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# Eccentric Loading of CFDST Columns

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***Abstract*****—**Columns have traditionally been constructed of reinforced concrete or structural steel. Much attention was allocated to estimate the axial capacity of the traditional column sections to the detriment of other forms of construction. Other forms of column construction such as Concrete Filled Double Skin Tubes received little research attention, and almost no attention when subjected to eccentric loading. This paper investigates the axial capacity of columns when subjected to eccentric loading. The experimental axial capacities are compared to other established theoretical formulae on concentric loading to determine a possible relationship. The study found a good correlation between the reduction in axial capacity for different column lengths and hollow section ratios.

***Keywords*****—**CSDST, CFST, Axial Capacity.



## I. Introduction

COLUMNS are structural members in buildings which transfer vertical loads from beams and slabs to the foundation. Traditionally, columns have been constructed from materials which are strong enough to withstand the combined effects of vertical loads and moments applied to it. The most common materials used for constructing columns are either reinforced concrete (RC) or structural steel. This is due to previous robust experimental research work which was conducted to provide expressions for column design. Most countries around the world have well-established codes of practice to analysis and design columns using the expressions developed from experimental work. The familiarity which design engineers have with traditional RC and structural steel columns have caused that other methods of construction have been overlooked. In the last few decades other forms of column construction developed to provide stability against forces caused by seismicity and to promote ease of construction. The most common alternatives to RC and structural steel are steel encased concrete columns and concrete filled columns shown in Figs. 1 (a) and (b).

Concrete-encased columns have been available for a few decades and much research work has been devoted thereto. However, concrete filled tubes are a relatively new method of construction which has not received as much attention as the traditional methods of constructing columns. The general scope of this paper deals with concrete filled which will now be elaborated upon. Concrete-filled steel tubes (CFSTs) have been used in many structural engineering applications, such as columns in high-rise buildings, industrial buildings, electricity transmitting towers and bridges [1]. CFST sections have the following advantages, namely:

- During construction the steel tube provides permanent formwork for the concrete.
- The steel tube can carry significant construction loads prior to being filled with column.
- Increased strength and ductility. The steel tube offers confinement to the concrete which increases the capacity of the concrete. The concrete also supports the steel tube, reducing or eliminating local buckling of the steel section resulting in increased load carrying capacity, ductility and energy absorption during earthquakes.
- The thermal properties of concrete increase the fire resistance of the steel tube.

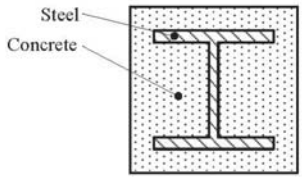


Fig. 1 (a) Concrete-encased columns

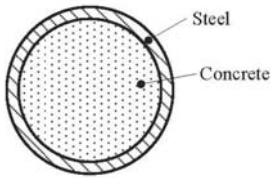


Fig. 1 (b) Concrete filled columns

These advantages result in quick and efficient construction. Numerous research projects were conducted on CFST columns to determine the advantages that this construction method offers. Research investigating the axial capacity of square, rectangular, circular and even elliptical steel tubes filled with concrete was conducted by [2]-[6]. The authors found that increasing the compressive strength of concrete has a significant increase in the load carrying capacity of the concrete filled column. However, the increasing compressive strength of concrete has an insignificant effect on the residual axial capacity after the ultimate load was reached.

CFST columns can be classified as short, intermediate or long. For short (stub) columns the axial capacity of the column is directly related to the section capacity of the CFST. For long (slender) columns the capacity is proportional to the bending stiffness of the section as opposed to the section capacity. Thus, a larger elastic buckling load is expected from CFST columns because of their increased bending stiffness. For intermediate length columns the concept of interaction of local buckling and member buckling also applies to CFST

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columns. However, local buckling is delayed, and could be eliminated, as a result of the support that the concrete core lends to the steel tube. The member capacity of CFST columns are calculated in a familiar manner, i.e. the member's capacity is equal to the product of the section capacity together with a slenderness reduction factor. The Chinese code DBJ13-51 uses a slenderness reduction factor; (called the column stability factor ϕ) that is a function of steel yield stress, concrete strength, steel ratio (area of steel over area of concrete) and the member slenderness.

In a publication three methods of designing slender composite columns, for both encased and single skin concrete-filled tubes are compared [7]. The three methods are:

- Eurocode 4: Part 1.1.
- BS 5400: Part 5.
- A modification of the British Standard for steel BS 5950 Part 1 which contains a design method for steel columns that is simple to use, clear to understand, well calibrated, and well accepted by the steelwork design profession in Britain.

The basis of the modification is to replace the appropriate steel section properties with those of the composite section. This method has been fully presented in a paper and its validity is supported by comparing the results from this method against a large number of tests on concrete filled composite columns [8]. The paper by Wang concludes that all three methods, the EC4, BS 5400 and the proposed modified method, yields conservative predictions when compared to experimental data. The closest predictor was the EC4 method followed by the proposed modified method and then the BS 5400 method. However, the proposed modified method gives a clear understanding of the behaviour of composite columns and is much easier to use than both the BS 5400 and the EC4 methods.

From previous research it is evident that extensive research was conducted on CFST columns. However, a variant of CFST columns that have not received the same level of attention is concrete filled double skin tube (CFDST) columns. The advantages of CFST columns are clear and should hold for CFDST columns as well, with the added benefit of being lighter due to the void in the centre. This paper now examines the axial capacity of CFDST columns.

### A. Estimation of the Axial Capacity of CFDST Stub Columns

Zhao and Han (reported on tests conducted by other authors on CFDST stub columns [9]. It found that the outer tube of CFDST behaves similarly to the CFST tubes and the inner tube of CFDST behaves like an unfilled tube. A significant increase in the ultimate load and ductility was observed when comparing the behaviour of a typical CFDST stub column to the corresponding unfilled outer steel tube. It is also evident that a larger increase in ductility and energy absorption is observed for slender CFDST columns.

The axial sectional capacity of the stub CFDST column can be determined from (1) [1]. For stub columns we expect failure to occur as a result of crushing at the base or apex of the short column, resulting in the so called "Elephants foot". This was verified by several researchers and is well documented. Equation (1) only applies to short columns.

$$N_{CFDST,u} = N_{OC,u} + N_{i,u} \tag{1}$$

The ultimate axial capacity of the stub column is a function of the yield strength and the cross sectional areas of the concrete and steel, the confinement of the concrete and the hollow section ratio. For a complete review of the relevant expressions which constitutes (1), the reader is referred to the paper by Tao [10].

### B. Estimation of the Axial Capacity of CFDST Slender Columns

Columns used in building applications are generally not short, but tend towards being slender columns. Therefore the above method cannot be used to predict the axial capacity when the columns are slender. A stability reduction factor was proposed to (1) to determine the axial capacity of slender columns presented as (2) [1].

$$N_{CFDST,cr} = \varphi \cdot N_{CFDST,u} \tag{2}$$

where: $NCFDST$ is axial capacity of stub columns and $\varphi$ is stability reduction factor. The stability reduction factor is a function of the slenderness ratio, the effective length of the column and the radius of gyration. There are numerous sub equations to determine the stability reduction factor. The reader is referred to Tao for a detailed description how to determine the stability reduction factor, where after the axial capacity of slender columns can be determine. The method is only valid for concentric loading and does therefore not account for eccentric loading.

This focus of the research was to establish whether there is a relationship between the axial capacity equations presented by Tao and when slender CFDST columns are subjected to eccentric loading.

## II. Experimental Method

This section describes the experimental setup of the CFDST columns, material used and the testing method used to obtain the axial capacity when columns are subjected to eccentric loading.

TABLE I
SUMMARY OF THE TEST SPECIMENS

| Designation | Length (mm) | Outer diameter (mm) | Inner diameter (mm) | Sections thickness (mm) |
|---|---|---|---|---|
| STK (Short thick) | 2500 | 177.8 | 76.2 | 3.0 |
| LTK (Long thick) | 3500 | 177.8 | 76.2 | 3.0 |
| STN (Short thin) | 2500 | 177.8 | 127.0 | 3.0 |
| LTN (Long thin) | 3500 | 177.8 | 127.0 | 3.0 |

Two different lengths were chosen as well as two different hollow-section ratios. For each combination of length and hollow-section ratio three test specimens were constructed. A summary of the test specimen showing the length, hollow

section ratio, number of specimens and designation of each test specimen is given in Table I. Figs. 2 (a) and (b) show the thin and thick concrete CFDST annulus, respectively.

Fig. 2 (a) Thin annulus

Fig. 2 (b) Thick annulus

### A. Concrete Properties

The column lengths and the limited space between the steel tubes made vibration very difficult. Therefore self-compacting concrete was required to fill the tubes. The mix proportions of the various aggregates used to obtain a 50 MPa concrete strength is presented in Table II. This mix achieved a slump flow of 690mm with a segregation of 3%.

TABLE II
MIX AGGREGATES' PROPORTIONS

| Constituents | Relative density | [kg/m$^3$] |
|---|---|---|
| Cement: CEM I 52.5N (PPC) | 3.14 | 246.4 |
| Fly Ash DuraPozz (Ash Resources) | 2.2 | 115.1 |
| Water | 1 | 190.0 |
| Malmesbury Sand | 2.64 | 990.0 |
| 6mm Greywacke stone | 2.7 | 800.0 |
| Super Plasticiser: SP1 (Mapei Dynamon) | 1.09 | 2.89 |

### B. Steel Properties

The structural hollow steel sections used in the experimental tests are produced in accordance with SANS 657: Part 1. The inner steel tubes are rolled from S355W steel with a yield strength of 355 MPa and an ultimate strength of 470 MPa. The steel used for the outer tube yields at 300 MPawith an ultimate strength of 450 MPa. The strengths of the steel tubes is determined by the grade of steel that was available at the time of purchase.

### C. Test Setup and Equipment Used

The experiments were performed using a hydraulic actuator with a compression capacity of 2 MN. The actuator can be either load or displacement controlled. The tests were conducted using a displacement rate of 1mm/min to simulate quasi-static conditions. To simulate pinned conditions pot bearings were used at both ends of the test specimen. The magnitude of the load was measured using a 2MN load cell, while the axial displacements were measured on the four edges of the base plate. Lateral displacement measurements were also recorded during the tests on the wood blocks around the perimeter of the column. A specimen ready for testing is presented in Fig. 3.

Fig. 3 Specimen ready for testing

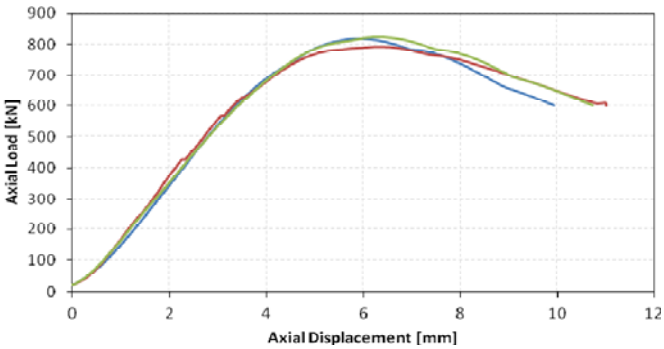


Fig. 4 Experimental tests results for STK

## III. RESULTS

### A. Experimental Results

The results of experimental tests are now presented. All tests were performed with a 20mm eccentricity. Fig. 4 shows the 3 test results of the short thick columns (STK), i.e. a

column length of 2 500mm with an outer diameter of 177.8 x 3.0mm and an internal diameter of 76.2 x 3.0mm. From Fig. 4 we notice that all 3 tests yield similar results without any discrepancies. The average peak load of the 3 tests is 811.3kN with a corresponding axial displacement of 6.2mm. The peak load of each column falls within 28.7kN of each other which results in 3.5% of the average peak load. The displacement at peak load for each column falls within 0.4mm of each other, which results in 6.5% of the average displacement at peak load.

The tests for the other 3 specimens yield similar peak loads with corresponding displacements. For the benefit of space these figures are omitted. Table III shows a comparison of the peak loads and corresponding axial displacements for the 4 specimens tested.

TABLE III
AVERAGE PEAK LOAD AND CORRESPONDING DISPLACEMENTS

| Test specimen designation | Average peak load (kN) | Average axial displacement (mm) |
|---|---|---|
| STK (Short thick) | 811 | 6.2 |
| STN (Short thin) | 745 | 6.9 |
| LTK (Long thick) | 672 | 6.0 |
| LTN (Long thin) | 624 | 6.8 |

### B. Concentric Axial Results from Tao

The axial capacity of the columns for concentric loading was determined using the equations presented by Tao. It is emphasized that these axial capacities were obtained using the same material properties for concrete and steel. Table IV shows the results obtained using the expressions from Tao.

TABLE IV
PEAK LOAD USING EXPRESSIONS FROM TAO

| Test specimen designation | Peak load (kN) |
|---|---|
| STK (Short thick) | 954 |
| STN (Short thin) | 1 024 |
| LTK (Long thick) | 1 066 |
| LTN (Long thin) | 1 174 |

## IV. COMPARISON OF RESULTS AND DISCUSSION

The purpose of the study was to determine whether there is a correlation between the axial capacities of the experimental tests and the results obtained from Tao's expressions. Table V presents the axial capacities for the above cases as well as the percentage difference.

TABLE V
COMPARISON OF RESULTS

| Test Specimen Designation | Concentric peak load determined from Tao's expressions (kN) | Experimental results for 20mm eccentric loading (kN) | Percentage difference (%) |
|---|---|---|---|
| STK (Short thick) | 1174 | 818 | 30.3 |
| STN (Short thin) | 1 066 | 745 | 30.1 |
| LTK (Long thick) | 1024 | 676 | 34.0 |
| LTN (Long thin) | 954 | 624 | 34.6 |

The trend in Table IV suggests that an estimated strength reduction of 32.5% could be assumed for an eccentricity of 20mm. The longer columns have an average reduction in strength of 34.3% with an insignificant 0.6% difference between the LTK and LTN models. While the shorter columns have an average reduction of 30.2% with an insignificant difference between the STK and STN models of 0.2%. An average reduction in axial capacity of around 32% is observed for an eccentricity of 20$mm$. The nature of the relationship between the column length and the reduction in axial capacity, whether it be linear or not, cannot be commented on without further experimental tests. However, it can be said that the results from this study does show a good, predictable trend between the length of the column and the reduction in axial capacity under eccentric loading.

## V. CONCLUSIONS

A study was conducted on CFDST columns. The purpose of this study was to serve as an introduction into this field of study while investigating methods of predicting failure loads of CFDST columns under eccentric loading. The goal was to identify methods to predict the eccentric load capacity in a computationally efficient manner with acceptable accuracy. Possible methods were identified from the literature study and yielded the following results.

This method used equations proposed in literature to predict the concentric axial capacity [10]. The calculated axial capacities were compared to eccentrically loaded experimental test results. The aim here was to determine whether there exists a trend that could be used to predict the capacities of eccentrically loaded CFDST columns from the calculated concentrically loaded capacities. The result of this part of the study showed promising results indicating a clear trend in the reduction percentage in axial load capacity. There was a near constant percentage difference for test specimens with the same length. The results showed a smaller difference for the shorter column. This shows that the equations take changes in hollow section ratio into account. There was little difference in the reduction percentages between two specimens with the same length and different hollow section ratio.

## VI. RECOMMENDATIONS

- This study did not draw any comparisons between CFDST columns and any other type of column. An in depth comparison between CFDST columns and RC columns, showing the advantages and disadvantages of both (including construction and cost), could go a long way in promoting the use of concrete filled composite sections in South Africa.
- This study showed a clear correlation between the reduction in axial load capacity predicted by simple equations and the length of the column. Further investigation into the trend of this correlation between different lengths and for different eccentricities is necessary.

## ACKNOWLEDGMENT

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