Concrete Filled Double Skinned Tubular Columns Subjected to Different Loading Conditions

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Abstract: The meteoric growth in light weight structures have opened doors to many revolutionary concepts and innovations. Studies have manifested that the lowered weight of the structures somehow help to fight the material cost with a better seismic performance. The hollow core structures aimed reducing the structural weight with an improved structural performance as well. The Concrete filled double steel tubes (CFDST) can be taken as amalgamation of Hollow core columns and CFST i.e. single skinned columns. The co-relation of CFST and Hollow core columns gave birth to Concrete filled double skinned tubular columns (CFDST) which can possess the advantages of both the concepts. A sedulous review of concrete filled double skinned columns is being conveyed through this article. The behavior of confined concrete as well as the confining inner and outer steel in the CFDST model and its overall structural behavior is being succinctly reviewed in this article and a simultaneous comparison of CFDST columns to solid concrete/ conventional columns is also being carried out where required.

Keywords: Concrete filled double steel tubes; composite columns; hollow core columns;

1. Introduction

The system of confining concrete with outer steel tubes of defined thickness termed out to be as concrete filled tube system (CFST) and was majorly proposed for accelerating bridge construction. CFST’s were aimed to reduce construction time with increased construction quality and safety [1–3]. Moreover, with the use of these columns nominal traffic interference with increased seismic performance could be kept. CFST’s have successfully showcased improved seismic, flexural and torsional behavior but on the other hand have faced several challenges as well. The centrally confined concrete took lesser amount of compression as compared to the steel per same cross sectional area [4–6]. The torsional strength seemed
to be ineffective of the centrally confined concrete. The concrete placed in the center added up a majority of weight making the system uneconomically heavy. Moreover, the concrete closer from the neutral axis proved to be ineffectual over its flexural strength. The possible downsides of CFST’s gave rise to the concept of Concrete filled double skinned tubes (CFDST), which possessed collective advantages of hollow core columns and CFST’s. This design confined the concrete between two hollow steel tubes of defined thickness which may or may not be of similar cross sections. It has been observed that the axial loading capacity of sandwiched tube i.e. CFDST, is 10-30% more as compared to combined capacities of individual components acting alone [7–9], see figure 1.

![Figure 1 Typical cross section on circular and square CFDST](image)

The very core part of the CFST was thought to be replaced or removed completely leaving a complete hollow section in the middle. The Concrete filled steel tubes (CFST) became the very base for the further studies on CFDST which were basically prepared to be used in submerged tube tunnels. Tests proved that the local buckling behavior of outer and inner steel was prevented/resisted due to confined concrete. The confining tubes may also affect the mode of failure of concrete and bring down its behavior from being brittle to ductile [10,11]. Through previous research one can conclude that the increased confining pressure over concrete positively affects its strength and ductility performance. Owing to the removal of ineffectual core concrete, significant reduction in the self-weight could be achieved. The light weight of this system helps in achieving better seismic performance and brings down the material cost as well making this a sustainable technology. The ultimate strength and composite modulus for CFDST using energy theory and unified theory was also presented. A core relation of steel ratio, Poisson’s ratio of steel and horizontal deformation coefficient of concrete with axial stiffness was established as well [12–14].

\[
\begin{align*}
    E_0 A & = E_s A_{si} + E_s A_{so} + E_c A_c \\
    E_{ssc} A & = E_{si} A_{si} + E_{so} A_{so} + E_c A_c \\
    \bar{E}_{si} & = E_s + \frac{E_s \nu_s (D_i - t_i) (4\nu_c - \nu_s \alpha)}{8t_i (1 - \nu_c - \nu_s)} \\
    \bar{E}_{so} & = E_s + \frac{E_s \nu_s (D_o - t_o) (4\nu_c - \nu_s \alpha)}{8t_o (1 - \nu_c - \nu_s)} \\
    \bar{E}_c & = E_c + \frac{E_c (4\nu_c - \nu_s \alpha)^2}{8(1 - \nu_c - \nu_s \nu_s)}
\end{align*}
\]
In order to truly understand the CFDST members the common approach is to separately analyze the inner steel, outer steel and the confined concrete in between. Simple superposition method (equation 1) was used for estimating the composite column stiffness. The overall result could be modeled by combining the separate behaviors. They further calculated modified elastic modulus separately for each component using energy theory. The behavior of each component could be separately calculated and put down together for combined results. The combined stiffness of the composites can be presented using 2nd equation above derived with considering the confining effects. The value for modified elastic modulus of inner steel, outer steel and concrete can be calculated using equations 3,4 and 5 respectively. The effectiveness of confinement could be improved using external steel ring spaced up differently. The load carrying capacity can be influenced positively by decreasing the spacing between external steel ring confinement. The load carrying capacities was found to be improved for about 11.5% and 9.5% on average for CFDST’s having hollowness ratios of 0.56 and 0.72 respectively [15–17].

2. Material Properties

Concrete: It is a composite brittle material used as a confined shell of definite thickness in CFDST. Concrete, when under compressive forces, tries to laterally deflect and brings the outer and inner steel tubes under lateral pressure. The distribution of stress can be easily visualized by Fig.2 which showcases different components of the stub column under lateral stress. The confinement pressure through the outer and inner tubes can be defined using confinement coefficient as in equation 6 where \( A_S \) and \( A_C \) are areas of steel and concrete, \( f_s \) and \( f_{ck} \) are strength of steel and concrete.

\[
\xi_{ssc} = \frac{\sum A_s f_s}{A_f f_{ck}}
\]

Steel: The inner and outer steel tubes are the paramount of this composite augmentation. Generally, both the tubes are kept of similar properties but as the outer tube is the most exposed part for environmental corrosion hence a precise manipulation can be effectual for improving the structure life. The tubes are very much crucial for providing the confinement to the concrete shell and are also resistive and bolster in curtailing the spalled concrete during contact explosion. Generally, two grades of cold-worked steel Fe415 & Fe500 with characteristic yield strength \( f_y \) of 415 N/mm² & 500 N/mm² respectively having Elastic Modulus of 200000 N/mm² are used.

3. Circumstantial Behaviors of CFDST

The behavior of both CFDST’s and CFST’s is somewhat relative in nature. The CFDST also helps in speeding up the construction process and their outer steel skin functions as pre-form work. These section types similarly affect the quick finishing of undertaking as of CFST’s. The real disappointment in regular sections have been coming through buckling. The buckling phenomenon in these kinds of segments is imperative too. The genuine comprehension of the failure mechanism could be picked up by independently considering the conduct of infill concrete and the external and internal steel tubes. The concrete under compressive loading tries to displace laterally. This lateral displacement is confined by the inner and outer tubes leaving both of them under lateral pressure. The developed pressure thus tries to cause lateral inward and outward deformation in the inner and outer steel tubes respectively, see figure 2.
A study took a shot at the disappointments of concrete filled double skin tubes keeping in thought the length, diameter and the strength of the external cylinders. The fallout coordinated that the sections with least given length for example 1m, flopped because of yielding of steel tube while in all the others large buckling was seen. Further it was also demonstrated that external buckling was the real reason for failure in external steel tubes though the internal steel tubes having bigger diameter to thickness proportion indicated internal buckling. However those with smaller ratios observed no buckling. Additionally, the increased specimen length caused a concurrent decline in compressive limits of CFDST's.

### 3.1 Behavior under large deformation Axial & Cyclic loading

The functioning of CFDST under large deformation axial and cyclic loading is persuaded with the loading conditions and the diameter to thickness ratios. The columns having slenderness below 110 were observed having multiple folds without any cracking, whereas the columns with slenderness greater than 110 showcased multiple folds with some sort of cracking. Further the study showed that the columns having slenderness less than 82 were not affected with the cyclic loading on deformation front. However, the effect of cyclic loading tried to increase in columns with slenderness between 82 -110. The effect was to be increased if the loads were to be applied late in the loading history. Columns with slenderness greater than 110mm were significantly affected with the cyclic loading applied at an early stage of total loading history. This was observed in columns with such greater slenderness that the outer steel starts buckling at an early stage affecting the results severely.

The Table 1 lists down the results obtained by one of the studies. The table demonstrates a definitive load conveying limit of the CFDST with 2 unique phases of presentation of cyclic stacking. One was at a beginning time when the load diminishes to 90% of the maximum load (Specimen name-90) and the second one comes late in the stacking history when the deformation achieves 60mm (name of specimen-60). Further the Figures 3A and 3B demonstrates the failure modes of CFDST's. The Figure 3(a) clarifies the failure of segments with slenderness ratio of around 82. For these sorts, various folds without splitting were seen. For these as well as for every segment with slenderness ratio under 110, numerous folds without breaking were observed. Be that as it may, for the segments with slenderness ratio more prominent than or equivalent to 110, various folds with splitting were seen as showed in the Figure 3(b).

**Table 1** Ultimate capacity of CFDST specimen by [21]

| Specimen label | D/t | λs | Pf (kN) |
|----------------|-----|----|--------|
| 0111-90        | 19  | 35 | 1615   |
3.2 Behavior under long term sustained loading

The CFDST’s and the CFST’s somewhat share lots of similarities under long term sustained loading behavior. The axial strain was observed to be increased significantly at preliminary stage and was most likely to attain 60% of the four months value within a month. After a span of approx. 100 days, the axial strain was observed to be stabilized at a slower note. The point of outward buckling on the outer tube and inward buckling on the inner tube were found nearly on similar positions with a crushed confined concrete behavior at that point. A comparable conduct of CFDST was correlated with CFST’s under long term sustained loading and had an exceptionally moderate impact on the Axial Strain Vs Deflection bend. Further examinations demonstrated that the load conveyed by the confined concrete would in general diminish for about 30.5% while an expansion of 31.2% of load on both the empty steel tubes internal just as external was seen, see figure 4.
The long term sustained loading in general created an extra moment in the section for which it exhibited a decline in its ultimate strength with concurrent increment in lateral displacement. The regular conduct of the segments after the tests can be effectively made out from the Figure 4. The individual conduct of the sandwiched concrete with internal and external steel can be comprehended through Figure 5(a).

The sustained loading over the column can be seen amid the stage from point A till point B. The extra moments produced in the test examples amid long term sustained loading dropped its ultimate load capacity as shown in Figure 5 (b). In any case, those moments were not created during short term loading, prompting an increased ultimate strength.

**3.3 Behavior against Corrosion**

The Concrete-filled double skinned tube structures when utilized in seaward zones are liable to depletion too. The impact of corrosion on these segments is almost certain equivalent to on different structures, for example it diminishes its load carrying capacity. It was seen that the load carried by the internal steel tubes was not affected amid the corrosion time frame. The general decay was taken by the external cylinders bringing about the decline of its load carrying limit. Notwithstanding, setup with various conditions were made for the tests i.e. with uniform erosion (C), corrosion with sustained loading (PC), re-loading and sustained loading (PL) and under pre-loading, sustained loading with corrosion (PLC). A safe relationship can be created between the strength of columns and the degree of corrosion utilizing the outcome information. With increment in the comparing corrosion levels, an immediate strength decrease in the columns could be affirmed. In any case, one progressively significant perception which was made out from the tests was that
the impact of consumption appeared to be autonomous from the combined loading. Fig.6 demonstrates the
strength comparison information which helps in understanding the genuine conduct of the sections. The
figure obviously characterizes that the segments with combined loadings LC-e, PLC-e are having same
strength proportions as of the sections under uniform corrosion C-e. The change in the strength can be just
seen through the rate change in corrosion levels which infers that the strength information is absolutely
subject to the degree of corrosion applied independent of the combined loading effects . Till now no
relationship could be made among corrosion and combined loading, see table 2 and figure .

### Table 2 Results under corrosion, pre-load and sustained load

| Specimen Label | Outer tube thickness after corrosion (mm) | Corrosion damage degree (%) | Measured ultimate Strength $N_{u,exp}$ (kN) |
|----------------|-----------------------------------------|-----------------------------|------------------------------------------|
| C-1            | 2.66                                    | 11.0                        | 1443                                     |
| C-2            | 2.63                                    | 12.0                        | 1433                                     |
| LC-1           | 2.36                                    | 21.1                        | 1391                                     |
| LC-2           | 2.33                                    | 22.1                        | 1386                                     |
| PL             | 2.99                                    | N.A                         | 1568                                     |
| PLC            | 2.36                                    | 21.1                        | 1349                                     |

Figure 6 Influence of corrosion on ultimate strength

3.4 Behavior under torsional loading

A rigorous analysis was done in order to unravel the response of CFDST columns under torsional loading.
Different parameters of this composite column were tried to be linked with the obtained behavior. The
observation directed that the inner steel tube was not much effective or influencive towards the column’s
ultimate torsion as shown in Figure 7(b). When the strength of the inner tube was allowed to increase
correspondingly the ultimate torsion too increased but the ratio wasn’t that high. Moreover, with the removal
of the same, the ultimate torsion came down than before. This somehow explained the moderate participation
and importance of inner steel tubes within the scenario of ultimate torsion. Though the percentage change in
ultimate torsion was seen to be much influenced with outer steel tubes as shown in Figure 7(a). The strength
of concrete was also a less governing factor when discussing about the ultimate torsional strength. Even
when the lateral stiffness was taken under consideration, the concrete marked itself to be an extremely
important element .
Also, the increase in the concrete shell thickness can relatively decrease the steel tube dimensions in turn decreasing the ultimate torsional strength of the column. The percentage change in ultimate torsion with varying strength of concrete can be seen through Figure 8(a). It notifies that the concrete may diminutively but do affected the ultimate torsional behavior. Further the increase in outer steel diameter to thickness (D/to) ratio do plays an important part in the columns ultimate torsional strength as shown in Figure 8(b). In totality it was observed that the behavior of the column under torsional loading is majorly dependent upon the outer steel tube.

3.5 Behavior under Contact Explosion

From all the elements of the composite column the behavior of concrete towards energy absorption was found to be outstanding as shown in Figure 9(a) and (b). About 80% of the energy imparted was being absorbed by the infilled concrete shell. Though some of the energy was also absorbed through outer steel tubes but on the other hand inner steel tubes came out to be least effective. In any case, the spalling of concrete was viably neutralized by the external steel tubes and an auxiliary harm through fast catapulted parts could be avoided. The harm caused on the internal and external steel tubes was to a noteworthy degree checked by the energy engrossing capacity of concrete under contact explosion.
Some extreme amount of compressive power generation could be observed under the scenario of contact explosion. This phenomenon tends to produce large plastic strains in outer steel which when exceeding the fracture strain of steel can drive it against rupturing failure or cracking. The software simulation had showed that the major impact of contact explosion was on the areas directly under explosives as shown in Figure 10. No further yielding in other parts of the inner or outer steel was observed. The studies further showcased that the one third of the front area was severely damaged from the contact area of explosion. Compressive waves tended to produce after the explosion propagated throughout the material from the load source. These stress waves were the reason for other observed damages throughout the material. The generated compressive stresses immediately caused concrete failure as they were ten times higher than the compressive strength of concrete.

4. External Strengthening Techniques

4.1 External Confinement using Steel rings

The procedure of externally confining CFDST with steel rings somehow tended to improve its mechanical properties like strength, stiffness and ductility. These properties were however much positively affected when the external rings get more closely spaced. The reason behind this might be the more continuous, uniform and greater confining pressure development due to the provision of external steel rings. Further it
could be contemplated that the arrangement of the rings diminished the effective length of the external steel tube which specifically caused delay in buckling. The steel rings were seen to enhance the steel-concrete interface holding with a concurrent advancement of higher confinement pressure and restricted lateral deformation.

4.2 Strengthening using FRP sheets

Strengthening structures using FRP was initiated in mid-1950’s. Since then it has been effectively used for rehabilitation of concrete structures. A study was carried out focusing on behavior of CFDST stub columns when confined using Fiber Reinforced Polymer. This system represented a combined benefit of FRP, Hollow steel tubes and Hollow concrete shell. The results demonstrated that confining CFDST with FRP sheets worked as an effective method of improving its strength. The failure in these types of jacketed columns started with a sudden rupture of FRP jacketing followed by buckling of steel tubes. It was seen that the buckling of steel tubes could be delayed using FRP jacketing. Further a bi-linear behavior in both load vs strain (specimen) & stress vs strain (concrete) curve was observed.

5. Conclusions

The following conclusions are drawn based on the literature of CFDST columns under different loading conditions:

1. The accompanying investigation opened up portals for seeing further in detail system of concrete filled double skinned tubes. The study shred lights on various practices of this subtle procedure with a point of evacuating this hypothetical idea from proposal and raising its utilization in continuous development. A framework of concrete filled double skinned columns under axial compression, large deformation loading, corrosion, blast loading and torsional loading was deduced.

2. It was recognizable that how successfully CFDST’s could bear a portion of the above element’s superior to any other type of construction such as the conventional columns and the concrete filled single skinned columns. Beforehand concrete filled single skinned columns were in more prominent logical consideration because of its enhanced flexural, seismic and torsional execution with a synchronous decrease in its development time attributable to the conduct of the external steel tube as pre-foam work.

3. However, the concrete filled double skinned columns are a further adjustment of CFST’s so as to neutralize the disadvantages of the last one. It general expel the inadequate center concrete and the heavy weight design, which was received utilizing an empty steel container of characterized thickness in the center. The mechanism of lateral displacement of concrete under axial compressive loading and the simultaneous confinement of the inner and outer steel tubes to the concrete shell could be obviously comprehended. The confining pressure from the internal and external cylinder advantageously affect the strength and performance of concrete.

4. It was seen that the evacuation of the center concrete helped in lessening oneself load of the structure which thus spared the material and development time too. This decreased weight didn’t just support up the structure monetarily yet in addition included to its seismic conduct, leaving a structurally, environmentally and financially sparkling idea driving.
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