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Study of Strength and Behaviour of Concrete Filled Double Skin Tubular Square Columns under Axial Compressive Loads

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***Abstract*—This paper investigates the strength and behaviour of concrete filled double skin tubular (CFDST) square columns with external stainless steel tubes under axial compression. The square CFDST column with inner circular tube is chosen. The lean duplex stainless steel material is chosen for outer steel tube. The square tube is chosen because it involves easy fabrication of beam column joints. The finite element analysis of the CFDST square column is conducted to validate the finite element model with existing experimental data. A further analysis is carried out by varying the dimensions of inner and outer tubes. The effect of various parameters on the strength and behaviour of the CFDST columns is studied. The results obtained from the finite element investigation are compared with the strength values predicted using existing formulations in the analytical investigation. A good correlation was found between the numerical investigation results and values obtained from existing formulations in the analytical investigation.**

Keywords—Concrete Filled Double Skin Tubes; Lean Duplex Stainless Steel; CFDST Square Columns, Hollow Ratio, Slenderness Ratio.

I. INTRODUCTION

The increased population and industrial demands for living and working spaces resulted in construction of high rise building. Using reinforced concrete members for high rise buildings resulted in bigger size members reducing the aesthetic appearance of the structures. This resulted in the evolution of composite sections. The main aim of composite construction is to utilize the properties of concrete and steel effectively. One such composite construction is concrete infill steel tubular members in which the traditional steel reinforcements are replaced by steel tubes in to which the concrete is poured. This reduces the time involved in the construction of reinforcement cages.

A. Background

The concrete infill steel tubular sections were first used in marine applications in submerged tube tunnels for pressure vessels. They were also used in some of the nuclear containments, liquid, gas retaining structures and blast resistant shelters. This form of construction was first devised to use as legs of offshore platforms in the deep waters, in structures subjected to ice loading and applied in sea-bed vessels [Xiao-Ling Zhao and Raphael Grzebieta]. The Siena footbridge in Italy, completed in 2006 was designed with CFDST columns with a design life of 120 years without expensive maintenance.

B. Concrete filled double skin tube sections

The Concrete filled double skin steel tubes are advanced composite construction in which two hollow steel tubes are concentrically placed and the annulus between the tubes is filled with concrete of desired grade. The hollow steel tubes can be chosen with any type of cross section depending upon the requirements. Generally circular and square tubes are preferred. These columns are similar to concrete filled steel tubular columns except that in the CFDST columns the central core concrete portion that plays very less role in the bending and torsion resistance in case of CFST members is replaced by a hollow steel tube.

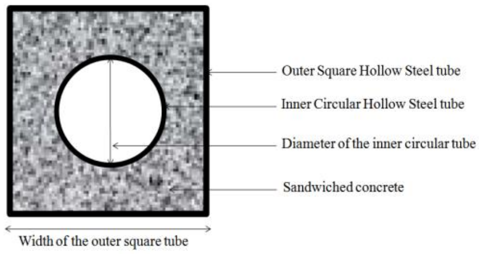

Fig 1: Cross section of a CFDST square column

The steel tubes in the columns also serve the purpose of formwork, thus eliminates the need for traditional formworks. This resulted in the reduced cross sectional dimensions of the members at the same time higher strength; reduced construction time; higher ductility and increased yield strength are achieved. The higher ductility and yield strength are results of the confinement effect developed by the hollow steel tubes. The improved performance of these columns compared to that of reinforced concrete members found its application in many bridges and high rise buildings.

C. Lean duplex stainless steel

Due to higher cost, the austenitic grade steel materials can be used only for minor applications and research works. For large scale works, these grades cannot be used. The higher cost of carbon steel material is mainly due to higher nickel content around 8% to 12%. In order to reduce the cost, combined with several advantages like corrosion resistance and superior mechanical properties, the lean duplex stainless steel material was introduced. The lean duplex stainless steel material has lesser nickel content in the range of 1.5% to 3%.

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The mechanical strength of lean duplex stainless steel material is about twice that of the austenitic grade steel. In lean duplex stainless steel alloy the higher cost elements like nickel and molybdenum are reduced. This reduction in the high cost elements is compensated by the addition of manganese and nitrogen to produce a balanced microstructure [S.Baldo, et al., 2012].

II. ANALYTICAL INVESTIGATION

The analytical investigation is carried out using the existing approaches recommended in previous investigations. The experimental investigations in the past conducted on CFDST columns showed good correlation with the existing approaches of analytical investigation.

A. Strength of short CFDST columns

The equation to predict the sectional capacity of CFDST square columns with inner circular tube was derived in the previous research works by modifying the formulations available for concrete filled steel tube columns. The ultimate axial strength of short square columns is

$$P_{u,analytical} = P_{osc,u} + P_{i,u} \quad (1)$$

Where,

$P_{osc,u}$ is the axial capacity of the outer steel tube along with the sandwiched concrete = $f_{scy}A_{sco}$

$P_{i,u}$ is the axial capacity of the inner steel tube = $A_{si}f_{yi}$

f_{yo}, f_{yi} , f_{ck} are yield strengths of outer steel tube, inner steel tube and characteristic compressive strength of concrete

$$A_{sco} = A_{so} + A_c \quad (2)$$

Where,

A_{si}, A_{so}, A_c are cross sectional areas of inner and outer steel tubes and sandwiched concrete

$$f_{scy} = c_1\chi^2 f_{yo} + c_2(1.18 + 0.85\xi) f_{ck} \quad (3)$$

Where,

$$c_1 = \frac{\alpha}{1+\alpha} \quad (4)$$

$$c_2 = [1+\alpha_n]/[1+\alpha] \quad (5)$$

Steel ratio $\alpha = A_{sco} / A_c$
Nominal steel ratio $\alpha n = A_{sco} / A_{c,nominal}$
χ = hollow ratio (D/B)
ξ = confinement factor ($A_{so}f_{yo}$ / $A_{c,nominal}$ f_{ck})

B. Strength of slender CFDST columns

The ultimate axial capacity of the slender square CFDST columns is determined from the sectional capacity determined from equation (1) by multiplying the values with a stability reduction factor. The following equation gives the ultimate axial capacity of slender columns.

$$P_{u,analytical,slender} = \phi P_{u,analyitcal} \quad (6)$$

Where, the stability reduction factor is,

$$\phi = \begin{cases} 1 & (\lambda \le \lambda_0) \\ a\lambda^2 + b\lambda + c \quad \text{for} & (\lambda_0 \le \lambda \le \lambda_p) \\ d(-0.23\chi^2 + 1)/(\lambda + 35)^2 & (\lambda \ge \lambda_p) \end{cases} \quad (7)$$

Where,

$$\begin{aligned} a &= [1 + (35 + 2\lambda_p - \lambda_0)e]/[\lambda_p - \lambda_0]^2 \\ b &= e - 2a\lambda_p \\ c &= 1 - a\lambda_0^2 - b\lambda_0 \\ d &= [13500 + 4810 \ln(235 / f_{yo})]x[25/(f_{ck} + 5)^{0.3}(\alpha_n / 0.1)^{0.05}] \\ e &= -d/(\lambda_p + 35)^3 \end{aligned} \quad (8)$$

The values of λ_0 and λ_p for square columns are determined from the following equation:

$$\begin{aligned} \lambda_0 &= \pi / [(220\xi + 450) / f_{scy}]^{(1/2)} \\ \lambda_p &= 1811 / (f_{yo})^{(1/2)} \end{aligned} \quad (9)$$

III. NUMERICAL INVESTIGATION

In this section, the behaviour and strength of square CFDST columns are investigated using finite element package ANSYS Workbench 14.5. The finite element method is extensively used to study the behaviour of steel concrete composite structures. The main concept behind finite element method is the discretization of the structural member in to finite number of elements, connected at finite number of points called nodes. The material properties such as Young's modulus(E), Poisson's ratio (υ) and stress/strain values and the geometric properties such wall thickness (t), diameter (D), length(l), width(b), depth (d) influences the strength CFDST columns. Therefore the material and geometric properties are taken as input parameters for modeling in ANSYS.

The Concrete Filled Double Skin tube column specimens were modeled in ANSYS Workbench 14.5 as 3D solid objects with identical geometry. The finite element modeling of the CFDST column gives accurate results when all the aspects are modeled correctly. The details obtained from previous research works of different authors were taken in to consideration.

A. Numerical modelling

The nonlinear analysis, based on finite element method was carried out using ANSYS Workbench 14.5. The full CFDST square columns were modeled in the investigation.

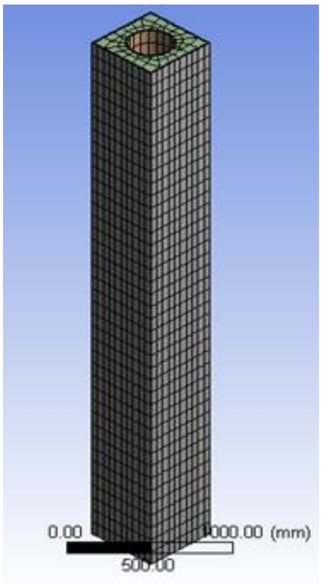

Fig 2: Meshed CFDST square column

The outer and inner steel tubes as well as the core concrete are discretized using the element type SOLID 186, which is a three dimensional 20 node structural solid element. The SOLID 186 element has 3 degrees of freedom per node they are translation in X, Y and Z directions. To stimulate bond between the steel tubes and sandwiched concrete CONTA 174 and TARGE 170 elements are used. The element types CONTA 174 and TARGE 170 are used to represent contact and target surfaces. Based on the previous convergence studies conducted on previous research works it has been found that mesh size has a negligible role in the strength predictions. An axial compressive load was applied uniformly on the top surface with displacement control. The load was applied on an incremental method and the nonlinear analysis is carried out.

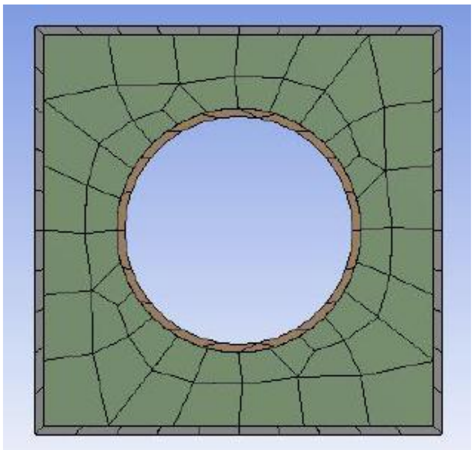
Fig 3: Meshed cross section of the CFDST square column with inner circular tube

B. Stress-strain relationships for different materials

The stress strain relationship for various materials used in this investigation is discussed below.

The properties of lean duplex stainless steel material used as outer steel tube, carbon steel used as inner steel tube and infill concrete are discussed below.

1) In this work cold formed lean duplex stainless steel material of higher grade is used. This material has yield strength of 530 MPa. The Young's modulus and Poisson's ratio values are taken as 200 GPa and 0.3 respectively.

2) The carbon steel material of grade S230 is used for inner steel tube. This material has minimum yield strength of 230 MPa. The Young's modulus and Poisson's ratio values are taken as 200 GPa and 0.3 respectively.

3) Concrete of grade M25 is used throughout the research. The concrete damaged plasticity model is used in modelling the sandwiched concrete.

C. Validation of the finite element model

The verification of finite element model developed in this investigation is considered to be an important step in the numerical study. To verify the accuracy and validity of the finite element model, the model is verified by simulating a number of experimental results. It has been found that there exists a good agreement between the predicted results and test results. And also the failure modes found using ANSYS agree with the past experimental results.

D. Parametric study

The validated finite element model is then used to analyse all the column specimens chosen. Totally 16 specimens were analyzed by varying the cross sectional dimensions. Group 1 columns were analyzed by increasing the length of the column keeping the cross sectional area of outer and inner steel tubes constant. The length of all the columns was kept constant as 1000mm for group 2 columns. Group 2 columns were analyzed by maintaining the same cross section area for outer tube and core concrete. The cross sectional area of inner tube alone is varied by changing its diameter and thickness.

The boundary condition for the column is chosen as both the ends hinged. The loading type was assumed to be concentrically acting compressive load. In this study both stub columns and intermediate length columns are investigated. Variation in column length was assumed such that there is a variation of member slenderness. The outer steel tube was chosen as lean duplex stainless steel tube with yield strength of 530 MPa and inner steel tube as carbon steel tube with yield strength of 230 MPa. Throughout this investigation the characteristic compressive strength of concrete was taken as 25MPa.

E. Behaviour of the specimens

The specimens were analyzed mainly to investigate the effect of hollow ratio, thickness of outer and inner steel tubes, area of concrete core on the strength and behaviour of the columns. It has been reported from the past investigations that increasing the hollow ratio causes a decrease in the axial load carrying capacity of the specimens. But this is mainly due to a reduction in the concrete core area. From this investigation it has been evident that keeping the area of concrete core and outer steel tube constant, if the dimensions of inner steel tube alone is altered in such a way that the hollow ratio increases. The ultimate axial load carrying capacity also increases.

The area of concrete core has greater influence on the strength of the specimens. Increasing the area of concrete core causes a steep increase in the strength of the columns. In case of stub and intermediate length columns, the area of concrete core and the compressive strength of concrete contribute highly for the strength of the columns. It is evident from the analysis that increasing the cross section area of the inner tube contributes only little to the strength of the columns. The contribution of inner steel tube on increasing section capacities is negligible. Increasing the thickness ratio for the columns resulted in increase of ultimate axial load capacity since the confinement effect for the concrete core increases. In the CFDST columns the steel tubes acts as longitudinal and transverse reinforcements. The sandwiched concrete serves to prevent local buckling in the columns.

IV. Effect of Various Parameters on the Strength and Behaviour of CFDST Square Columns

A. Effect of Slenderness ratio

The slenderness ratio (λ) is the main factor that affects the strength and behaviour of CFDST columns. The columns listed under Group 1 were analyzed to study the effect of slenderness ratio on the strength and behaviour of CFDST columns. In group 1 columns, the cross sectional area and the material properties of the columns were kept constant and the height of columns alone is increased from 500mm to 4500mm. The effect of increased slenderness on the strength of CFDST columns is studied. The ultimate axial strength of the columns decreases as the slenderness ratio of the columns increases. In the design codes it has been mentioned that the columns having slenderness ratio values $\lambda \geq 22$ are considered as slender columns. And also it has been evident from previous investigations that the slenderness limit of 22 is applicable for CFDST composite columns

TABLE I. Details of CFDST column specimens tested under Group 1

No	B_O X T_O mmXmm	D_i X T_i mmXmm	f_{yo} MPa	f_{yi} MPa	f_c MPa	Slenderness ratio λ
C1	480X8	240X8	530	230	25	3.3
C2	480X8	240X8	530	230	25	7
C3	480X8	240X8	530	230	25	9.9
C4	480X8	240X8	530	230	25	13.2
C5	480X8	240X8	530	230	25	16.5
C6	480X8	240X8	530	230	25	19.8
C7	480X8	240X8	530	230	25	23
C8	480X8	240X8	530	230	25	26
C9	480X8	240X8	530	230	25	30

Where,
B_o = Width of the outer steel tube in mm
T_o = Thickness of the outer steel tube in mm
D_i = Diameter of inner steel tube in mm
T_i = Thickness of inner steel tube in mm
f_{yo} = Yield strength of the outer steel tube in MPa
f_{yi} = Yield strength of the inner steel tube in MPa
f_c = Characteristic compressive strength of concrete in MPa
λ = Slenderness ratio

TABLE II. Comparision of Ultimate Axial Strengths of CFDST columns determined by Finite Element Method and Analytical investigation for columns tested under group 1

No	L (mm)	λ	$P_{U,analytical}$ (kN)	P_{FE} (kN)	$P_{U,analytical}$ / P_{FE}
C1	500	3.3	14,136	14,314	0.99
C2	1000	7	13,845	13,996	0.99
C3	1500	9.9	13,753	13,848	0.99
C4	2000	13.2	13,640	13,780	0.98
C5	2500	16.5	13,460	13,730	0.98
C6	3000	19.8	13,101	13,666	0.95
C7	3500	23	12,850	13,632	0.94
C8	4000	26	12,540	13,605	0.92
C9	4500	30	12,360	13,576	0.91

Where,
L = Length of the column
λ = Slenderness ratio
$P_{U,analytical}$ = Ultimate axial strength of CFDST column determined from analytical investigation
P_{FE} = Ultimate axial strength of CFDST column determined from Finite Element analysis using ANSYS.

For columns having the slenderness ratio below 22, the numerical and analytical investigation results do not vary much. But as the length of the columns increases the difference between the ultimate axial capacity values obtained from the analytical and numerical investigations increases.

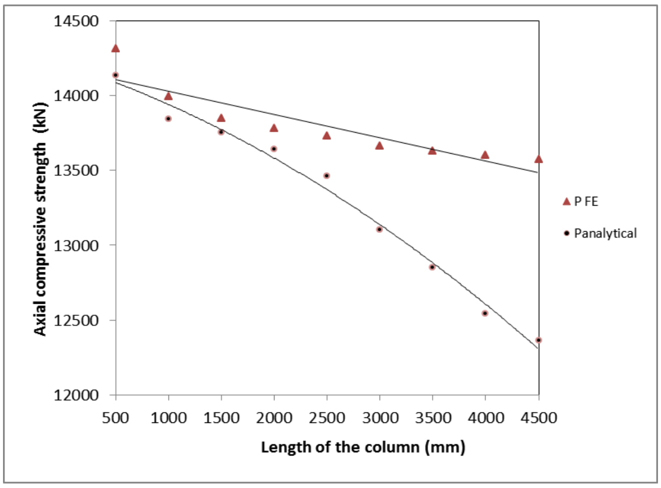

Fig 3: A graph showing the variation of ultimate axial compressive strength with increase in length of the column

B. Effect of hollow ratio

The hollow ratio χ is the ratio of inner tube dimension to the outer tube dimension. From the past investigations it has been evident that when the hollow ratio of a column cross section increases, the ultimate axial capacity of the columns decreases appropriately. This is mainly because of the reduced area of concrete core. The concrete core bears major load that acts on the column. Upon reduction in the cross sectional area of concrete core, the load carrying capacity decreases. In this work, the group 2 columns listed under table 3 was tested by keeping the area of cross section of outer steel tube and concrete core constant. The cross sectional area of inner steel tube alone is varied by varying its dimensions and thickness values.

TABLE III. DETAILS OF CFDST COLUMN SPECIMENS TESTED UNDER GROUP 2

No	B_O X T_O mmXmm	D_i X T_i mmXmm	A_{so} mm^2	A_{si} mm^2	A_c mm^2	Hollow ratio χ
C10	250 x 3	100 x 3	3000	942.5	53155	0.4
C11	267.8 x 2.8	147.5 x 2.8	3000	1298	53155	0.55
C12	288.5 x 2.6	190.7 x 2.6	3000	1557.6	53155	0.66
C13	312.5 x 2.4	234 x 2.4	3000	1764.4	53155	0.75
C14	340.9 x 2.2	280 x 2.2	3000	1935	53155	0.82
C15	375 x 2	330.8 x 2	3000	2079	53155	0.88
C16	416.7 x 1.8	389 x 1.8	3000	2201	53155	0.93

Where,
B_o = Width of the outer steel tube in mm
T_o = Thickness of the outer steel tube in mm
D_i = Diameter of inner steel tube in mm
T_i = Thickness of inner steel tube in mm
A_{so} = Area of cross section of the outer steel tube in mm2
A_{si} = Area of cross section of the inner steel tube in mm2
A_C = Area of concrete core
χ = Hollow ratio.

TABLE IV. COMPARISION OF ULTIMATE AXIAL STRENGTHS OF CFDST COLUMNS DETERMINED BY FINITE ELEMENT METHOD AND ANALYTICAL INVESTIGATION FOR COLUMNS TESTED UNDER GROUP 2

No	χ	$P_{U,analytical}$ (kN)	P_{FE} (kN)	$P_{U,analytical}$ / P_{FE}
C10	0.4	3118.2	3160.9	0.99
C11	0.55	3196.5	3246.5	0.98
C12	0.66	3256.4	3306.7	0.98
C13	0.75	3320	3348.5	0.99
C14	0.82	3336.1	3357.4	0.99
C15	0.88	3320.6	3373.4	0.98
C16	0.93	3245.3	3277.3	0.99

Where,
λ = Slenderness ratio
$P_{U,analytical}$ = Ultimate axial strength of CFDST column determined from analytical investigation
P_{FE} = Ultimate axial strength of CFDST column determined from Finite Element analysis using ANSYS.

This leads to changes in hollow ratio values. The % increase in the ultimate axial capacity is higher for hollow ratio ratios up to 0.5. Upon increasing the hollow ratio above 0.5 the % increase in the strength is very less. And for hollow ratio values above 0.9 the ultimate axial capacity value decreases. The fig.4 shows the graphical representation of the variation of ultimate axial load capacities of the column with increase in the hollow ratio. From the graph it is evident that the in case of group 2 columns the compressive strength values increases up to a hollow ratio of 0.8. After that the axial load capacity of the column starts decreasing.

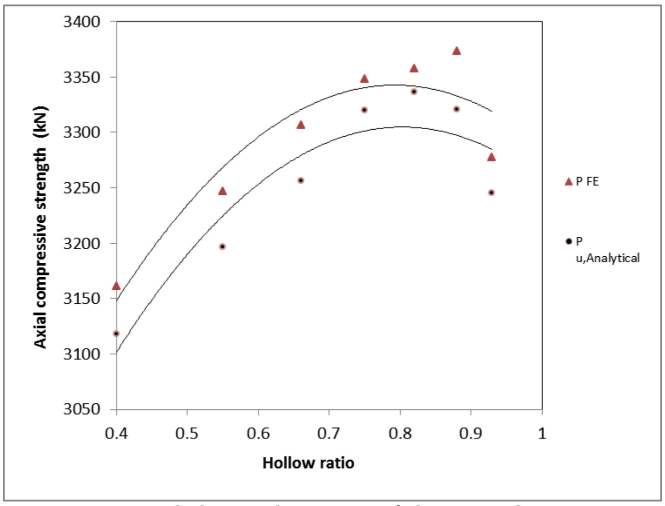

Fig 4: A graph showing the variation of ultimate axial compressive strength with increase in hollow ratio

C. Effect of other parameters

Width to thickness ratio of outer steel tube: As the width to thickness ratio of outer steel increases, the ultimate axial strength value of the CFDST columns also increases.

The change in cross sectional dimensions of inner steel tube has very less influence on the strength of CFDST columns. The increase in ultimate axial capacity of columns is very negligible in this case.

The contribution of inner steel tube to the strength of the column is very negligible. The main role of the inner steel tube is to provide confinement to the core concrete at initial stages of loading.

V. COMPARISION AND DISCUSSION

The predicted ultimate axial compressive strength values from the numerical and analytical investigations was compared. The axial compressive strength values obtained from finite element investigation was higher compared to that of the analytical investigation results. The percentage variation of analytical and numerical investigation is smaller in case of stub columns. Upon increasing the length of the CFDST columns, there is an increased difference in the ultimate axial compressive strength values.

VI. CONCLUSION

The strength and behaviour of CFDST square columns under axial compression are presented in the paper. In this study stainless steel material is used for outer steel tube because of its low cost and superior characteristics compared to that of the austenitic grades. The finite element model was developed using ANSYS Workbench 14.5 and validated. The values obtained were compared with the analytical investigation results. Slight variation was found between the analytical and numerical investigation results. It has been found that the even if the hollow ratio value is increased, the strength of the columns can be increased by keeping the area of concrete core constant. Also the investigations show that the inner steel tube contributes negligibly for the axial load capacity of the CFDST columns. In case of intermediate length columns the effect of concrete core area and strength is more pronounced. Finally, it is recommended that extensive experimental investigations are required.

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