# CONCRETE-FILLED TUBULAR COLUMN MADE OF VARIOUS TYPES OF MATERIAL: A REVIEW

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***Abstract**:* Concrete-filled tubes (CFT) are gaining popularity due to their excellent performance under compression. Various materials have been used to produce CFTs. Their behavior varied significantly due to the properties of the materials. In this study, numerous articles related to CFT were reviewed. The effects of carbon steel, stainless steel, fibre-reinforced polymers (FRP), plastic materials, and various kinds of concrete on CFT were observed. The fundamental principles governing the behavior of CFT were then determined. The confinement effect of the tube was the key to the outstanding performance of CFT. CFT performed well when the tube had high compressive strength, elastic modulus, tensile strength, ultimate strain, and corrosion resistance. The concrete with high compressive strength and ultimate strain, as well as low elastic modulus and shrinkage, experienced greater strength enhancement under confinement. Nevertheless, confinement effectiveness was greatly affected by the slenderness ratio. Short CFT subjected primarily to axial loads was preferred.

**Keywords:** *Concrete-filled tube, composite column, axial load, confinement effect, behavior*

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## INTRODUCTION

Concrete-filled tube (CFT) is a composite column made of a tube and concrete infill [1]. It is popularly used in modern structures, such as high-rise buildings, bridges, military facilities, industrial workshops, subways, electricity transmission towers, and foundation piles [2] – [6]. CFT exhibits excellent constructability [1], [7]. The tube acts as a permanent formwork and supports construction loads at the early stage of concrete [8]. This results in quick and efficient construction [9], which subsequently saves material costs and construction time [6]. CFT performs outstandingly under axial loads [1], [7]. Compared with unconfined concrete, CFTs generally possess higher ultimate axial strength, ductility, energy absorption, and post-peak strength [10] – [13].

CFT is gaining the attention of researchers, with an increasing number of articles published recently. Various materials were used to produce CFTs. For the unique characteristics of materials, the behavior of CFT varies considerably. Despite the diversity, the fundamental principles governing the load response are the same. These principles shall be considered when designing CFT.

In this study, articles on CFTs made of steels, fibre-reinforced polymers, and plastics were consulted. The effects of the materials on CFT's performance were scrutinized. The fundamental principles governing the behavior of CFT were then determined. Lastly, the prospects and future studies were discussed.

## MATERIALS FOR CFT

Researchers used various materials as tubes for CFTs. This included steel [2], [14] – [16], stainless steel [17] – [19], fibre-Reinforced Polymer (FRP) [7], [18], [20], High Density Poly Ethylene (HDPE) [21], Unplasticized Polyvinyl Chloride (uPVC) [5], [12], [22] – [25], and Polyvinyl chloride (PVC) [1], [10], [26] – [31]. The behavior of CFT differed owing to the unique characteristics of these materials.

### A. STEEL AND STAINLESS STEEL TUBES

Carbon steel tubes took part in resisting axial compression [32], although concrete offered a greater contribution [14]. However, steel was susceptible to corrosion. When exposed to aggressive environments, localized corrosion pits would develop on the steel surface. It can affect the structural performance of CFT in long term.

According to [33], the corrosion pits affected CFTs in four aspects; (a) concentration of stress around the corrosion pits, (b) local buckling of the steel tube, (c) lower strength of steel tube, and (d) weaker confinement on the concrete. For every 1.2 mm thickness loss of steel due to corrosion, the ultimate strength of CFT decreased by 31.7% [34]. Protective coatings may be provided on the steel surface to prevent corrosion. However, this was not always effective, particularly over a long period and under less-than-ideal operational or maintenance conditions [35].

Stainless steel was more durable and corrosion-resistant than carbon steel [36]. It required fewer maintenance costs [36]. It was principally used as an exposed element for its pleasant appearance [37]. However, stainless steel was about 4 times more expensive than carbon steel [38]. CFTs made of stainless steel showed improved ductility, higher energy dissipation ability, and superior fire performance compared with carbon steel [17]. It was due to the higher strength of stainless steel than carbon steel (Table 1).

Stainless steel bonded poorly with concrete due to its smooth surface. The bond strength was 32% to 69% lower than carbon steel [43]. This may not be a problem in normal service conditions when the tube and the concrete were simultaneously loaded [17]. It should be considered when transferring a load between the tube and concrete via bond [17]. For example, when CFT was subjected to moment, buckling, flexural bending, or eccentric load. The bond strength may be enhanced by welding rings or shear studs onto the tube surface [43]. However, this may slightly alter the properties of stainless steel in the welded region. Alternatively, expansive concrete may be used to improve the bond, but it was not effective [43].

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Table 1 Properties of carbon steel and stainless steel

| | Description | Elastic Modulus (*GPa*) | Yield strength (*MPa*) | Ultimate strength (*MPa*) | Ultimate strain (%) | Poisson's Ratio | Ref. |
|---|---|---|---|---|---|---|---|
| Carbon steel | Square section | 210 | 210 | 350 | | 0.3 | [30] |
| | Circular section | 205 | 300 | 362 | | 0.3 | [30] |
| | Circular section | 200 | 300 | | | | [39] |
| | Circular section | 226.04-337.62 | 237.45-326.72 | 297.45-386.31 | | | [40] |
| Stainless steel | Austenitic (Grade 1.4301) | | 230 | | 45 | | [36] |
| | Austenitic (Grade 1.4401) | | 240 | | 40 | | [36] |
| | Duplex (Grade 1.4162) | | 530 | | 30 | | [36] |
| | Duplex (Grade 1.4362) | | 450 | | 20 | | [36] |
| | Duplex (Grade 1.4462) | | 500 | | 20 | | [36] |
| | Austenitic (Grade 1.4301) | | 230 | 540 | | | [41] |
| | Austenitic (Grade 1.4318) | | 350 | 650 | | | [41] |
| | Duplex Grade 1.4462 | | 480 | 660 | | | [41] |
| | Tube diameter 50 to 165 mm | | 225.7 – 281.1 | 562.1 - 656.4 | | | [42] |

## B. FRP TUBES AND WRAPPINGS

Fiber Reinforced Polymer (FRP) was insensible to chloride-induced corrosion [44]. It was expensive due to the costs of materials and labor [26]. There are Carbon Fiber Reinforced Polymer (CFRP) [45] – [47], Glass Fiber Reinforced Polymer (GFRP) [48] – [50], E-Glass Fibre [51], Basalt Fibre Reinforced Polymer (BFRP) [42], [52], [53], and Polyester Fibre Reinforced Polymer (PFRP) [54].

FRP was good in tension but poor in compression [44]. Its tensile strength can exceed a Grade 500 steel bar. FRP had a low ultimate strain, barely exceeding 4.4% (Table 2). This led to linear elastic behavior with brittle failure of CFT [7].

Table 2 Properties of FRP

| Types | Elastic modulus (GPa) | Ultimate tensile strength (MPa) | Ultimate strain (%) | Area weight (g/m$^2$) | Ref. |
|---|---|---|---|---|---|
| BFRP | 105 | 2100 | 2.6 | 300 | [55] |
| | 91.3 | 1849 | 2.02 | 300 | [56] |
| CFRP | 243 | 4420 | 1.67 | | [39] |
| | 213 | 3200 | 1.5 | | [54] |
| | 240 | 4900 | 2 | 300 | [55] |
| | 230 | 3200 | 1.48 | 300 | [56] |
| | 250 | 4571 | | | [57] |
| | 251 | 3421 | 1.37 | | [58] |
| GFRP | 60.78 | 660 | 3.27 | | [39] |
| | 60.8 | 967 | 1.6 | | [54] |
| | 71.7 | 1718 | 2.26 | 450 | [56] |
| PFRP | 0.9-2.0 | 27.1–45.1 | 3.4-4.4 | | [54] |
| E-Glass | 79.18 | 1449 | 1.85 | | [58] |

FRP confined concrete well but offered limited axial strength. The confinement effectiveness must be sufficiently high to have the ultimate strength increased [59]. This was dependent on the type, orientation, and amount of FRP used to confine concrete.

Among FRPs, CFRP had the highest elastic modulus and ultimate strength. It, therefore, confined concrete most effectively. [39] confirmed this, with CFRP and GFRP strength improvements of 361.2% and 124.41%, respectively. [60] further affirmed this, reporting a reinforcing effect of 237.35% for CFRP against 68.67%-195.18% for BFRP.

FRP confined concrete better when oriented in the hoop direction [7]. The ultimate tensile strength and elastic modulus of FRP in the hoop direction were higher than in the longitudinal direction, as demonstrated in Table 3. This is conditional on the use of uni-directional FRP. For concrete partially wrapped with equally spaced FRP strips, the confinement effect increased as the hoop spacing decreased [57].

The strength and energy absorption capacity of confined concrete increased with the number of FRP layers [61]. According to [53], the compressive strength and ultimate axial strain of CFT confined by double-layer FRP were higher than the single-layer. Extra layers of FRP increased the elastic modulus and tensile strength, as seen in Table 4. It restrained the expansion of concrete more effectively. This strengthening effect was more pronounced for lower-strength concrete [61]. The concrete experienced larger expansion under load due to its lower elastic modulus.

Table 3 Properties of FRP in longitudinal and hoop directions (mean values) [42]

| Type | Longitudinal direction | | | | Hoop direction | | | |
|---|---|---|---|---|---|---|---|---|
| | $f_{ul}$ (MPa) | $\varepsilon_{ul}$ | $E_l$ (GPa) | $v_l$ | $f_{uh}$ (MPa) | $\varepsilon_{uh}$ | $E_h$ (GPa) | $v_h$ |
| CFRP | 242.9 | 0.0088 | 40.5 | 0.26 | 592.8 | 0.01 | 66.7 | 0.52 |
| BFRP | 124.0 | 0.0142 | 12.7 | 0.29 | 331.1 | 0.0149 | 24.3 | 0.30 |
| GFRP | 217.6 | 0.0190 | 20.1 | 0.32 | 308.8 | 0.0139 | 25.2 | N/A |

*Note: $f_{ul}$ = Ultimate strength in longitudinal direction of FRP (tensile coupon test); $f_{uh}$ = Ultimate strength in hoop direction of FRP (disk-split test); $\varepsilon_{ul}$ = Ultimate strain of FRP in longitudinal direction (tensile coupon test); $\varepsilon_{uh}$ = Ultimate strain of FRP in hoop direction (disk-split test); $E_l$ = Elastic modulus of FRP in longitudinal direction; $E_h$ = Elastic modulus of FRP in hoop direction; $v_l$ = Poisson's ratio of FRP in longitudinal direction; $v_h$ = Poisson's ratio of FRP in hoop direction.

### C. PLASTIC TUBES

Plastic materials were also used to produce CFT. There were Polyvinyl Chloride (PVC) [1], [10], [28], [58], Unplasticized Polyvinyl Chloride (uPVC) [5], [11], [12], [63], [64], High-Density Polyethylene (HDPE) [65], and Polyethylene (PE) [39]. The properties of plastic materials are given in Table 5.

Table 4 Test results of PFRP flat coupon test [62]

| Number of layers | Thickness (mm) | Tensile stress (MPa) | Tensile strain (%) | Elastic modulus (GPa) |
|---|---|---|---|---|
| 2 | 1.72 | 31.52 | 8.50 | 0.89 |
| 4 | 2.89 | 37.51 | 11.61 | 0.92 |
| 6 | 4.25 | 40.81 | 14.87 | 0.96 |
| 8 | 5.12 | 43.48 | 16.04 | 0.99 |
| 12 | 7.06 | 41.65 | 17.66 | 0.84 |

Table 5 Properties of plastic tubes

| Type | Modulus of elasticity (GPa) | Yield strength (MPa) | Ultimate tensile strength (MPa) | Ultimate stain (%) | Poisson ratio | Reference |
|---|---|---|---|---|---|---|
| PVC | 3.0 – 3.3 | | 52 | 50 – 80 | 0.4 | [28] |
| | | 41.3 | 50.93 | 4.27 | | [51] |
| | 0.3 | | 22.5 | 16 | | [54] |
| | 2.76 | | 50 | | | [57] |
| | 4.03 | 41.26 | 50.36 | 46 | 0.419 | [58] |
| UPVC | 2.45 – 4.03 | | 20.2 – 107. 0 | | 0.342 – 0.419 | [12] |
| | 3.595 | | 49.92 | | 0.3405 | [23] |
| | 2.62 | 50 | 70 | | 0.34 | [30] |
| | 3.38 | | 27.5 - 52 | 34 | 0.38 | [64] |
| | | 43.2 | 46 | 42.5 | | [66] |
| | 3.2 | | | | 0.38 | [67] |
| HDPE | 0.66 | | 26 | 350 | | [65] |
| | >0.6 | | 26 | >350 | | [68] |
| PE | 0.8 | 10 | | | | [39] |

Plastic materials were cheap, lightweight, easy to handle, not affected by corrosion or other forms of degradation, and locally available in abundance [1]. They were impervious to gases and liquids and had a high strength-to-weight ratio [69]. Plastic materials were also highly durable with a service life exceeding 50 years [68, 69].

CFTs confined by plastic materials experienced insignificant strength loss under severe environments. Under the protection of HDPE tubes, the peak load marginally decreased from 0.3% to 1% when submerged in water, acid, and sulfate [65]. This was much lower than the 45% to 50% strength loss of unprotected concrete [65].

Confining concrete using plastic materials increased the ultimate strength of CFT. Plastic tubes offered little axial load capacity due to the low modulus of elasticity and yield strength [51]. Nevertheless, it underwent significant plastic deformation to cope with concrete dilation [7]. This allowed the confined concrete to undergo straining beyond the elastic state without failure for a prolonged period [12]. For that, the CFT presented ductile behavior with gradual post-peak strength degradation [7]. According to [10], PVC tube continued playing its role even after concrete failed. It contained the failed concrete and exhibited large lateral deformation before failure.

Plastic tubes enhanced concrete through confinement, although the effects were lesser than their steel counterparts [67]. The benefits of confinement were distinct when PVC pipe gave a strength increment of 21.3% to 55.2% [28], while UPVC tube increased the strength by 1.32 times [25]. Compared with PVC and UPVC, the confinement effect given by HDPE was lower [65], [68]. This was attributed to the lower elastic modulus and ultimate strength of HDPE (Table 5). Nevertheless, HDPE had an exceptionally high ultimate strain, which subsequently increased the ductility of CFT. Due to the prolonged post-peak strain-softening, exceptionally high energy absorption capacity was obtained [65]. This was preferred when ductility was of more importance [68]. High ductility and energy absorption capacity were favorable for resisting seismic actions [9], [70].

The increase in tube thickness enhanced the confinement of concrete [71]. This subsequently increased the peak compressive strength and the elastic modulus of CFT. Similar responses were reported by [72] using HDPE pipe, [73] using GFRP tube, and [65] using HDPE pipe with Self-Compacting Concrete.

### D. INFILL MATERIALS

The infill for CFT was initially normal concrete. Then, High Strength Concrete (HSC) [74], Self-Compacting Concrete (SCC) [65], Lightweight Aggregate Concrete (LAC) [75], [76], Polypropylene Fiber Reinforced Concrete (PFRC) [67], Geopolymer Concrete (GC) [50], [55], [53], Recycled Aggregate Concrete (RAC) [46], [77], Recycled Brick Aggregate Concrete (RBAC) [78], [79], Recycled Glass Aggregate Concrete (RGAC) [80], Seawater Coral Aggregate Concrete (SCAC) [81], and Seawater and Sea Sand Concrete (SSSC) [82] were adopted. For the unique properties, the concretes influenced the behavior of CFT differently.

High concrete strength increased the axial capacity [73], lowered the confinement effectiveness [12], [64], [83], and reduced the ductility and energy absorption [64] of CFT. This was owing to the high elastic modulus (Table 6) that led to smaller expansion under load. This delayed the response of the tube confining the concrete, and thus reduced the confinement effectiveness.

Table 6 Properties of concrete [84]

| Class | $f_{cu}$ (MPa) | $f_{ck}$ (MPa) | $f'_c$ (MPa) | $E_c$ (GPa) |
|---|---|---|---|---|
| C30 | 30 | 20 | 24 | 23.172 |
| C50 | 50 | 34 | 41 | 30.287 |
| C70 | 70 | 48 | 60 | 26.638 |
| C90 | 90 | 64 | 80 | 42.306 |

*Note: $E_c$ = Elastic modulus of concrete; $f'_c$ = Concrete cylinder strength; $f_{ck}$ = Characteristic concrete strength ($f_{ck}$ = 0.67$f_{cu}$ for normal strength concrete); $f_{cu}$ = Concrete cube strength

Self-compacting concrete (SCC) was also known as Self-Consolidating Concrete and High-Performance Concrete. It had high workability, flowability, and pumpability. It can flow through and fill the gaps of reinforcement and the corners of molds without needing vibrating compaction [85]. This improved the durability of concrete and the bond with reinforcements. It was produced by limiting aggregate content, lowering the water/powder ratio, and using a superplasticizer [86]. It worked well in CFT due to good compacting quality during casting. SCC was especially convenient for double-tube CFT, where there were small gaps between the outer and inner tubes [87].

Lightweight concrete had low density, excellent thermal insulation, and superior durability [88]. It reduced a structure's dead load. Lightweight concretes included Lightweight Aggregate Concrete (LAC), aerated concrete, and no-fines concrete [89]. To the best knowledge of the authors, only Lightweight Aggregate Concrete (LAC) was used in CFT thus far. The lightweight aggregates used can be Grade 600 and Grade 800 crushed shale Ceramsite [40], [75]. Confining LAC with CFRP and steel tubes increased both the ultimate strength and ductility [40]. The increment rate was governed by the effectiveness of confinement given by the tube. Under weak confinement, the strength improvement of LAC was comparable to normal concrete [90]. Under strong confinement, the strength improvement of LAC was less significant than normal concrete [90].

Geopolymer concrete was an environmentally friendly concrete made of industrial byproducts, such as fly ash, Ground Granulated Blast-Furnace Slag (GGBS), and metakaolin [91]. These materials had a large quantity of silica and alumina [91]. Geopolymer concrete did not require heat and produced no carbon dioxide. Compared with normal concrete, geopolymer concrete experienced lower shrinkage [53]. This increased the confinement effectiveness of CFT. Shrinkage led to the interface gap between the concrete and the tube [92]. This gap delayed the activation of the confinement mechanism [92].

Fibre-reinforced concrete (FRC) was a concrete containing fibrous materials that strengthen the concrete. Having the same mix proportion, FRC would have a higher compressive strength than normal concrete (Table 7). The fibres provided cracking resistance to concrete [76], and thus strengthened the concrete. FRC confined by UPVC pipe gave significantly higher load capacity and ductility than normal concrete [24].

Table 7: Concrete design mix proportion used by [24]

| Grade | W/C ratio | Water | Cement | Sand | Coarse Aggregate | $f_{ck}$ for normal concrete (MPa) | $f_{ck}$ for FRC (MPa) |
|---|---|---|---|---|---|---|---|
| M20 | 0.48 | 0.48 | 1 | 1.555 | 2.877 | 28.00 | 32.87 |
| M25 | 0.44 | 0.44 | 1 | 1.452 | 2.733 | 34.38 | 39.93 |
| M30 | 0.41 | 0.41 | 1 | 1.357 | 2.599 | 39.53 | 40.44 |

Recycled Aggregate Concrete (RAC) was material for sustainable development. RAC was less economical than normal concrete at this moment. This was due to the higher labor cost and energy consumption associated with crushing construction and demolition wastes and producing recycled aggregates [93], [94]. Compared with natural aggregate, recycled aggregate had lower density, and higher water absorption, Los Angeles abrasion, and sulphate content [94] (Table 8). For the high water absorption capacity, recycled aggregate tended to absorb water from the adhering cement paste [95]. This reduced the water-cement ratio in concrete, which subsequently affected the workability and increased the strength of RAC [93]. Recycled aggregates may be pre-wetted before casting to improve the workability, but this would slightly affect the strength [93].

Table 8 Water absorption and density of aggregates [96]

| Aggregates | Absorption (%) | Density (kg/m$^3$) |
|---|---|---|
| Natural | 0.31 | 2730 |
| Recycled | 2.69 | 2570 |

Compared with Natural Aggregate Concrete (NAC), RAC had lower compressive and tensile strengths, elastic modulus, and durability [93]. The ultimate strain, shrinkage, and creep of RAC were slightly larger [93]. The strength and elastic modulus of concrete were adversely affected by the amount of recycled concrete (Table 9). This subsequently affected the performance of CFT. The peak strain, compressive strength, and elastic modulus of CFT reduced as the replacement rate of recycled aggregate increased [46].

Table 9 Properties of concrete containing recycled aggregates [96]

| Concrete | Slump (mm) | Unit weight (kg/m$^3$) | Young's modulus (MPa) | Compressive strength (MPa) | Peak axial strain (%) | Splitting tensile strength (MPa) |
|---|---|---|---|---|---|---|
| NAC | 180 | 2420 | 31667 | 36.52 | 1.84 | 4.04 |
| RAC30% | 170 | 2385 | 28617 | 33.59 | 1.64 | 3.87 |
| RAC60% | 80 | 2382 | 24533 | 30.42 | 1.73 | 3.90 |
| RAC100% | 55 | 2346 | 20750 | 29.10 | 2.05 | 3.32 |

*NAC = Natural Aggregate Concrete, RAC = Recycled Aggregate Concrete

## E. INTEGRATION OF VARIOUS MATERIALS

The simplest form of CFT was a single tube filled with concrete. CFT then evolved to have internal tubes, steel reinforcements, and external wraps (Figure 1). Several materials may be used in a CFT to complement each other. In double-tube CFTs, the inner and outer tubes can be of different materials, whereas the core and the shell can be different concretes. The material combinations found in the literature are outlined in Table 10.

Table 10 Combinations of materials in CFT columns

| Reference | Infill material | Outer tube | Inner tube | Wrapping / jacket |
|---|---|---|---|---|
| Fakharifar and Chen [7] | Concrete (25, 50 MPa) | PVC | - | GFRP |
| Javed *et al.* [30] | Concrete | Steel (SHS) | Steel, PVC | |
| Guo *et al.* [39] | Concrete (C30) | PVC, PE, Carbon steel | - | CFRP, GFRP |
| Lama *et al.* [41] | Concrete (30, 50 MPa) | Stainless steel (230, 350, 480 MPa) | Carbon steel | - |
| Fakharifar and Chen [51] | Concrete (50 MPa) | PVC | - | CFRP, E-Glass |
| Teng *et al.* [97] | Concrete (26.2 - 37.2 MPa) | GFRP | Carbon steel | - |
| Deng *et al.* [98] | Concrete | Steel | - | CFRP, BFRP |
| Hassanein *et al.* [74] | Concrete (40, 60, 80, 100, 120 MPa) | Stainless steel, Carbon steel | Carbon steel | - |
| Ekmekyapar and Al-Eliwi [99] | Normal strength core concrete (30.55 MPa) and high strength shell concrete (68.09 MPa), and vice versa | Carbon steel | Carbon steel | - |
| Lam *et al.* [100] | Ultra-high performance concrete with 2.5% steel fibre content (155.4, 171.9 MPa) | CFRP | - | - |
| Zhou *et al.* [40] | Lightweight concrete (39.8 MPa) | CFRP | Steel | - |
| Li *et al.* [75] | Lightweight concrete (39.8 MPa) | - | - | CFRP |
| Liu *et al.* [76] | Lightweight aggregate concrete reinforced with Carbon and polypropylene fibers (32.61 - 50.13 MPa) | | | CFRP |
| Kurtoglu *et al.* [65] | Self-Compacting Concrete (SCC) reinforced with Steel Fibres (32 MPa) | HDPE | - | - |
| Han *et al.* [87] | Self-consolidating concrete (60 MPa) | Stainless steel | Carbon steel | - |
| Ahmad *et al.* [50] | Geopolymer concrete reinforced with GFRP bar (average 39 MPa) | GFRP | - | - |
| Ozbakkaloglu and Xie [53] | Geopolymer concrete (25 MPa) | BFRP, CFRP, GFRP | - | - |
| Alzeebaree *et al.* [55] | Geopolymer concrete | - | - | BFRP, CFRP |
| Mohammad Askari *et al.* [67] | Polypropylene fiber reinforced concrete (40 and 50 MPa) | UPVC | - | - |
| Bandyopadhyay *et al.* [24] | Plain cement concrete and fibre reinforced concrete (M20, M25 and M30) | UPVC | | |
| Li *et al.* [82] | Seawater and sea sand concrete (29.8, 32.8, 35.8 and 42.8 MPa) | GFRP, CFRP, BFRP | - | - |
| Li *et al.* [18] | Seawater and sea sand concrete (31.4 MPa) | Stainless steel, CFRP, BFRP | Stainless steel, CFRP, BFRP | - |
| Li *et al.* [42] | Seawater and sea sand concrete (32.8, 35.8, 39.4 MPa) | Stainless steel, CFRP, BFRP | Stainless steel, CFRP, BFRP | - |
| Wang *et al.* [81] | Seawater coral aggregate concrete (64.35 MPa) | GFRP | - | - |
| Lu *et al.* [46] | Recycled Aggregate Concrete (0%, 50%, 100% replacement) | PVC | - | CFRP |
| Gao *et al.* [54] | Recycled Aggregate Concrete (50%, 70% and 100%) | PVC | | PFRP |
| Chen *et al.* [77] | Recycled Aggregate Concrete (0%, 100% replacement) | - | - | CFRP |
| Bandyopadhyay *et al.* [101] | Recycled Aggregate Concrete (R20, R25, R30) | UPVC | | |
| Huang *et al.* [62] | Recycled brick aggregate concrete (25.19 - 33.17 MPa) | PFRP | - | - |
| Jiang *et al.* [78] | Recycled brick aggregate concrete (0%, 10% and 20% replacement) | CFRP | - | - |
| Jiang *et al.* [79] | Recycled brick aggregate concrete (0%, 15%, 30%, 60%, 100% replacement) | - | - | CFRP |
| Zeng *et al.* [80] | Recycled glass aggregate concrete (0%, 25%, 50%, 100% course aggregate replacement, 0%, 12.5%, 25%, 50% fine aggregate replacement) | - | - | CFRP |
| Cai *et al.* [56] | Geopolymeric recycled aggregate reinforced concrete (55.8 MPa) | BFRP, GFRP, CFRP, Flax | - | - |

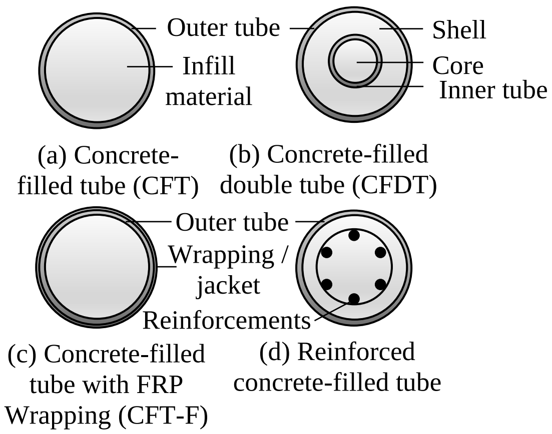


Figure 1 Typical designs of Concrete-filled tube (CFT)

Combining two materials of different natures in a double-tube CFT was advantageous. This can be seen in the study by [30] that involved PVC and steel tubes. The outer PVC pipe protected the concrete and the inner tube from chemical attacks and corrosion, while the concrete and the inner tube strengthened the CFT.

On the other hand, wrapping PVC and steel tubes with FRP gave dual confinement to the concrete. It further enhanced the strength, stiffness, and ductility of CFT. This was confirmed by [7], [54], [60], and [98] in their studies.

FRP wraps provided additional confinement, inhibited local buckling of PVC tube, and restrained the lateral dilation of the encased concrete [7]. The two materials worked well together. The lack of ductility in FRP composite materials was compensated by ductile polymer PVC tubes [60]. This enabled CFT to carry more load. The strength increment of CFT confined by PVC tube and PFRP wraps was 34.2%, while PVC tube and PFRP wraps alone were 0.1% and 26.0% respectively. Furthermore, this effect was dependent on the type of FRP used. According to [39], the strength improvement given by CFRP was far greater than GFRP wrapping. Nevertheless, GFRP wrapping provided significantly greater strain enhancement for CFT than CFRP [51]. This was owing to the larger ultimate strain of GFRP than CFRP (Table 2).

A similar response was observed by [98]. When steel CFT was wrapped with CFRP and BFRP, the axial capacity increased by 61.4% and 17.7% respectively. The strength and ductility of CFT were more significantly improved by CFRP wrapping. This was attributed to (a) the higher tensile strength and modulus of elasticity of CFRP [42], [55], [102], and (b) the lower ultimate strain of CFRP [42] compared with BFRP (Tables 2 and 3).

## FUNDAMENTAL PRINCIPLES

Figure 2(a) shows the typical stress-strain curve of a CFT. The properties indicated in the curve are explained in Table 11. Different materials affected the behavior of CFT differently, as demonstrated by Figure 2(b). This was largely dependent on the physical and mechanical properties of these materials.

Figure 3 shows the properties of tube and concrete that influenced the performance of CFT. CFTs performed well with (a) the tube having high compressive strength, elastic modulus, tensile strength, ultimate strain, and corrosion resistance, and (b) the concrete possessing high compressive strength and ultimate strain, as well as low elastic modulus and shrinkage.

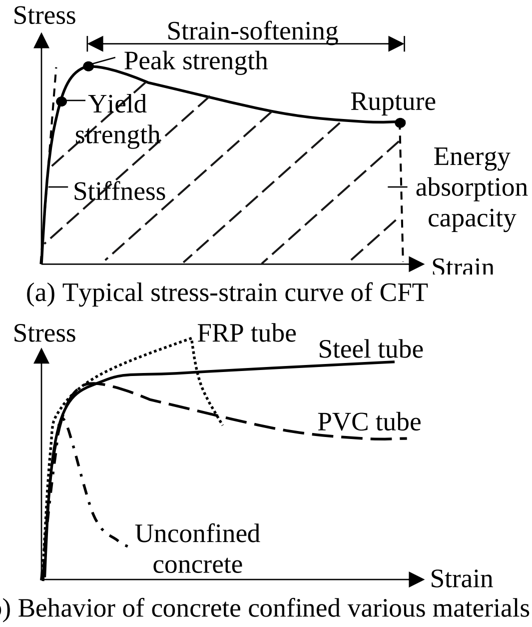


Figure 2 Typical behavior of Concrete-filled tube (CFT)

Table 11 Properties of CFT reflected by the stress-strain curve

| Properties | Definition | Stress-strain curve |
|---|---|---|
| Stiffness | Resistance to elastic deformation when a load is applied | The gradient of the stress-strain curve in the elastic region |
| Yield strength | The limit of elastic behavior and the beginning of plastic behavior. | a point on the curve where the elastic stiffness decreased by 5% or more |
| Peak strength | The point of maximum load corresponds to the onset of material damage or complete failure. | The highest point on the curve |
| Strain-softening | The deterioration of material strength with increasing strain after the peak load | A descending curve between the peak strength and rupture |
| Strain-hardening | The increase of strength during plastic deformation | An ascending curve between the yield point and rupture |
| Ductility | the ability of a material to sustain a large permanent deformation under a load up to the point of fracture | A ratio of axial strain corresponding to rupture relative to elastic strain. |
| Toughness | The ability of a material to absorb energy before reaching the ultimate state | The area under the curve up to peak strength |
| Energy absorption | The ability of a material to absorb energy and plastically deform without rupturing | The area under the curve up to rupture |

The axial resistance of the tube and concrete both contributed to the compressive strength of CFT. The concrete gave more strength due to the larger cross-sectional area than the tube. Benefiting from the interaction between the concrete and the tube [2], the materials performed better together than their individuals (Figure 4). The tube served as the external reinforcement to the concrete [14], confined and restrained the lateral expansion [22], and controlled the shearing cracks in concrete. This subsequently enhanced the axial strength of concrete. The concrete, on the other hand, occupied the space and resisted the tube from buckling inward. This delayed the local buckling of the tube [9], and thus increased the axial strength of the tube.

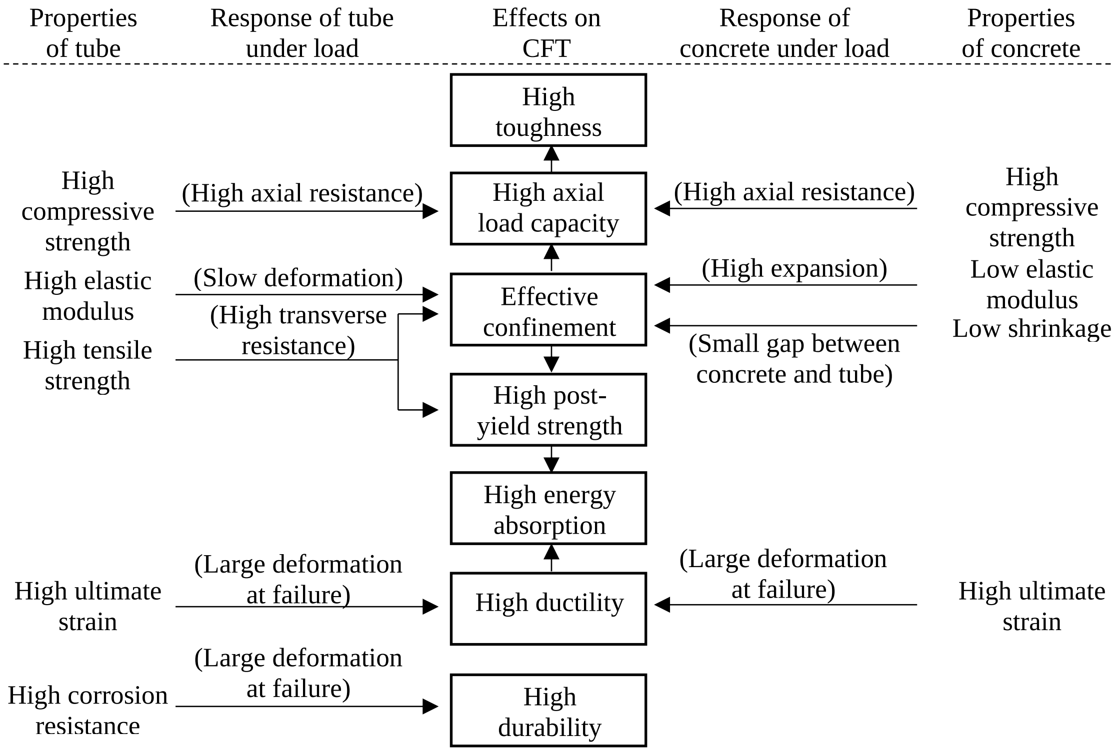

Figure 3 Properties of tube and concrete governing the performance of CFT

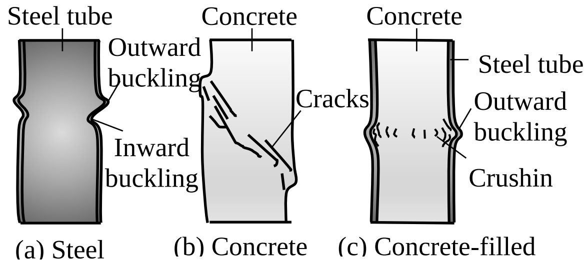

Figure 4 Failure of CFT components

Despite this interaction, the axial strength of CFT was significantly affected by its slenderness. When CFT's height increased, the initial stiffness and the peak compressive load decreased [19]. Slender CFT was susceptible to buckling, which dictated the overall failure before the activation of confinement [64]. This lateral deflection triggered the secondary bending moment and, hence, reduced the concrete's mean compressive strain [19]. For that, [19] recommended ignoring the confinement effect in the design of very long CFT with a slenderness ratio exceeding 50.

The confinement effect was an important feature of CFT. However, this effect was not in place at the initial stage [6]. Due to the larger Poisson's ratio, the tube expanded faster in the radial direction than the concrete. As the axial compression increased, the concrete plasticized and the lateral expansion of concrete caught up with the tube. Only then, the confinement effect was initiated [6]. On this basis, the methods to improve the confinement effectiveness in CFT were identified in Table 12.

The confinement of the tube allowed the concrete to undergo straining beyond the elastic state without failure for a prolonged period compared with the unconfined concrete [23]. It decreased the axial strength reduction after the peak load and increased the ductility of CFT [83]. This subsequently increased CFT's energy absorption capacity.

Table 12 Methods to improve the confinement effectiveness of CFT

| | Tube | Concrete |
|---|---|---|
| Underlying principles | The confining tube should be rigid and strong enough to restrain the expansion of concrete under compressive load. | The expansion of concrete should be great enough to trigger the confinement response of the tube. |
| Methods | • Use the tubes with higher elastic modulus and tensile strength.<br>• Increase the thickness of the tube [65], [71], [72], [73], [101].<br>• Provide additional layers of FRP wrappings [53], [61].<br>• Use circular tubes for uniform confining pressure instead of square or rectangular counterparts [4], [59].<br>• Use FRP in the hoop direction instead of the longitudinal direction, with the FRP strips closely spaced [7], [57]. | • Use the concrete with a lower elastic modulus for greater expansion under load [61].<br>• Use concretes with lower shrinkage to reduce the gap between the concrete and the tube [92].<br>• Use expansive concrete to eliminate the gap while inducing normal pressure onto the tube walls*.<br>• Ensure good compacting quality of concrete during casting. |

**Note: no relevant studies were found yet*

## FUTURE PROSPECTS AND STUDIES

Based on the review, CFT has good potential as a structural element. CFT offers the following benefit:

a. Saving material costs by reducing concrete wastage and eliminating the temporary formworks.
b. Saving construction time due to simple design and minimizing steel reinforcing works.
c. Better quality of compaction without reinforcements and by controlling the loss of moisture during casting.

For the confinement effect, the performance of short CFT is greatly improved. The strength enhancement for slender CFT would be minimal, owing to buckling deformation. On this basis, explicit slenderness limits for CFTs made of various materials would be useful to avoid buckling. This has not been established yet and thus could be a good research direction in the future.

Constrained by the availability of the size of standard tube sections, it is foreseen that the application for CFT would be more popular for moderately and lightly loaded structures. To ensure CFT withstands large loads without buckling, large tube sections would be required. For the application of CFT in heavy structures, custom-made tubes would be required. This often incurs extra costs. Alternatively, columns may be closely spaced to share the loads. This would compromise the clear spacing between columns.

CFT relies on effective confinement to function well. The tube needs to maintain confining pressure throughout the service life. Exposure to an adverse environment may deteriorate the performance of CFT in long run. This includes the corrosion of carbon steel, the abrasion and damage of FRPs, the decomposition of plastic materials under sunlight, and others. The implications of these problems need to be assessed. Furthermore, most of the materials currently used for CFT are susceptible to fire, where the strength can be greatly affected. With that, a sophisticated maintenance program may be required (a) to monitor the well-being and the safety of CFT in long run, and (b) to repair and rehabilitate CFT when necessary.

CFTs may have problems connecting with the beams. Most CFTs do not have internal reinforcements. The rigidity and the load capacity of the joints with beams may be a concern. One might need to work out an effective mechanism to transfer stress between CFT and the adjoining beams. The behavior of the joint is not as extensively studied as the CFT itself.

The application of CFT may be extended to non-circular tubes. Although circular CFTs generally perform better, there are circumstances where non-circular CFTs are more practical. Rectangular sections, for example, are advantageous in resisting axial loads accompanied by large bending moments. Square and rectangular sections are easier to work with when joining with beams.

The tubes for CFT typically have smooth surfaces, which bond poorly with the concrete. This may not be a problem when CFTs are predominantly subjected to axial load. When subjected to moment or buckling, a good bond between the tube and the concrete would be advantageous to CFTs. Hence, further studies are required to examine the effects of the bond under various circumstances, as well as to develop ways to improve the bond.

A wide variety of concrete has been used as the infills for CFT. The physical and mechanical properties vary greatly due to different compositions and mixed proportions. For the best performance of CFT, the concrete should have (a) low elastic modulus, (b) high compressive strength, (c) high workability, (d) low shrinkage, and (e) high ultimate strain. Thus far, there are concretes having some of these characteristics, but none have them all. It would be a great breakthrough if a new concrete possessing all these characteristics could be developed.

The double-tube type of CFT could be studied in future. This could be a way to overcome the limitations of CFT caused by the slenderness limit. Different materials can be used for the inner and outer tubes, as well as the infills. The materials could be used to compensate for each other's weaknesses. There are still many material combinations unexplored. However, these CFTs may have issues with concrete casting. The limited space between the outer and inner tubes might obstruct the flow of fresh concrete, resulting in honeycombs in CFT.

The innovation of CFTs is still in the exploratory stage. Most studies focused on experimenting the small-scale specimens under uniaxial compression. Future research may extend to full-scale tests of the structural system under cyclic, fatigue, impact, and torsional loads, as well as freeze/thaw cycles and aggressive environments.

Moreover, the investigation of CFTs was generally based on ideal conditions. The specimens were properly cast without any defects, the quality of materials meets the specification and the axial load was uniformly applied along the central axis of CFT without any eccentricity. However, imperfections occur in reality. These should also be adequately studied to assess the potential risks of imperfections.

Numerous analytical studies have been conducted to predict the load response of CFT. The majority of them obtained the equations empirically from experimental results. The equations varied greatly on the circumstances and materials used. There is no explicit guide for the design of CFT yet.

The existing codes such as AS 5100 [103], AISC 360 [104], DBJ/T 13-51 [105], ACI-318 [106], and Eurocode 4 [107] are mainly for CFT made of carbon steel. These codes were found to underestimate the load capacity of CFT made of stainless steel [17] [41]. The strain-hardening characteristics of stainless steel had not been beneficially considered under the code [17]. Although ACI-318 forecasted the ultimate strength better than Eurocode 4 and AISC 360, it failed to take into account strain hardening of stainless steel, local buckling of steel tubes, and improved confined concrete strength due to composite confinement [41]. Likewise, the existing codes might not be applicable for CFT made of other materials, such as plastic and FRP tubes. With that, further studies are required (a) to assess the extent of applicability of the existing codes for new materials, and (b) to consolidate a design guide for industrial application.

## CONCLUSIONS

This paper provided a comprehensive review of concrete-filled tubes (CFT) made of various materials subjected to axial load. The purpose was to acquire the fundamental principles governing structural performance. The paper also pointed out some future studies for CFT.

The main conclusions are summarized as follows:

a. The axial resistance of CFT was largely governed by the properties of the materials used. The tubes with high compressive strength, elastic modulus, tensile strength, ultimate strain, and corrosion resistance were favourable to the performance of CFT. Meanwhile, the concrete with high compressive strength and ultimate strain, as well as low elastic modulus and shrinkage showed a greater strength enhancement of CFT.
b. CFT performed outstandingly owing to the confinement effects. This was conditional to the concrete experiencing a larger expansion rate than the tube. The confinement effectiveness was greatly improved when the difference in the expansion rates was amplified.
c. CFT had good potential for industrial applications. It performed well when axial compression was predominant. However, the performance of CFT was greatly affected by the slenderness ratio and buckling deformation. Thus, a low aspect ratio of CFT was recommended.

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