reduction factor

ABSTRACT

Concrete filled steel box columns have recently experienced a renaissance in their use throughout the world. This has occurred due to the significant advantages that the construction method can provide. This paper deals with the strength behavior of short columns under the axial compression.

The Concrete-Filled Steel Tube (CFT) Structural System is a relatively latest system based on filling steel tubes with concrete. The CFT Structural System promises excellent structural characteristics including, strength, deformation capacity and fire resistance for use in various fields of construction. These characteristics result from combining the advantages of steel tubes with those of concrete. The formwork is almost completely eliminated and speed of construction is extremely rapid. Various strength and durability advantages are obtained from this composite structure.

Chapter 1

INTRODUCTION

1.1 General

Columns are the most important members in a structure since failure of a column affects the performance of the entire structure whilst failure of a beam will have a relatively less hazardous effect on a structure. In the design of structures today, great effort is made to increase the structural flexibility. This has resulted in a demand for columns with reduced cross sections and capable of taking higher loads. To achieve a high load bearing capacity with a small cross sectional area, it is worthwhile to study the possibility of utilizing normal strength concrete along with composite effects due to containment in steel tubes.

Concrete filled steel tubular (CFT) columns have become increasingly popular in structural applications. This is partly due to their excellent earthquake resistant properties such as high strength, high ductility, and large energy absorption capacity. The enhancement in structural properties is due to the composite action between the constituent elements. The confinement created by steel casing enhances the material properties of concrete by putting the concrete under a triaxial state of stress. Conversely, the inward buckling of the steel tube is prevented by the concrete, thus increasing the stability and strength of the column as a system. Among other advantages of CFT columns are speed of construction, saving formwork for the concrete core, and possible use of simple standardised connections.

1.2 Concrete filled steel tubes

Where the fire risk to a structure is small, as in a bridge, columns made from concrete-filled tubes may be cheaper than concrete encased I-sections or non-composite steelwork. A hollow steel section is more expensive than an open section of equal weight, but its bending strength and resistance to buckling are greater, due to the more efficient shape of the cross-section. No formwork or reinforcement is required for the concrete, and its surface is protected from impact and abrasion. For a given loading, a filled tube can usually be made more slender than an encased section.

In the construction of filled tubes, it is essential to ensure that the concrete is properly compacted, for no subsequent inspection is possible, and to provide holes for drainage and for the relief of excessive vapors pressure that may build up during a fire.

1.3 Composite Action in Concrete Filled Tubes

Concrete filled tubes (CFT) have been used as columns for seismic design of buildings. The construction involves the erection of hollow steel tube columns with steel beams and bracing. As the construction advances, the tubes are then filled with concrete. CFT columns offer advantages over either pure steel or reinforced concrete members. The concrete fill adds stiffness and compressive strength to the tubular column and reduces the potential for local buckling. The steel tube reinforces the concrete to resist tension, bending moment, and shear. Additionally, the tube acts as formwork for the concrete, thus saving a major construction cost. The structural benefits require stress transfer between the steel and the concrete in order to ensure their composite action. In practice, this has been attained by relying on either shear connectors on the inside of the tubes or the natural bond between steel and concrete.

1.4 The Composite Column (steel and concrete only)

1.4.1 Types.

1.4.1.1 **Steel section encased in concrete**

In this type of composite columns standard steel sections i.e. H sections, I sections and Channels are encased in concrete. These are used in Steel Structures and encasing is done for fire protection or corrosion protection etc. Fig 1.1 shows a cross section.

1.4.1.2 **Combimation of RCC and Steel section**

In this type of composites Steel section is placed inside a normal RCC column. Fig 1.2 shows a cross section.

1.4.1.3 Concrete Filled Tubular Columns

In this type of composite culumns, concrete is filled in tubular section of square, circular, rectangular or hexagonal shapes etc. Thickness of steel pipes depends upon area of steel required. Fig 1.3 shows the cross section of a circular and a square column.

The composite column like its beam counterpart uses two materials to carry the load. Composite columns of steel and concrete are widely used. The concrete filled pipe column has a long respected history in construction. The steel rolled section encased in concrete is also used, Strictly speaking, every reinforced column is a composite member because it uses both steel and concrete to carry the load, However in our context only those concrete columns which are reinforced with preformed shapes will be considered.

Some codes formerly used to recognize a separate classification known as a combination column, which was steel rolled shape encased in concrete. The true composite column has to include longitudinal reinforcing bars as well as the rolled shape.

Under current codes, AISC makes no mention of a composite column. The composite column is covered by the ACI code, which defines the composite column as including all concrete compression members, reinforced longitudinally with steel shapes or tubing and with or without longitudinal reinforcing bars. Combination of other materials into composite columns is virtually nonexistent. The steel-concrete column is the only one set accepted world over to an extent.

The concrete-filled tube makes an excellent column. An analogy can be drawn between this type of column and the spirally reinforced concrete column. The spiral column is known to have a higher reserves of strength than the tied column. In the tied column at failure load, the exterior concrete spells off, the longitudinal bars begin to buckle, and the concrete inside the ties begins to fail and shears off, coming out between the ties. In the spiral column, the exterior concrete spells off, but the spiral with its close spacing restrains the core concrete, providing a reserve of strength. Fig 1.4 shows typical failures of tied and spiral columns. In the concrete-filled pipe or tube, all the concrete is completely confined, helping to provide strength. In addition, the concrete fill helps to provide stability against buckling in the steel shell that provides the formwork for the casting of the concrete.

1.4.2 **Types of failures CFT columns**

1.4.2.1 **Buldging of Tube walls**

In this type of failure steel tubes buldge at one or more locations. This is mainly due to excessive internal pressure of concrete on tube walls. Fig 1.5 shows this kind of failure.

1.4.2.2 Local buckling of steel at top or bottom ends

In this type of failure steel walls give away and buckle outward at either top or bottom ends. Fig 1.6 shows this type of behaviour.

1.4.2.3 Column buckling

In this type of failure the column over all fails due to buckling. This is the common characteristic of columns with large l/d ratios, mainly Long columns undergo such type of failure. Fig 1.7 shows this type of failure.

The ACI code specifies that any load assigned to the concrete must be transferred to the concrete by members or brackets in direct bearing on the compression member concrete. This direct bearing can be provided by lugs, studs plates or sections of reinforcing bar welded onto the steel shape. Infact, we are providing a shear connector to ensure that the steel and concrete act together in carrying the load. In the externally encased, structural steel shape, the brackets or lugs are easily welded to the steel member.

1.5 Construction Practices

The procedures for obtaining high quality concrete in columns are especially important in composite columns because the concrete must be intimately bonded to the bearing units. Ideally, long drops in the placement of concrete should be avoided because concrete tends to segregate. Where it is possible to use them, drop chutes will prevent segregation in many cases. In the tube column, this is probably the best solution. In the encased column, there may not be enough room to place a vertical chute. Windows in the formwork are sometimes used to place concrete in these narrow quarters. Concrete should not be chuted in and allowed to bounce off of the steel section. It is preferable to use a small hopper outside the opening, which will allow a better flow of the concrete into the form.

In columns, the concrete should be placed to within 1 ft or so of the top and then allowed to settle for about 1 hr. Concreting must be resumed before cold joints have formed.

Column concrete is usually placed from the top and is normally placed by bucket, rather than by chute. As a rule, vibrations is not needed to consolidate different lifts because most one-story columns contain less than 2 yd of concrete, and the concrete bucket may well be larger than this. Vibration is needed in the composite column to ensure full contact of the brackets and the surrounding concrete. When placing the last 1 ft of concrete at the top of a column, vibration is necessary to prevent the formation of a cold joint at that point.

1.6 Erection Sequence

If the composite beam is an encased beam, the formwork is relatively simple. The columns, complete with the load-transfer lugs or brackets, are erected and plumbed. In the usual steel frame, column sizes are normally kept constant for a height of two stories, with the column splice about 3 or 4 ft above the floor level, where the ironworkers have easy access to the splice. In the composite column, the steel section can be kept constant for as many as five stories and erected in one piece. The size of the concrete encasement, within limitations, can vary according to design loads. The five-story column, about 60 to 70 ft long, should weigh about 3 tons and can be handled by normal construction equipment. The long column probably does not save any money in erection. The amount saved in splices will be applied to the extra costs needed to brace and plumb the long column. The savings will be in terms of construction time.

After the columns are set, the steel beams are connected to the columns. The ACI code states that any load not assigned to the concrete shall be developed by direct connection to the steel member.

If the steel composite beam is encased, the column, beam, and slab forms can then be erected, and the casting sequence proceeds as for any reinforced concrete structure.

With the concrete-filled steel tube, the problems are slightly different. The tubes are smaller sections and are generally used in shorter structures. The tubes should be prepared with the load-transfer brackets and then erected and plumbed. At intermediate story levels, the beams can rest on top of the columns. A two or three- story tube column is light enough to erect and plumb easily with standard equipment, but filling the column might present a few problems.

Chapter 2

AIM, BACKGROUND AND LITERATURE REVIEW

2.1 Aim

The aim of this research is to study structural behavior of composite columns consisting of square and circular hollow steel sections filled with concrete and the increased concrete compressive strength due to confinement provided by tubes, and the overall improvements in the behaviour of composites including effects on strength.

2.2 Background

The first recorded use of concrete filled tubes as columns was by Sewell in 1901. Sewell’s motives were to use the concrete to resist internal rusting of steel box columns. After some of these columns had been accidentally over loaded, Sewell concluded that the stiffness had been increased by at least 25 percent. Research on the behavior of triaxially loaded concrete is relevant to this study, Mr. Considere published results on the behavior of restrained sand, reinforced concrete and restrained concrete in his books published in 1903 and 1906.

Composite columns consisting of concrete-filled steel tubes have become increasingly popular in structural applications around the world. Today's possibility to produce concrete with higher compressive strengths allow the design of more slender columns which lead to greater usable area, hence profits. By using composite columns consisting of concrete-filled steel tubes instead of traditional reinforced concrete columns the problems of concrete durability like cover spalling etc can be avoided. Furthermore, the concrete core increases the stability and the strength of the steel column as a system and prevents buckling of the steel tube. No work on such composite structures has been done in Pakistan although some literature on research done abroad is available.

In the mid-1980s several buildings constructed in Seattle, Wash, (USA) became well known for their use of concrete filled tubular (CFT) columns. Most of these buildings were high-rise that utilized CFTs as primary columns. The notoriety of these building systems was due to the large diameter CFTs used, ranging from 2.3 to 3.2 m, and to the use of high-performance concrete, with target Strengths of 96 MPa and cylinder strengths of 130 MPa. The depth-to-wall thickness (D/t) ratios of these large dimension columns ranged from 180 to 250 and length to depth (L/D ratios ranging from 2 to 14. Although stiffness was the primary concern for these large columns, the calculated strength of these CFTs was extrapolated from results of small scale test specimens with quite different material and column properties. Although these large composite columns are beyond the scope of current design specifications, smaller CFTs were used in low to mid rise construction projects. Circular CFTs were used in braced frames and a smaller percentage were used in moment resisting frames. Compared to the extremely large CFTs, the steel tube dimensions used in the low to mid rise buildings were in a more practical range of 0.36-0.76m. Depth to wall thickness rations for the smaller diameter CFTs ranged from 26 to 48 and L/D ratios from 5 to 9. These smaller size CFTs have the most common application in current building construction and are the focus of this research. Although the use of CFT columns is becoming more common , concrete core confinement is not well understood. The prevailing attitude is that the steel tube can be used for longitudinal and confining reinforcement. Confinement in a CFT is continuous, unlike the conventional spiral reinforced concrete column. Therefore, CFTs are generally considered to posses favorable characteristics for use in regions at high seismic risk, However, if the concrete core and the steel tube are loaded simultaneously, the steel tube expands more than the concrete core under moderate loads, since poisons ratio is higher for the steel section. This suggests that the steel tube may offer little confinement under certain conditions. This paper presents an experimental and analytical study on the behavior of the CFTs loaded in compression. Test results include data from 28 CFT specimens concentrically loaded to failure. The shape of the steel tube and the wall thickness were the primary parameters in the test program. These factors were studied to determine their influence on the ultimate strength of the CFT and the confinement offered by the steel tube. Yield strength results were compared to applicable design specifications governing CFT behavior.

The primary purpose of the analytical investigation was to investigate the effect of the D, r ratio on the axial compressive strength of the CFT and to extrapolate these effects to the large dimension columns used in construction. Depending on the shape of the steel tube, CFTs can offer substantial post yield axial ductility. However the post-yield behavior for the square and rectangular tubes depended on the D/t ratio. Current design specifications offer a reasonable prediction of the strength of the CFT column, although it produced conservative results for some small dimension square tube columns.

CFT columns have been used longer in Japan than in the United States. Extensive research studies have been conducted in Japan; however, the practice, tube dimensions, and proportions there differ from those in the United States. The research and practice are reviewed, and the locations of critical bond stress demand are identified time and again depending upon the requirement.

2.3 Literature Review

Research reported on this subject in Pakistan is negligible and little material on the subject is available abroad. Concrete Filled Steel Tubular columns have been tested and used at a limited scale whilst the behaviour is under study for long and short columns. Buckling is yet to be commented upon because the behaviour differs due to strength of concrete along with size and material of steel tubes. Circular pipes are more common as compared to square ones.

2.3.1 Strength of filled tubes

A method of computing the load-deflection curve and the maximum load for an eccentrically loaded concrete-filled tube has been developed at Imperial College USA and compared with the results of tests on columns of circular cross-section. It was assumed in the theory that a plane sections remain plane and that the uneasily stress-strain curves for steel and concrete are applicable. Good agreement between theory and tests was found for columns with length-diameter ratios exceeding about 15, but stocky cylindrical columns were found to be stronger than the theory predicted

Tests to investigate the axial strength of CFT columns have been performed on a variety of cross-sectional shapes and D/t and L/D ratios. Furlong (1967) investigated 13 Specimens with D/t ratios ranging from 29 to 98. Results indicated that each component of the composite column resisted load independent of each other, and consequently there was no increase in the load resisting capacity due to confinement of the concrete core. Gardner and Jacobson (1967) investigated 22 composite columns with D/t ratios between 30 and 40. These results suggested that at ultimate load the steel tube was at failure but the concrete core was not. However an increased strain level was noted for the steel tube without local buckling suggesting that the concrete stabilized the tube wall.

Knowles and park (1969) studied 12 circular and seven square columns with D/t ratios of 15, 22, and 59 and L/D ratios ranging from 2 to 21. Results indicated that the tangent modulus method accurately predicted the capacity for columns with L/D ratios 11 but was slightly conservative for columns with small slenderness ratios. It was concluded that this larger than expected capacity for composite columns with L/D, 11 was due to increase of concrete strength resulting from trail confinement effects. It was observed that for certain values of longitudinal strain the concrete began to increase in volume due to micro cracking which induced concrete confinement by the steel tube. This confinement increased the overall load resisting capacity of CFT column. However this increase was noted for circular tubes only, not for square or rectangular shapes. Furthermore, it was determined that this increase occurred only in short columns. For columns with large L/D ratios the composite section failed by column buckling before reaching the strains necessary to cause an increase in concrete core volume.

Tomii et al. (1977) investigated almost 270 circular, octagonal, and square composite columns. Values of D/t ranged from 19 to 75, and L/D ranged from 2 to 9, Results suggested that the post yield behavior for the vertical load may be characterized as either (1) Strain-Hardening (2) perfectly plastic or (3) degrading stiffness type. Circular and many octagonal shapes were classified as either Type 1 or 2, while some of the octagonal and all of the square cross sections were categorized as Type 3. At high axial loads, concrete confinement was observed in the circular and many octagonal cross sections, which explained the strain-hardening characteristics for these specimens. Square tubes provided very little confinement of the concrete because the wall of the square tube resisted the concrete pressure by plate bending, instead of the membrane-type hoop stresses. Consequently, there was no axial load increase due to the triaxial compression effects for the square tubes.

Sakino et al, (1985) tested 18 circular specimens with D/t rations ranging between 18 and 192. In this investigation, three otherwise identical specimens were subjected to different load conditions. Axial load was applied to the concrete and the steel tube simultaneously for the first specimen group. The load was applied exclusively to the concrete core in the second specimen group, and the load application was similar to this in the third group except the inside tube wall was greased before casting the concrete. Results indicated that when the steel tube and the concrete core were loaded simultaneously, the tube provided no confinement until post-yield behavior, In the concrete loaded only specimens, some longitudinal stresses were noted in the steel tube even for the columns with the greased wall. Therefore, regardless of the loading condition, the wall of the steel tube appeared to the primarily in a biaxial stress state. Although test results indicated that the axial stiffness of the concrete loaded only columns were about half that of the other CFTs tested, the concrete loaded only columns obtained a greater yield and ultimate axial load capacity.

Lundberg (1993) assembled available experimental data for axially loaded column and beam-column tests on CFTs. The ultimate strength was compared to current strength specifications of composite columns according to the AISC's Manual of Steel Construction: Load and Resistance Factor Design (LRFD) (Manual 1994). The ultimate strength for the CFTs exhibited a large variation compared to predicted strengths obtained by the LRFD. The average strength of the axially loaded CFTs was about 1.32. More scatter, and higher actual to predicted strength ratios, were observed for stub CFT columns compared to the relatively slender columns, Stub columns were defined by the column slenderness parameter being less than 0.20. This over strength was generally explained by more confinement of the concrete core exhibited by the stub columns than observed for more slender columns. It was suggested that this concrete-steel interaction was not fully addressed by the current composite column strength specification. Finally, a Monte Carlo simulation was performed on all of these CFT columns to determine the overall reliability of the design specifications. Although the steel ratio had large variation, the reliability index was within target values for elements designed according to the LRFD specifications.

This previous research demonstrated that slender columns did not exhibit the beneficial effects of composite behavior, in which the concrete strength increased over that of the cylinder strength due to core confinement. Thus, it was concluded that the concrete core and the steel tube acted independent of each other. Short columns however exhibited greater than that predicted capacity, generally associated with the higher concrete strength due to the confinement offered by the steel tube. The focus of this research was to investigate the effect of the steel tube shape and the wall thickness on the yield strength of the CFT and confinement of the concrete core. Only short columns were investigated in this research.

2.4 U.S. and Japanese Practice

Most U.S structures with CFT columns are braced frames. These columns develop axial forces under lateral loading with a consequent demand for bond stress capacity. The diameters of CFT columns in the

United States are usually in excess of one meter (40 in) and diameters up 3 meters (120 in) exist. The d/t ratios for the steel tubes are commonly about 100 and one structure has a ratio of nearly 200. Axial stiffness is often the motivating influence for the use of CFT columns.

CFT columns have had a much wider usage for seismic resistant design in Japan. Both circular and rectangular columns are used exclusively in moment frames in Japan. The diameters of circular columns are usually less than 700 mm (28 in). with d/t ratios less than 50. Shear connections are seldom used inside CFT columns in Japan, but innovations to enhance the natural bond capacity have been developed, such as the use of steel ribs on the inside of tubes.

Structural member under compression forces can fail in combination of three basic modes i.e. crushing, general buckling or local buckling. Local buckling was not observed to occur in any of the experimental results described in this report and, therefore is ignored in the theoretical treatment.

2.5 Structural behaviour of Concrete Filled Tubes

Many engineers have had the idea that concrete columns could be reinforced more effectively by hoop reinforcement than longitudinal reinforcement. The extreme in hooped concrete is to have the concrete encased in a steel tube.

Circular tubular columns have an advantage over all other sections when used as compression members in that for a given cross-sectional area, they have a large uniform flexural stiffness in all directions. Filling the tube with concrete must increase the ultimate strength of the member with out a significant increase in cost. No removable form is required for the column since the tubing serves as a form. The concrete delays local bucking of the tube wall (since the tube can only buckle outwards) and the concrete itself, in the restrained state, is able to sustain higher stresses and strain that when it is unrestrained.

Current design methods do not predict the ultimate loads of concrete filled steel tubes under axial compression. Unfortunately, full scale tests of proposed columns are expensive and time consuming, thus a theoretical means of estimating safe loads is required.

Most investigators have attempted to relate the strength of concrete filled steel members, in some way to the commonly performed unconfined compressive strength tests. But the concrete strength is influenced by specimen end effects. Unless the influence of these effect on the control concrete strengths is known correlation and comparison of the results of different investigators becomes suspect. This paper attempts to predict the ultimate load of short concrete filled tubes.

The performance of CFTs under sustained load is different from ordinary reinforced concrete columns. In RCC columns, concrete experiences contraction as it sets during its early age. This is followed by a lengthy period of shrinkage and creep under load. In the case of CFT columns, because of the humid environment inside the steel tube, the coefficient of contraction is low and shrinkage proceeds very slowly. However, inside corrosion of the steel tube can be expected. Concrete expands more than its steel jacket under large longitudinal strain. Thus, contraction of the concrete hardly affects the load carrying capacity of CFTs.

The buckling mode of short cylinders is predominately a so-called ring buckling. Ring buckling consists of an axisymmetric deformation with longitudinal waves along the length of cylinder.

2.6 INNOVATIONS

2.6.1 Pre Cast Composite Columns

Portland Cement Association has introduced pre casted composite columns. The Portland column consists of 16 guage tubular steel pipe filled with concrete and are used as structural members to transfer axial compressive loads, from steel or wooden beams to footings. The column is available in two sizes, 4 inch and 3.5 inch. The 4 inches diameter column is available in lengths of 5 to 14 feet. The 3.5 inches diameter column is available in lengths of 6 to 12 feet. The tubular steel pipe consists of low carbon steel with a minimum yield str of 33,000 psi and an ultimate strength of 45,000 psi.

Steel top and bottom plates are provided with the columns for installation in the field. Tubular steel pipe is filled with concrete which has a minimum 28-day compressive strength of 2500 psi.

2.6.2 Steel jacket retrofitting

Ductility and strength of existing substandard reinforced concrete columns can be enhanced by steel jacketing. In this technique the existing columns is encased in a steel tube and the gap is filled with a cement-based grout, resulting in a system that more or less is similar to CFT columns.

Research results have shown that the confining effect of a steel jacket increases the compressive strength, flexural capacity and ductility of the columns

2.6.3 Tubular structures

CFT structure building constructed in Chuo-ku, Kobe City

While being located in the area of very disastrous earthquake motion, the buildings endured the earthquake without significant damage, thereby exhibiting the excellent earthquake resistance of the CFT structure. During disastrous Kobe earth quake the only building showing strength wer CFT buildings. The photographs of two such structures have been pasted in photo gallery

e.g Sannomiya Intes (Photograph No. 2.1)

Hyogo (Completed in 1994)

Design: Takenaka Corporation

Total Floor Space: 20,642 m^2

2 floors below ground, 12 floors above ground

Also Sannomiya Grand Building (Photograph No. 2.2)

Hyogo (Completed in 1995)

Design : Takenaka Corporation

Total Floor Space: 35,787 m^2

3 floors below ground, 12 floors above ground

chapter 3

SPECIMEN, MATERIALS, FABRICATION, TEST PROGRAMME & TEST RESULTS

3.1 **Description of Specimens** (fabrication, categories, marking etc)

A total of 28 samples were made for testing. Out of these 16 were filled with concrete and 12 were kept hollow. 4 and 6 inches diameter pipes were brought from market, from these circular pipes the square ones were moulded, meaning thereby that cross sectional area was changed but the area of steel in cross section was constant for both cases. a Total of eight series were prepared and in each series of filled ones a column was furthur welded with #3 deformed bars which were welded in transverse direction alternatively at a distance of 6 inches centre to centre. Detail of specimens is given at Table 3.1.

3.2 Materials used

3.2.1 Steel Pipes

These pipes were made up of mild steel of grade 40 steel sheets produced in Pakistan Steel Mills Karachi. These sheets are furthur seam welded in Maula Buksh Pipe Industries Lahore. These sheets available in the market are of different thickness varying from 1.98 mm to 10 mm. Also the sizes of pipes available are from 2 inches diameter to 18 inches diameter. Lengths of pipes available is 20 feet each but only with the circular cross section. A photograph showing godown is shown in picture gallery at Photograph No. 3.1.

(1) The circular pipes were furthur cut into pieces of 30 inches each using special cutters. For the square ones the moulding was done by special purpose machines, which without heating the pipes moulded/turned them into square shapes. An internal pressure was applied onto these pipes through lugs at four corners equally spaced. Although the cross sectional area was reduced during this process of moulding the steel cross sectional area however remained the same as of the circular ones. Thes square pipes were also cut into 30 inches lengths each using lyth cutters. These samples have been laid out as shown in Photograph No. 3.2

The point to be stressed upon is that all the materials of pipes and furthur conversion, cutting etc is available in Pakistan’s local market and to be specific in Lahore.

3.2.2 **Cement**

Cement used was of Cherat Cement Factory. All the tests were performed in MCE concrete laboratory for checking the properties. After tests it proved to be satisfactory to be incorporated in preparation of concrete.

3.2.3 Aggregates

Aggregates were from Margalla crushers. All the tests were conducted on these aggregates for utilization in the preparation of 4000 psi compressive strength concrete.

3.2.4 Sand

Lawarencepur sand has been used which is considered to be a bit coarser but best in pakistan due to its properties. its fineness modulus was calculated to be 2.45.

3.2.5 Water

Locally available water i.e Risalpur water was used in preparation of concrete as well as curing of the samples. As it was cold during casting and curing there fore hot water was used for curing. Water temperature at the time of curing was 60-70 degree centigrade.

Photographs No. 3.3 to 3.5 are showing the stages of testing materials and formulation of mix design.

3.3 Concrete Strength

After three trial mixes the strength of concrete was adjusted to be 4000 psi. results of cylinders tests at 7 and 28 days are listed at Table 3.2 and Table 3.3. Compressive strength was 4000 psi at 28 days.

3.4 Testing Arrangement

Since no testing arrangement is available with MCE and NIT Risalpur for testing beyond 12 inches high samples and loading in excess to 50 tons therefore the samples were taken to UET Peshawar laboratories. At UET Peshawar upto 36 inches high and loading upto 200 tons can be applied. SHIMADZU company of Japan has donated this equipment in 1994 to UET Peshawar for Structural Engineering laboratories.

3.5 Test setup & Procedure.

The objective was to observe the behaviour of the specimens under axial load. The load was applied after proper caping with plaster of paris if required, centring and alignment of the specimens in the testing machine and making the necessary connections for reading the strain measurements. The load was applied with medium rate of loading. Strain gage readings were also recorded after each interval of 5 tons of load till failure. The testing proceedure described above generally took ten to fifteen minutes for each sample.

The test procedure was simply to make a number of pipe’s square and circular columns and axially load them to failure. To ensure the results were reasonable at least three columns of each size were made and tested.

A total of 28 test specimens were casted and tested under concentric axial compression. Detail of these specimens is given at Table 3. 1

All steel tubes were cold-formed carbon steel with specified yield strength of 40000 psi. All tubes were seam welded.

Photographs of specimens before, during and after testing are shown in the photo gallery from photograph No. 3.6 to 3.19

3.6 Experimental Results

Load-displacement relation for all specimens is shown in Table 3.4 to 3.11. For clarity, test results have been separated by tube shape, and therefore their graphs show behavior for the circular and square steel tubes separately. Similarly the stress strain values have been tabulated at Table 3.12 to 3.23

3.6.1 Behaviour of specimen series.

3.6.1.1 **4 SH**

4 inches equivalent square and hollow columns were moulded from 4 inches circular pipes. These were kept hollow to understand the failure mode of the walls of the square columns. It is observed that failure of walls occurred due to buckling either inward or out wards.

3.6.1.2 **4 SF**

4 inches equivalent square and filled with the concrete showed much stronger as compared to hollow columns of same cross sections. The concrete inside the pipes resisted inward buckling and pipes in return exerted hoop stresses on concrete thereby increasing the strength of concrete. Almost 100 percent increase in strength was observed.

3.6.1.3 **4 SFW**

4 inches equivalent square columns, filled with concrete and also welded from inside with #3 deformed bars at 6 inches centre to centre distance. This type showed a strange kind of behaviour. Instead of strength increase there was a decrease in strength observed, this was probably due to disturbance of steel pipe walls due to welding action. Deformations in the shape of curves were observed all along the columns.

3.6.1.4 **6 SH**

6 inches equivalent square columns and kept hollow. These were fabricated from 6 inches circular pipes. The mode of failure was same as that of 4 SH. But this showed the least of strength out of all hollow series.

3.6.1.5 **6 SF**

6 inches equivalent square columns filled with concrete although showed a strength increase as compared to hollow columns of same cross sections but were the lowest of all the filled columns.

3.6.1.6 **6 SFW**

6 inches equivalent square columns filled with concrete and welded also. In these #3 bars were welded similar to that of 4 SFW. This gave the strength almost equal to non welded columns.

3.6.1.7 **4 CH**

4 inches circular hollow columns showed more strength as compared to 4 SH. Mode of failure was buckling of walls either at the top or bottom of the columns.

3.6.1.8 **4 CF**

4 inches circular filled columns. These failed at an average load of 59 Tons. Mode of failure was the yielding of column walls at on or more than one places.

3.6.1.9 **4 CFW**

4 inches circular filled with concrete and welded too. This type of column showed the strength less than their counter part filled one.

3.6.1.10 **6 CH**

6 inches circular hollow columns. These proved to be the strongest of all hollow columns. Failure load was almost 33 tons and strain was 0.005 at failure.

3.6.1.11 **6 CF**

6 inches circular filled with concrete coluimns. These were the strongest of all filled columns. Failure load was 129.60 tons against expected 65 tons. Strength increase was almost 100 %.

3.6.1.12 **6 CFW**

6 inches circular filled with concrete and welded columns. Although the strength was much higher as compared to theoretical expected but still it was less than the 6 CF columns

Graphs 3.1 to 3.8 show the pre yield behavior of each series of columns. In general, circular tube shapes exhibited strain hardening characteristics. Graph 3.9 to 3.16 shows post yield behaviour of all types of columns i.e load displacement relationship is given in these graphs. The summaries of these behaviours are also given at Graph No. 3.17 to 3.20. The stress vs strain values have been shown at Graphs No. 3.21 to 3.32. also the summaries have been shown at Graph No. 3.33 to 3.35.

The ultimate loads for each specimen are listed in Table 3.36. The ultimate load was the maximum axial load observed during each test.

Calculated values of strength according to the books and ACI Code for respective RCC Columns are also listed in Table 3.37.

Graph 3.38 illustrate the comparison of the measured to predicted failure loads for each CFT specimen.

Graph 3.39 shows variation of a normal stress strain curve. Graph No. 3.40 to 3.43 show the behaviour of different types of columns under applied loads, curve slope, yield point and failure point have been marked with dark black lines etc.

Photographs No. 3.18 and 3.19 in photo gallery shows the typical wall buckling that occurred for these specimens. Circular and square tubes had different local buckling behavior, only a few photographs are shown for an example. Clearly, most of the local wall buckling of the circular cross section was due to a radial expansion of the tube. The square tubes, however, showed clear signs of wall bulging. Local buckling occurred equally on every face for the square tube. Photograph no. 3.16 illustrates how ineffective the flat tube wall was in confining the concrete core. In general, tubes with large D/t rations had more local wall buckling, with higher apparent distortions, compared to the sections with small D/t rations.

Chapter 4

ANALYTICAL STUDY

4.1 General

The enhanced properties of CFTs can be explained in terms of concrete core. In the early stages of loading the Poisson’s ratio for concrete is lower than that for steel. Thus, the steel tube has no confining effect on the concrete core. As the longitudinal strain increases, the lateral expansion of the unconfined concrete gradually becomes greater than that of the steel. A radial pressure subsequently develops at the steel concrete interface. At this stage, the concrete core is stressed triaxially and the steel tube biaxially. Because of the presence of hoop tension (i.e., biaxial state of tress), the steel tube cannot sustain the normal yield stress, therefore, there is a transfer of load from the tube to the core. The load corresponding to this mode of failure can be considerably greater than the sum of the uncoupled steel and concrete failure loads. The level of increase in the failure load caused by the confining effect of the steel tube on the concrete core depends on several factors, namely the thickness of steel tube, slenderness ratio, eccentricity, and cross-sectional shape. In the case of circular CFT columns, the steel tube has more confining effect than in the square columns. The center and the corners of square sections go under higher confining pressure than the sides, but a uniform distribution of lateral pressure is expected in the circular columns. The l/d and d/t ratios are given at Table 4.1 L/d or L/b ratios are in the range of 4-9 i.e columns are stocky. D/t or b/t ratios are in the range of 35-65

4.2 ACI Code Parameters And Limitations (ACI 318-95)

4.2.1 Composite Compresion Members.

Ser	Item	Code	Commentry
10.16.1	Composition	Composite compression members shall include all such members reinforced longitudinally with structural shapes, pipes or tubing with or without longitudinal bars.	Composite columns are defined without reference to classifications of combination, composite or concrete filled pipe column. Reference to other metals used for reinforcement has been ommited because they are seldom used with concrete in construction.
10.16.2	Strength	Strength of a composite member shall be computed for the same limiting conditions applicable to ordinary reinforced concrete members.	The same rules used for computing the load-moment interaction strength for reinforced concrete sections can be applied to composite sections.

10.16.6		**Structural Steel Encased Concrete Core**	
10.16.6.1	Pipe Thickness	For a composite member with concrete core encased by structural steel, thickness of the steel encasement shall be not less than	Steel encased concrete sections should have a metal wall thickness large enough to attain longitudinal yield stress before buckling outward.
		For square and rectangular sections for each face of width “b”	
		Not less than $b \cdot \sqrt{\frac{fy}{3Es}}$	
		For circular sections of diameter h	
		Not less than h. $\sqrt{\frac{fy}{8Es}}$	

Strength comparison has been given at Table 4.2 which shows that only square column of 6 inches equivalent showed comparitavily less strength, other all columns were much beyond required.

The thickness requirements have been shown at Table 4.3. Here it is observed that thickness required for 6 inches equivalent columns in less by 0.18 mm.

Strength comparison as of actual with CRSI hand book has been tabulated at Table 4.4. Also the strengths have been shown in graphical shape at Graph 4.1. The strength of CFT columns tested is much more than those given in CRSI hand book.

4.3 Strain Comparison

Stress strain curves of the concrete filled tubular columns are required to be compared with normal RCC columns.

A normal stress strain curve is given at Graph No 4.2.

Stress strain curves of CFT columns are at Graph No 4.3 to 4.6.

Following is concluded

- Columns start yielding at 85 % of the ultimate strength.
- Till 85% of the strength the stress to strain behaviour is a straight line with an approximate slope of 1:2.5.
- Yielding to failure is similar to normal RCC columns.

- After failure slope becomes mild and comes down at an angle of 15- 18 degrees. Which shows that load carrying capacity is reducing and strains are enlarging at a slower rate.

The graphs have been marked with black lines for understanding

Concrete Strain At Yielding =0.003

Steel Strain At Yielding =40000/29000000

=0.00138

yielding strains and loads have been shown at Table 4.5

4.4 Implication Of Results

In general, the circular CFT columns offered more axial ductility than the square shapes. All of the circular pipes tested in this experimental study were categorized as strain hardening. On the other hand, less strain hardening was observed in the square shapes. This strength increase was attributed to the confinement of the concrete core once the CFT reached yield. Clearly, the circular tube offered more concrete confinement than the square tubes once the column yielded.

Many buildings constructed with CFTs utilized the composite column in braced frame structural systems. Results from this study suggested that circular CFT columns offer more ductility than the square columns. Consequently, square and rectangular tubes should be avoided for buildings constructed in regions of moderate to high seismic risk if CFT columns are desired. CFT behavior of square and circular sections is better as compared to conventional reinforced concrete, or perhaps even structure steel, columns.

4.5 Advantages

CFT columns can be credited with advantages such as:

- Excellent axial and flexural loads carrying capacity.
- High shear resistance.
- Large ductility and energy absorption capacity.
- Greater critical load in buckling (i.e., higher stiffness)
- Saving of formwork for the concrete core.
- Column sections in the CFT Structural System may be reduced because of high strength of the composites.
- Vibrations caused by earthquakes and winds may be reduced due to higher ductility.
- Speedy Construction.
- Economical.
- Useful in high-rise buildings where high workability is required and maximum open space is desired.
- Due to the composite action of concrete constrained by the steel tube, a CFT structural system maintains high yield strength and deformation capacity with large horizontal deformation, thus increasing strength.

- Steel tube casing reduces the effects of offensive agencies on concrete.
- Prevents spalling of concrete if used as casing of normal RCC columns
- Increases the amount of usable space in the building due to smaller sections therefore more space saving.

4.6 Disadvantages

- Fire hazards i.e. may give away strength under high temperatures
- Extensive rust proofing would be required at start and would be maintained throughout the life of structure.
- Special connectors are required for joining columns to beams and foundations and the requirement would be problematic if different sizes of members are used.

Chapter 5

PROPOSED EQUATIONS AND RECOMMENDATIONS

5.1 Existing equations

Now the strengths of the tied and spiral columns will be compared with the actual achieved in testing and an equation is proposed for CFT columns. The strengths of tied columns and spiral columns have already been compared to CFT columns at Table 4.2. Achieved str is much higher than the theoretical.

5.1.1 For Tied columns

Po = 0.85fc(Ag-Ast)+fyAs

Pn =0.8[0.85fc(Ag-Ast)+fyAs]

Pn =0.80Po

Fc =4 ksi

Fy =40 ksi

Φ =0.70

5.1.2 For Spiral columns

$Po = 0.85fc(Ag-Ast)+fyAs$

$Pn = 0.85[0.85fc(Ag-Ast)+fyAs]$

$Pn = 0.85Po$

$Fc = 4 \text{ ksi}$

$Fy = 40 \text{ ksi}$

$\Phi = 0.75$

5.2 Equations Proposed For CFT Columns

$Po = 0.90fc(Ag-Ast)+fyAs$ Eqn-1

$Pn = 0.90[0.90fc(Ag-Ast)+fyAs]$ Eqn-2

$Pn = 0.90Po$

$\Phi = 0.85$

If the properties of the section are same as for the tests, the results with the proposed equation would be as shown at Table 5.1. Here it is quite interesting that capacities calculated using proposed equation are quite safe except for square moulded from 6 inches dia circular pipe.

5.3 Limitations

Now by observations on the results after application of the proposed equation we can put some limitations on the application of proposed equation.

That is this equation is applicable if following conditions are fulfilled

- Columns are circular.
- Columns are short i.e. L/d ratios are less than 10.
- Concrete compressive strength range is 3000-6000.
- Minimum thickness of pipes is 2 mm and maximum 5 mm.
- Columns diameters 3- 6 inches
- Pipes are made up of mild steel with a yield strength of 40000 psi
- Pipes are seam welded.
- Only axial type of loading is applied.
- Columns are not exposed to fire.

5.4 Major Conclusions

- Concrete Filled Tubular columns gave more strength to concrete encased in them thereby increasing the overall load carrying capacity of columns increased.
- When the basic geometry of a pipe was disturbed by changing its shape from, circular to square its strength was reduced. This implies that instead of moulding, if welded sheets of same thickness would have been used, the results might have been different.
- Circular columns showed better results as compared to square, meaning thereby that it puts concrete inside it in a triaxial state of stress thereby increasing the loading capacity.
- Stress strain behaviour confirms to the previous studies i.e. it is almost linear for first part till yielding. Also after failure it is mild.
- Although hollow columns can also be used but their cost will be more as compared to the same load carrying RCC columns. Wall buckling may also be more in hollow columns,
- Special joints arrangement will be required for joining these columns to footings and beams.

5.5 Recommendations.

- CFT columns are better than their counterpart of normal RCC columns of same dimensions
- Stress strain curves of CFT columns show that they behave better than RCC columns and exhibit better properties, will give more reaction time to the user to do remedial or strengthening measures.
- Jacketing can also be done in case of using tubes as retrofitting and strengthening of damaged or weak RCC columns. Grout of cement will be filled in the gaps of jacket.
- Bracing of Tubes with the help of welding etc be avoided as it reduces the load carrying capacity of columns.
- Hollow tubular columns are too costly to be used in Pakistan.
- Areas of application of CFT in Pakistan

  Use of CFT in Pakistan is recommended in following

  - Short and medium span bridges.
  - Strengthening of existing RCC bridges.
  - Construction of Columns in multi storey buildings, sheds, hangers etc.
  - Construction of Railway overhead bridges.
  - Construction of Underpasses

5.6 Research needs

- Due to good seismic performance and other advantages, the system of CFT columns is becoming increasingly popular. However, there are still many problems that need to be investigated in order to understand the response of CFTs.
- A number of potential research needs can be:
  - The ultimate strength of CFT columns is not well predicted. In the earlier procedure, the benefits of confinement for increasing the ultimate capacity is generally ignored. Analytical studies should be conducted that will take the confinement effects into consideration in the estimation of the ultimate strength of CFTs. Effects of important factors such as the slenderness ratio, cross-sectional shape and creep need to be furthur investigated.
  - Although research had shown that composite action is achieved with stocky columns, there is uncertainty about the effect of bond between the steel and concrete of slender columns. Therefore, a comprehensive study is needed to evaluate the bond effect and predict the stiffness of CFTs..
  - CFT columns are commonly used for their large stiffness. It is believed that high strength concrete can be used to maximize the flexural stiffness. Research is needed to investigate the optimum use of high strength concrete and its effect on the ultimate strength

and ductility of CFTs. Since there is uncertainty about the order of occurrence of local buckling of the steel tube and crushing of the concrete core, the mechanism of local buckling needs to be studied in details.

5.7. Conclusion

A set of detailed experiments has been conducted on hollow and filled short columns. The experiments have shown that strength increase in circular columns is much more than that of square ones. Increase in strength of circular columns of one series was even more than 100 percent. Also the local wall buckling was observed in square columns both hollow and filled. The strength increase may also be due to good quality of concrete caused by the retention of moisture.

There is scope for further research in conducting experiments on columns with slenderness ratio greater than 15 i.e long columns. And also the effect of usage of high strength concrete instead of normal concrete.

TABLES