https://doi.org/10.1016/j.istruc.2020.08.044

Circular concrete filled steel tubes made of eco-concrete with limestone fines added as cementitious paste replacement

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Abstract: One effective method of reducing the cement content and carbon footprint so as to produce eco-concrete is to add limestone fines to replace an equal volume of cementitious paste. This method is herein applied to the concrete infill of concrete filled steel tubes (CFSTs). To study the properties of the eco-concrete so produced and the effects of using such eco-concrete on the axial performance of CFSTs, circular steel tubes infilled with such eco-concrete or conventional concrete had been tested under axial compression. The steel tubes were of grade S355 and had diameters ranging from 88.9 to 168.3 mm, whereas the concrete infills had water/cement ratio of 0.35~0.55, and limestone fines content by concrete volume of 8%. The results revealed that at same water/cement ratio, the eco-concrete generally had higher compressive strength and the CFSTs infilled with the eco-concrete had better axial performance. However, at same concrete strength level, the CFSTs infilled with the eco-concrete had similar axial performance. Lastly, the test results were compared with predictions by the existing design equations in various codes and it was found that the existing design equations may also be applied to CFSTs infilled with such eco-concrete.

Keywords: Cementitious paste replacement; concrete filled steel tubes; limestone fines; strength enhancement index; stub columns.

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1. Introduction

Concrete filled steel tubes (CFSTs) are widely used structural members for their excellent structural performance benefitted from the synergistic actions of the steel tube providing confinement to the concrete core and the concrete core preventing early local buckling of the steel tube [1]. They have been used as mega-columns in high-rise buildings, chord members in long-span bridges, bridge piers, transmission towers and piled foundations [2]. More recently, they are also being considered to be used in submarine pipeline structures [3,4]. Among them, circular CFSTs are the most popular because of better confinement effect. In the past few decades, experimental, numerical and analytical investigations have been carried out to study the structural behaviour of circular CFSTs under various loading conditions, as summarized in literature [5-8]. With advancements in materials and fabrication techniques, high-performance materials have become available; for examples, high-strength steel tubes with proof stress higher than 1000 MPa [9] and high-strength concrete with cylinder strength up to 190 MPa [10]. These advancements have led to the advent of high-performance CFST columns made of high-strength steel and high-strength concrete [10].

On the other hand, efforts are being made to develop more environmentally friendly construction materials. Particularly, it has been advocated in recent years to replace conventional concrete by eco-concrete with lower cement content in order to reduce the cement consumption and carbon footprint of the concrete production so as to mitigate global warming due to manufacturing of cement [11]. To reduce the cement content in concrete structures, various attempts from the materials standpoint have been made, such as adding alkali activated binders to completely replace cement [12-16] and adding limestone fines to partially replace cement [17-21], etc. Attempts from the structural standpoint have also been made to employ more efficient structural forms, such as CFSTs, so that at same structural strength requirement, the member size and cement consumption may be reduced, as in the present study, which is on the use of eco-concrete as the concrete infill of CFSTs.

It should, however, be noted that the cement content should not be inadvertently reduced. First, there is a need to maintain the water/cementitious materials (W/CM) ratio, which governs the strength and durability. If the cement content is reduced, a supplementary cementitious material should be added to replenish the cementitious materials content so that the W/CM ratio remains unchanged. This is equivalent to adding a supplementary cementitious material as cement replacement, i.e. adding a supplementary cementitious material to replace an equal weight of cement. Second, there is a need to maintain the paste volume for filling the voids between aggregate particles and forming paste films on aggregate surfaces to impart workability. If the paste volume is reduced because of the reduction in cementitious materials content, then a powder material should be added to replenish the paste volume so that the paste volume remains unchanged. For the powder to form part of the paste, the powder has to be finer than 75 μm so that it would intermix with the cementitious materials and water to form a paste [21]. And, if the powder is not cementitious, then the water content also has to be reduced so that the W/CM ratio is not changed [22]. This is equivalent to adding a powder as cementitious paste replacement, i.e. adding a powder to replace an equal volume of cementitious paste (cementitious materials plus water) without changing the W/CM ratio [21,22].

This research focused mainly on the use of limestone fines (LF) as the powder to replace part of the cementitious paste for reducing the cement content of the concrete infill of CFSTs. LF is a by-product of the limestone quarry industry, which, if not used, has to be dumped as solid waste [21]. Conventionally, LF has been used either as replacement of the fine aggregate [23-27] or as replacement of the cement [28-33]. However, the usage of LF as replacement of the fine aggregate would not reduce the cement content and the usage of LF as replacement of the cement would increase the W/CM ratio and thus adversely affect the strength and durability. Recently, it has been proposed to use the LF as cementitious paste replacement, which not only reduces the cement content (the percentage reduction in cement content is the same as the percentage reduction in cementitious paste volume), but also significantly increases the compressive strength, tensile strength and stiffness of the concrete [21], and improves the dimensional stability by reducing the heat generation during curing [34] and the drying shrinkage strain [35]. However, since such eco-concrete with LF added as cementitious paste replacement is still relatively new, there has been little research on the use of such eco-concrete in various structural elements.

Particularly, eco-concrete with LF added as cementitious paste replacement has not been used as the concrete infill of CFSTs yet, albeit it is envisaged that the structural system of CFSTs with eco-concrete used as the concrete infill should have relatively low cement content and carbon footprint and relatively high structural efficiency. In this research, to explore the feasibility and to facilitate the structural design of this new structural system, the axial compression behaviours of circular CFSTs infilled with such eco-concrete or conventional concrete were investigated and compared. A total of 40 CFST specimens were tested. These were constructed of hot-finished steel tubes and eco-concrete with various amounts of LF added as cementitious paste replacement and water/cement ratios. Lastly, the applicability of the existing design equations in the codes AISC [36], ACI [37], AIJ [38] and EC4 [39] to CFSTs infilled with such eco-concrete was assessed by comparing the measured yield loads of the specimens tested to the predicted strengths by these design equations.

2. Experimental investigation

2.1 Material properties of circular steel tubes

Hot-finished steel circular hollow sections were used as the steel tubes of the CFST specimens. The nominal cross-sectional dimensions ($D \times t$) of the steel tubes were 88.9×5.0 mm, 139.7×5.0 mm, 139.7×6.3 mm and 168.3×12.5 mm, where D and t are the outer diameter and thickness, respectively. The four different sized steel tubes were all made of grade S355 steel. Coupons with a nominal gauge length of 25 mm and a width of 4 mm were cut from the steel tubes for tensile tests [9]. The outer radius, width and thickness of the coupons were first measured and then the coupons were each tested in a 50-kN MTS testing machine under displacement control at loading rates of 0.05 mm/min and 0.20 mm/min within the elastic range and plastic range, respectively. Figure 1 shows the tested stress-strain curves of the coupons while Table 1 lists the material properties of the steel so determined.

2.2 Material properties of ingredients for concrete

An ordinary Portland cement (OPC) of strength class 52.5N complying with European Standard EN 197-1: 2000 [40] and a limestone fines (LF) containing 95% calcium carbonate were used for the concrete mixes. The OPC and LF used had similar fineness and were the same as those used in a previous study on just the eco-concrete itself [21]. For each and every concrete mix, the powder paste volume (cementitious paste volume plus LF volume, expressed as a percentage of concrete volume) was fixed, such that when the LF volume was increased by adding more LF, the cementitious paste volume was decreased by the increased LF volume. It should be noted that the LF was added as cementitious paste replacement, not as cement replacement. As the LF was added, both the cement content and water content were decreased but the water/cement (W/C) ratio was not changed.

The fine aggregate (maximum size 5 mm) and coarse aggregate (maximum size 20 mm) used were both crushed granite rock. With the powder paste volume fixed, the total aggregate volume (fine aggregate volume plus coarse aggregate volume) was also fixed. In every concrete mix, the fine to total aggregate ratio was set at 0.40 and the 10 mm to 20 mm aggregate ratio was set at 1.0. Hence, in every concrete mix, the fine aggregate content, 10 mm aggregate content and 20 mm aggregate content were fixed at 689, 517 and 517 kg/m^3, respectively. A superplasticizer (SP) was added to increase the workability of each concrete mix to higher than 200 mm slump. The methodology of the concrete mix design had been described by Li and Kwan [21].

2.3 Concrete mixes and properties of concrete

In this study, eight concrete mixes were produced for infilling into the CFSTs. The eight concrete mixes had five different W/C ratios of 0.35, 0.40, 0.45, 0.50 and 0.55, two different LF volumes of 0% and 8%, and a constant powder paste volume of 34%. Those concretes with a LF volume of 0% were actually conventional concrete with no LF added and a cementitious paste volume of 34%, whereas those concretes with a LF volume of 8% were eco-concrete with LF added as cementitious paste replacement and a cementitious paste volume of 34% - 8% = 26%. The concrete mixes were each identified by a label of W/C-LF, in which W/C is the W/C ratio and LF is the LF volume (%). Details of the concrete mix proportions are presented in Table 2. It should be noted that because of the reduction of the cementitious paste volume from 34% to 26%, the cement contents of the eco-concrete mixes were each 23.5% lower than the respective conventional concrete mixes with the same W/C ratio.

The workability of each concrete mix was measured in terms of slump and flow by the slump-flow test in accordance with British Standard BS EN 12350-8: 2010 [41]. After the workability measurement, the concrete mix was re-mixed and used to cast cylinders for testing of compressive strength and to infill into the steel tubes to make the CFST specimens. The cylinders had diameter of 150 mm and height of 300 mm. From each concrete mix, four cylinders were cast, two for testing at the age of 28 days and another two for testing at the day of testing the CFST specimens (about 2 months after casting). The average strength of the two cylinders tested at same time was taken as the concrete cylinder strength (f_c). The workability and strength results of the eight concrete mixes are presented in Table 3. Similar to the findings by Li and Kwan [21], at W/C ≥ 0.40, the eco-concrete with LF added as cementitious paste replacement generally attained higher compressive strength than the corresponding conventional concrete with the same W/C ratio and no LF added. For example, the concrete 0.55-8 attained cylinder strengths of 35% and 38% higher than the concrete 0.55-0 at the age of 28 days and at the time of testing the CFST specimens, respectively, albeit the concrete 0.55-8 had 23.5% lower cement content than the concrete 0.55-0.

2.4 CFST stub column specimens and labelling

A series of circular CFST stub column specimens were made from the four different sized steel tubes and the eight different concrete mixes. For reflecting the effects of the infilled concrete, the unfilled steel tubular stub columns i.e., the hollow steel tubes, were tested first, as depicted in Table 4. These unfilled steel tubular stub column specimens were labelled according to their nominal ($D \times t$) dimensions, as listed in the first column of the table. However, the actual measured D and t dimensions were slightly different, as depicted in the second and third columns of the table. One repeated test for the steel tube 88.9×5.0 was conducted, as indicated by the "-r" at the end of the specimen label. The length (L) of each steel tube was set as $2.5D$ in order to avoid overall buckling, as listed in the fourth column of the table.

The four different sized steel tubes were then each infilled with one of the eight concrete mixes labelled W/C-LF to form 32 concrete filled steel tubular stub column specimens for testing, as depicted in Tables 5 and 6. Each specimen was identified by a label starting with the steel tube label in the form of the nominal ($D \times t$) dimensions and following by the concrete mix label of 0.35-0, 0.35-8, 0.40-0, 0.40-8, 0.45-8, 0.50-8, 0.55-0 or 0.55-8. In addition to these 32 specimens, 8 repeated specimens, each marked with "-r" at the end of the specimen label, were also made for testing. In total, 40 circular CFST stub column specimens were tested.

2.5 Testing of unfilled steel tubes and CFST specimens

The unfilled steel tubes and CFST specimens were tested by a 5000 kN servo-controlled testing machine. Figure 2 shows a typical test setup. Four 50-mm range LVDTs (Linear Variable Displacement Transducers) were used to measure the end shortening of the specimen. These four LVDTs were placed between the top and bottom bearing plates at evenly located positions. To prevent "elephant foot" failure, end-stiffeners in the form of steel rings with 30 mm width were screwed onto the specimen near its ends. As the top surfaces of the infilled concrete and the steel tube might not be at same level, a plaster material was used to fill the small gap between the top surfaces of the infilled concrete and the steel tube [42].

A ball bearing was added at the top end of the specimen. Axial compression was then applied to the specimen. An initial pre-load of 5 kN was applied to the specimen before testing. During pre-loading, any possible gaps between the specimen and the contacting surfaces of the testing machine were eliminated. The compressive load was applied under displacement control at a constant rate of 0.5 mm/min until the load had reached a peak value and then dropped by more than 15%. Due to limited stroke of the actuator of the testing machine, the test was sometimes stopped earlier when the axial shortening of the specimen had reached 15 mm. A data logger was used to record the readings from the LVDTs and the testing machine at time intervals of 1 second. Photographs were taken during the test to record the failure modes.

3. Experimental results

3.1 Load-strain curves

The axial load-strain curve of each unfilled steel tube and CFST specimen, in which the axial load was taken from the testing machine and the axial strain was calculated as the average of the four LVDT readings divided by the specimen length (L), is plotted in Figures 3-6 for the specimens with steel tube ($D \times t$) sizes of 88.9×5.0, 139.7×5.0, 139.7×6.3 and 168.3×12.5, respectively. From each load-strain curve, the first peak load within 2% axial strain (P_{peak}), the proof load at 2% axial strain ($P_{2\%}$) and the ultimate load (P_u) are obtained, as tabulated in Tables 4 to 6. When there is no peak in the load-strain curve within 2% axial strain, the value of P_{peak} in such case is just given as "-". Since the test had to be stopped when the axial shortening of the specimen exceeded 15 mm albeit the load was still increasing and had not reached the ultimate yet, the value of P_u in such case is just taken as the maximum load recorded during the test, as marked by an asterisk "*" in the table. The values of P_{peak} and $P_{2\%}$ of the two specimens, 168.3×12.5-0.35-0 and 168.3×12.5-0.35-8, were not available because the applied load had reached the 5000 kN capacity of the testing machine.

Overall, it is seen that the specimens all showed similar linear behaviour up to the axial strain of 0.4%, at which yielding started. However, after yielding, some specimens exhibited continual increase of axial load even when the axial strain further increased to beyond 2% (i.e. exhibited strain hardening), but some specimens reached their respective peak loads before the axial strain reached 2% and thereafter exhibited gradual decrease of axial load as the axial strain further increased. In this regard, previous studies [43,44] had shown that the axial strain corresponding to the peak load was generally smaller than 2.0%. Hence, for detailed analysis in this study, the yield load (P_y) of the specimen is taken as the first peak load within 2% axial strain (P_{peak}) or the proof load at 2% axial strain ($P_{2\%}$), whichever is the larger.

For checking the repeatability of the axial compression tests of the CFST specimens, the load-strain curves of the repeated specimens (those with "-r" at the end of the specimen label) are compared with those of the respective original specimens in Figure 7, and the P_{peak}, $P_{2\%}$ and P_u values of the repeated specimens are also tabulated in Tables 5 and 6 for comparison. From these comparisons, it can be seen that the load-strain curves and the P_{peak}, $P_{2\%}$ and P_u values of the repeated specimens agree quite well with those of the respective original specimens, indicating that the tests conducted were repeatable and thus reliable.

3.2 Effects of using eco-concrete as concrete infill

From the load-strain curves, it can be seen that the curves of the steel tubes infilled with the eco-concrete 0.35-8, 0.40-8 or 0.55-8 are on the whole very similar to those of the same steel tubes infilled with the conventional concrete 0.35-0, 0.40-0 or 0.55-0. This indicates that the use of the eco-concrete in place of the conventional concrete as the concrete infill has no significant effects on the overall load-strain characteristics. Hence, the addition of LF as cementitious paste replacement to reduce the cement content of the concrete infill also provides sound axial performance. In fact, comparing the load-strain curves and the values of the yield load (P_y) of the CFST specimens with the same W/C ratio, it can be seen that the CFST specimens made of the eco-concrete have yield loads up to 10% higher than the CFST specimens made of the conventional concrete. For example, the 2126.1 kN yield load of the specimen 139.7×6.3-0.55-8 made of eco-concrete is higher than the 1937.7 kN yield load of the specimen 139.7×6.3-0.55-0 made of conventional concrete by 9.7%. This was due to the higher compressive strength of the eco-concrete.

3.3 Failure modes

For the unfilled steel tube specimens, both inward and outward local buckling occurred during testing, as depicted at the left side of Figure 8, which shows the failure mode of the specimen 88.9×5.0. Basically, all the unfilled steel tube specimens failed not just by yielding, but also by local buckling except the specimen 168.3×12.5, which has a relatively small D/t ratio. Nevertheless, for the CFST specimens, no inward buckling occurred due to restraint by the concrete core, and only minor outward bulging occurred at some locations, as depicted at the right side of Figure 8, which shows the failure mode of the specimen 88.9×5.0-0.40-8. Such restraint of the concrete core against local buckling of the steel tube had allowed the composite action between the steel tube and the concrete core to be more fully developed to exploit the synergistic effects of the steel tube confining the concrete core and the concrete core restraining local buckling of the steel tube.

The typical failure modes of the CFST specimens made of the 139.7×5.0 steel tubes and conventional concrete or eco-concrete are depicted in Figure 9. It is noted that the failure modes shown therein are similar to each other. Hence, the use of the eco-concrete in place of the conventional concrete as the concrete infill has little effect on the failure mode. One interesting point about the failure modes shown in the figures is that in the failure mode of each CFST specimen, two obvious bulge-outs were formed at opposite faces, indicating that the concrete core inside had an inclined shear crack formed due to shear sliding failure under tri-axial compression [44].

4. Detailed analysis of experimental results

4.1 Strength enhancement index

The synergistic effects of the steel tube confining the concrete core and the concrete core restraining bulking of the steel tube may increase the yield load (P_y) to higher than the sum of the strength of the steel tube (f_yA_s) and the strength of the concrete core (f_cA_c), where A_s and A_c are the sectional areas of the steel tube and the concrete core, respectively. Such synergistic effects may be quantified in terms of the dimensionless strength enhancement index (SEI) defined by $SEI = P_y/(f_yA_s + f_cA_c)$. The SEI values of the specimens tested have been calculated, as presented in Tables 7 and 8. From these SEI values, it can be seen that within the ranges of structural parameters covered in this study, the *SEI* varied from 1.18 to 1.33 for the CFST specimens infilled with conventional concrete and from 1.12 to 1.36 for the CFST specimens infilled with eco-concrete. Hence, the eco-concrete infill offers similar synergistic effects to give more or less the same range of *SEI*.

For further analysis, the values of the section constraining factor (ξ) defined by $\xi = (f_y A_s)/(f_c A_c)$ are also calculated, as listed in Tables 7 and 8. Basically, the section constraining factor (ξ) is a dimensionless measure of the relative strength of the steel tube. To study the effect of the factor ξ on the *SEI*, the variation of the *SEI* with the value of ξ is plotted in Figure 10. It is seen that the *SEI* did vary with the value of ξ, but no clear trend of how the *SEI* varied with the value of ξ could be identified. Hence, to analyse or predict the value of *SEI*, further research is needed.

4.2 Infilled to unfilled strength ratio

To evaluate the effectiveness of the concrete infill in increasing the strength of the tubular stub column, the ratio of the yield load of the steel tube infilled with concrete (listed in Tables 5 and 6) to the respective yield load of the unfilled steel tube (listed in Table 4) has been worked out. Such infilled to unfilled strength ratio of the tubular stub column is hereafter abbreviated as the strength ratio, and the strength ratios so worked out are listed in the second last column of Tables 7 and 8. It is evident from these results that the infilling of the steel tubes with the conventional concrete had increased the yield load up to 2.44 times (Specimen 139.7×5.0-0.35-0), and the infilling of the steel tubes with the eco-concrete had increased the yield load up to 2.51 times (Specimen 139.7×5.0-0.35-8). The higher strength ratio of Specimen 139.7×5.0-0.35-8 than Specimen 139.7×5.0-0.35-0 was because of the increase in concrete strength after adding LF as cementitious paste replacement.

For further analysis, the variations of the strength ratio with the *D*/*t* ratio and the concrete strength are plotted in Figure 11. It should be noted that in the lower part of the figure, the data points with concrete strength equal to zero are those of the unfilled steel tubes. Generally, the strength ratio increased almost linearly with both the *D*/*t* ratio and the concrete strength. Such variations are expected because a larger *D*/*t* ratio implies a larger concrete sectional area and a higher concrete strength implies a larger strength increase due to the infilling of concrete.

On the other hand, the effect of ξ on the strength ratio is depicted by plotting the strength ratio against the value of ξ in Figure 12, from which it can be seen that as the value of ξ increased from 0.97 to 4.18, the strength ratio gradually decreased from the highest value of 2.51 to the lowest value of 1.44. More importantly, the data points for the CFST specimens infilled with conventional concrete (solid symbols) and the data points for the CFST specimens infilled with eco-concrete (hollow symbols) are all very close to the same trend line, indicating that the relation between the strength ratio and the value of ξ is not dependent on whether the concrete infill is conventional concrete or eco-concrete.

4.3 Strain-hardening ductility performance

Whether the CFST specimen had exhibited strain-hardening can be judged from the shape of its load-strain curve. If the load-strain curve, after passing through the point of 2% axial strain, gradually increased to reach an ultimate load (P_u) higher than the yield load (P_y), then it may be said that strain-hardening had occurred. The specimens that had exhibited strain-hardening are marked by "Yes" in the last columns of Tables 7 and 8. Without the specimens made of conventional concrete and the specimens made of the eco-concrete separately considered, the conditions for strain-hardening to occur may be analysed as follows. Out of the 40 CFST specimens tested, 30 specimens had exhibited strain-hardening and the other 10 had not exhibited strain-hardening. Checking their ξ values, it is noted that those specimens that had exhibited strain-hardening had ξ values of 1.23 or higher, whereas those specimens that had not exhibited strain-hardening had ξ values of 1.21 or lower. Hence, as a rough guide, a minimum ξ value of 1.23 is needed for attaining strain-hardening ductility performance. With the specimens made of conventional concrete and the specimens made of the eco-concrete separately considered, the corresponding minimum ξ values are found to be 1.23 and 1.25, respectively, which are almost the same.

5. Applicability of codified design rules

Design rules for circular CFST stub columns have been provided in the following design codes: American Specification for Structural Steel Buildings (AISC 360-16) [36]; Building Code Requirements for Structural Concrete (ACI 318M-14) [37]; Japanese Specification: Recommendations for Design and Construction of Concrete Filled Steel Tubular Structures (AIJ) [38]; and Eurocode 4: Design of Composite Steel and Concrete

Structures (EC4) [39]. These design rules were developed based on tests on steel tubes infilled with conventional concrete, and therefore it is not known whether these design rules are also applicable to steel tubes infilled with other types of concrete. Herein, the applicability of these design rules to steel tubes infilled with eco-concrete are assessed by comparing their predicted strengths with the measured yield loads of the specimens tested in this study.

5.1 American Specification AISC 360-16

In AISC 360-16 [36], design rules for estimating the nominal compressive strength (P_{AISC}) of circular CFSTs subjected to axial compression are given in Section I2.1b. Cross-sections are categorized as compact, non-compact or slender sections according to the diameter to thickness ($\lambda = D/t$) ratio of the steel tube, as stipulated in Section I1.4 and Table I1.1a. Strength reductions and critical buckling stress of the steel tube are then considered for non-compact and slender sections, respectively. In this study, the circular hollow steel tubes may all be categorized as compact section ($\lambda \leq 0.15\ E_s/f_y$). Hence, the nominal compressive strength (P_{AISC}) can be determined using the following equation given in the specification:

$$P_{AISC} = f_y A_s + 0.95 f_c A_c \quad (1)$$

In the above equation, the strength enhancement due to the confinement effect of the steel tube on the concrete core has been conservatively neglected.

5.2 American Building Code ACI 318M-14

In ACI 318M-14 [37], design rules for estimating the nominal compressive strength (P_{ACI}) of circular CFSTs subjected to axial compression are given in Chapter 10. Cross-sections are not categorized into compact or non-compact sections but the thickness of the steel tube is required to be large enough to avoid outward buckling before yielding. Specifically, it is required to satisfy the condition of $D/t \leq 2.828(E_s/f_y)^{0.5}$, as stipulated in Section 10.3.1.6. In this study, the circular hollow steel tubes all satisfy this condition and thus the nominal compressive strength (P_{ACI}) may be determined using the following equation given in the code:

$$P_{ACI} = f_y A_s + 0.85 f_c A_c \quad (2)$$

In the above equation, the strength enhancement due to the confinement effect of the steel tube on the concrete core has been conservatively neglected.

5.3 Japanese Specification AIJ

In AIJ [38], provided the section slenderness of the steel tube satisfies the slenderness limit $D/t \leq 0.18E_s/f_y$, the nominal compressive strength (P_{AIJ}) of circular CFSTs subjected to axial compression may be estimated using the following equation given in the specification:

$$P_{AIJ} = 1.27 f_y A_s + 0.85 f_c A_c \tag{3}$$

In this study, the circular hollow steel tubes are all within the above slenderness limit and thus the above equation may be used. It should be noted that in the above equation, the coefficient of 1.27 applied to the strength of the steel tube is to account for the increase in strength of the concrete core due to confinement. This coefficient represents a hoop stress of $0.19f_y$ and an axial stress of $0.89f_y$ in the steel tube.

5.4 Eurocode EC4

In EC4 [39], design rules for estimating the nominal compressive strength (P_{EC}) of circular CFSTs subjected to axial compression are given in Section 6.7. A limit on the local slenderness of the steel tube is imposed as $D/t \leq 90(235/f_y)$, beyond which local buckling needs to be explicitly accounted for. With both the beneficial confining effect of the steel tube on the concrete core and the reduction in strength of the steel tube caused by the circumferential stresses arising from the restriction of the lateral expansion of the concrete core allowed for, the nominal compressive strength (P_{EC}) may be estimated as:

$$P_{EC} = f_y A_s \eta_{a0} + f_c A_c \left[1 + \eta_{c0} \frac{t}{D} \frac{f_y}{f_c}\right] \tag{4}$$

where the steel reduction factor η_{a0} and the concrete enhancement factor η_{c0} are given by the equations below:

$$\eta_{a0} = 0.25\,(3 + 2\,\bar{\lambda}) \leq 1 \tag{5a}$$

$$\eta_{c0} = 4.9 - 18.5\,\bar{\lambda} + 17.0\,(\bar{\lambda})^2 \geq 0 \tag{5b}$$

and $\bar{\lambda}$ is the relative member slenderness.

5.5 Comparisons of measured yield loads with code predictions

To assess the applicability of the various design codes, the measured yield loads of the CFST specimens tested are compared with the respective predicted strengths by the design codes in Tables 9 and 10. In the calculations of the predicted strengths, all safety factors were set to unity and the actual measured material properties and dimensions were used. The comparison is made in the form of measured yield load to predicted strength ratios. A ratio close to 1.0 indicates accurate prediction, whereas a ratio lower than 1.0 means un-conservative prediction and a ratio higher than 1.0 means conservative prediction. The mean and COV (coefficient of variation) of such ratios are presented in the last two rows of the tables.

From Table 9 for CFST specimens infilled with conventional concrete, it can be seen that the mean ratios of P_y/P_{AISC}, P_y/P_{ACI} and P_y/P_{AIJ} are equal to 1.27, 1.32 and 1.12, respectively, which are all higher than 1.0. Likewise, from Table 10 for CFST specimens infilled with eco-concrete, it can be seen that the mean ratios of P_y/P_{AISC}, P_y/P_{ACI} and P_y/P_{AIJ} are equal to 1.26, 1.32 and 1.13, respectively, which are all higher than 1.0. Hence, the strength predictions by AISC, ACI and AIJ are conservative. More importantly, each of these codes gives similar measured yield load to predicted strength ratios regardless of whether conventional concrete or eco-concrete is used as the concrete infill. On the other hand, the mean P_y/P_{EC} ratio for CFST specimens infilled with conventional concrete and the mean P_y/P_{EC} ratio for CFST specimens infilled with eco-concrete are equal to 0.91 and 0.92, respectively, which are both lower than 1.0. Hence, the strength prediction by EC4 is un-conservative. Moreover, EC4 gives similar measured yield load to predicted strength ratios regardless of the type of concrete infill.

Among the four design codes, AISC, ACI and AIJ are conservative, whereas EC4 is un-conservative. Both AISC and ACI are conservative because they do not account for the strength enhancement due to the confinement effect of the steel tube on the concrete core. On the other hand, AIJ and EC4 do account for the strength enhancement due to the confinement effect and are therefore more accurate than the other design codes. However, AIJ is slightly conservative whereas EC4 is slightly un-conservative. More importantly, the four design codes are equally applicable regardless of whether conventional concrete or eco-concrete is used as the concrete infill. In other words, CFSTs infilled with eco-concrete with LF added as cementitious paste replacement may be just designed using these four design codes.

6. Conclusions

The feasibility of using an eco-concrete with part of its cementitious paste replaced by an equal volume of limestone fines (LF) as the concrete infill for circular CFSTs has been studied by testing the axial compression behaviour of 5 unfilled steel tubes and 40 CFSTs infilled with such eco-concrete or similar conventional concrete with the same W/C ratios. Four different sized hot-finished steel tubes and eight concrete mixes with or without LF added as cementitious paste replacement were used to make the CFST specimens for testing. The findings are summarized as follows:

(1) The addition of 8% LF as cementitious paste replacement without changing the W/C ratio could increase the 28-day cylinder strength by up to 35%, despite 23.5% decrease in cement content. Hence, the LF concrete so produced is more environmentally friendly than conventional concrete and thus may be classified as an eco-concrete.

(2) Apart from the effects caused by the increase in concrete strength, the use of such eco-concrete in place of conventional concrete as the concrete infill would not cause any fundamental change in the axial behaviour of circular CFSTs. Particularly, regardless of whether eco-concrete or conventional concrete is used, the circular CFSTs have similar axial load-strain curves and failure modes.

(3) Overall, the use of such eco-concrete as the concrete infill would also provide sound axial performance as for the use of conventional concrete. In fact, due to the increase in concrete strength, the use of such eco-concrete in place of conventional concrete as the concrete infill could increase the yield load of the circular CFSTs by up to 10%.

(4) Regardless of whether conventional concrete or eco-concrete is used as the concrete infill, circular CFSTs could have a yield load higher than the sum of the strength of the steel tube and the strength of the concrete core. Quantifying such synergistic effect in terms of the strength enhancement index (*SEI*) defined by $SEI = P_y/(f_yA_s + f_cA_c)$, the range of *SEI* obtained is within 1.12 to 1.36.

(5) Regardless of whether conventional concrete or eco-concrete is used as the concrete infill, the section constraining factor (ξ) defined by $\xi = (f_yA_s)/(f_cA_c)$ has major effects on the axial performance of circular CFSTs. First, there is good correlation between the infilled to unfilled strength ratio and ξ. Second, at $\xi \geq 1.23$, the circular CFSTs would exhibit strain-hardening ductility.

Lastly, the applicability of the existing design equations in AISC [36], ACI [37], AIJ [38] and EC4 [39] to circular CFSTs infilled with the eco-concrete was assessed. It was found that these design equations give similar measured yield load to predicted strength ratios regardless of whether the circular CFSTs are infilled with eco-concrete or conventional concrete. Hence, these equations should remain applicable after using eco-concrete in place of conventional concrete as the concrete infill. However, the AISC and ACI equations are overly conservative, the AIJ equation is slightly conservative and the EC4 equation is slightly un-conservative. In this regard, further research is recommended to improve their accuracies.

Acknowledgment

The authors are thankful to the assistance of Mr. On TO and Mr. Chi Cheung POON, who helped with some of the experimental works as parts of their respective MSc project and final year BEng project at The University of Hong Kong.

Conflict of interest

The authors declare that there is no conflict of interest in the research work presented in this paper.

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Table 1: Material properties of circular steel tubes.

$D \times t$ (mm×mm)	E_s (GPa)	f_y (MPa)	f_u (MPa)	ε_u (%)	ε_f (%)
88.9×5.0	193	388.0	495.0	18.1	34.2
139.7×5.0	204	458.0	546.1	13.8	27.3
139.7×6.3	207	397.0	502.2	14.9	31.1
168.3×12.5	193	460.0	536.9	7.8	19.5

Note: E_s = Young's modulus; f_y = yield strength, f_u = ultimate strength; ε_u = strain at ultimate strength; ε_f = strain at fracture.

Table 2: Mix proportions of infilled concrete.

Concrete mix	W/C ratio	LF volume (%)	Cementitious paste volume (%)	Water content (kg/m^3)	Cement content (kg/m^3)	SP dosage (kg/m^3)
0.35-0	0.35	0	34	177	505	5.1
0.35-8	0.35	8	26	135	386	12.7
0.40-0	0.40	0	34	188	470	4.1
0.40-8	0.40	8	26	144	359	10.3
0.45-8	0.45	8	26	151	336	6.8
0.50-8	0.50	8	26	158	315	5.7
0.55-0	0.55	0	34	214	389	2.1
0.55-8	0.55	8	26	164	297	5.0

Table 3: Workability and strength results of the concrete mixes.

Concrete mix	Slump (mm)	Flow (mm)	Cylinder strength f_c (MPa)	
			At 28-day	At day of CFST testing
0.35-0	230	525	75.3	72.9
0.35-8	230	530	74.9	72.6
0.40-0	250	725	64.0	66.8
0.40-8	240	660	78.1	78.7
0.45-8	230	665	65.5	65.2
0.50-8	230	615	63.3	61.7
0.55-0	220	480	39.8	39.9
0.55-8	240	580	53.9	55.2

Table 4: Experimental results of unfilled steel tubular stub columns.

Specimen label	D (mm)	t (mm)	L (mm)	P_{peak} (kN)	$P_{2\%}$ (kN)	P_u (kN)
88.9×5.0	89.13	4.96	222.2	-	554.2	650.3
88.9×5.0-r	89.06	5.03	222.2	-	543.9	650.3
139.7×5.0	139.02	5.10	349.2	-	1053.7	-
139.7×6.3	140.88	6.37	349.0	-	1115.9	1282.1
168.3×12.5	168.50	12.08	420.9	-	3059.5	3505.4*

Note: "*" means the ultimate load was only the maximum load recorded during the test.

Table 5: Results of CFST stub columns infilled with conventional concrete.

Specimen label	D (mm)	t (mm)	L (mm)	P_{peak} (kN)	$P_{2\%}$ (kN)	P_u (kN)
88.9×5.0-0.35-0	89.00	5.04	222.9	1064.7	1060.9	1064.7*
88.9×5.0-0.35-0-r	88.98	5.10	222.8	1047.9	1030.3	1047.9*
88.9×5.0-0.40-0	89.14	4.93	222.0	-	982.6	1047.4*
88.9×5.0-0.55-0	89.01	5.02	222.6	-	859.6	1000.7*
139.7×5.0-0.35-0	139.35	5.06	349.9	2569.7	2555.9	2569.7
139.7×5.0-0.40-0	139.06	5.13	349.1	-	2315.5	2330.2
139.7×5.0-0.55-0	139.56	5.08	350.0	-	1968.1	2085.8*
139.7×6.3-0.35-0	140.66	6.32	349.5	-	2445.2	2450.4
139.7×6.3-0.40-0	141.14	6.35	349.0	-	2373.0	2386.0
139.7×6.3-0.55-0	140.39	6.28	349.7	-	1937.7	2190.5*
139.7×6.3-0.55-0-r	140.54	6.26	349.7	-	1998.1	2225.5*
168.3×12.5-0.35-0	168.53	11.93	420.0	-	-	4979.7*
168.3×12.5-0.40-0	168.27	12.06	420.7	-	4760.0	4984.9*
168.3×12.5-0.55-0	168.14	12.06	420.5	-	4407.9	4917.2*

Note: "*" means the ultimate load was only the maximum load recorded during the test.

Table 6: Results of CFST stub columns infilled with eco-concrete.

Specimen label	D (mm)	t (mm)	L (mm)	P_{peak} (kN)	$P_{2\%}$ (kN)	P_u (kN)
88.9×5.0-0.35-8	89.03	5.03	222.9	1055.3	1018.1	1062.3*
88.9×5.0-0.40-8	89.11	4.97	222.5	-	1004.6	1085.4*
88.9×5.0-0.45-8	89.04	5.00	222.9	-	998.5	1077.5*
88.9×5.0-0.45-8-r	89.04	4.94	222.7	-	1011.7	1054.8*
88.9×5.0-0.50-8	89.02	5.06	222.7	-	972.4	1050.7*
88.9×5.0-0.50-8-r	89.04	4.99	222.8	-	971.5	1053.9*
88.9×5.0-0.55-8	89.00	4.92	222.8	-	946.3	1050.9*
139.7×5.0-0.35-8	139.6	5.10	349.7	2645.2	2551.0	2645.2
139.7×5.0-0.40-8	138.9	5.15	349.1	2510.3	2510.3	2510.3
139.7×5.0-0.45-8	139.4	5.10	349.3	-	2320.6	2332.2
139.7×5.0-0.50-8	139.3	5.07	349.3	-	2284.7	2308.8
139.7×5.0-0.50-8-r	139.48	5.09	350.0	-	2287.7	2312.4
139.7×5.0-0.55-8	139.35	5.09	347.8	-	2088.6	2131.7*
139.7×5.0-0.55-8-r	139.68	5.09	349.0	-	2154.2	2204.1*
139.7×6.3-0.35-8	140.33	6.29	349.7	2663.7	2622.1	2663.7
139.7×6.3-0.40-8	140.92	6.34	349.0	-	2537.4	2550.3
139.7×6.3-0.45-8	140.54	6.28	349.5	-	2380.0	2418.0*
139.7×6.3-0.45-8-r	140.78	6.31	379.0	-	2350.9	2406.6*
139.7×6.3-0.50-8	140.75	6.29	349.6	-	2241.8	2302.8*
139.7×6.3-0.55-8	140.80	6.28	349.6	-	2126.1	2238.9*
139.7×6.3-0.55-8-r	140.88	6.32	349.2	-	2129.1	2249.6*
168.3×12.5-0.35-8	168.44	11.98	420.8	-	-	5000.0*
168.3×12.5-0.40-8	168.33	12.08	421.0	-	4792.4	4955.5*
168.3×12.5-0.45-8	168.57	11.98	420.5	-	4881.4	4992.1*
168.3×12.5-0.50-8	168.33	11.85	420.2	-	4786.4	4992.3*
168.3×12.5-0.55-8	168.44	11.98	420.7	-	4431.2	4873.5*

Note: "*" means the ultimate load was only the maximum load recorded during the test.

Table 7: Axial behaviour of CFST stub columns infilled with conventional concrete.

Specimen label	*D*/*t*	A_c (mm^2)	A_s (mm^2)	*SEI*	ξ	Strength ratio	Strain-hardening
88.9×5.0-0.35-0	17.65	4891	1330	1.22	1.45	1.94	Yes
88.9×5.0-0.35-0-r	17.45	4874	1344	1.20	1.47	1.91	Yes
88.9×5.0-0.40-0	18.08	4936	1304	1.18	1.53	1.79	Yes
88.9×5.0-0.55-0	17.75	4900	1323	1.21	2.63	1.57	Yes
139.7×5.0-0.35-0	27.54	13117	2134	1.33	1.02	2.44	No
139.7×5.0-0.40-0	27.11	13029	2158	1.25	1.14	2.20	No
139.7×5.0-0.55-0	27.50	13152	2144	1.31	1.87	1.87	Yes
139.7×6.3-0.35-0	22.25	12872	2668	1.22	1.13	2.19	No
139.7×6.3-0.40-0	22.23	12957	2689	1.23	1.23	2.13	Yes
139.7×6.3-0.55-0	22.36	12835	2646	1.24	2.05	1.74	Yes
139.7×6.3-0.55-0-r	22.45	12873	2641	1.28	2.04	1.79	Yes
168.3×12.5-0.35-0	14.12	16436	5870	-	-	-	Yes
168.3×12.5-0.40-0	13.95	16320	5918	1.25	2.50	1.56	Yes
168.3×12.5-0.55-0	13.94	16291	5913	1.31	4.18	1.44	Yes

Table 8: Axial behaviour of CFST stub columns infilled with eco-concrete.

Specimen label	D/t	A_c (mm^2)	A_s (mm^2)	*SEI*	ξ	Strength ratio	Strain-hardening
88.9×5.0-0.35-8	17.71	4899	1326	1.21	1.45	1.92	Yes
88.9×5.0-0.40-8	17.93	4923	1314	1.12	1.32	1.83	Yes
88.9×5.0-0.45-8	17.82	4907	1319	1.20	1.60	1.82	Yes
88.9×5.0-0.45-8-r	18.04	4923	1304	1.22	1.58	1.84	Yes
88.9×5.0-0.50-8	17.58	4888	1336	1.19	1.72	1.77	Yes
88.9×5.0-0.50-8-r	17.86	4910	1316	1.19	1.69	1.77	Yes
88.9×5.0-0.55-8	18.08	4921	1300	1.22	1.86	1.72	Yes
139.7×5.0-0.35-8	27.35	13141	2155	1.36	1.03	2.51	No
139.7×5.0-0.40-8	26.98	12995	2164	1.25	0.97	2.38	No
139.7×5.0-0.45-8	27.36	13118	2150	1.26	1.15	2.20	No
139.7×5.0-0.50-8	27.51	13113	2137	1.28	1.21	2.17	No
139.7×5.0-0.50-8-r	27.41	13130	2149	1.28	1.21	2.17	No
139.7×5.0-0.55-8	27.36	13103	2148	1.22	1.36	1.98	Yes
139.7×5.0-0.55-8-r	27.42	13169	2154	1.26	1.36	2.04	Yes
139.7×6.3-0.35-8	22.32	12819	2648	1.34	1.13	2.39	No
139.7×6.3-0.40-8	22.23	12916	2681	1.22	1.05	2.27	No
139.7×6.3-0.45-8	22.38	12865	2648	1.26	1.25	2.13	Yes
139.7×6.3-0.45-8-r	22.32	12902	2665	1.24	1.26	2.11	Yes
139.7×6.3-0.50-8	22.36	12900	2658	1.21	1.33	2.01	Yes
139.7×6.3-0.55-8	22.40	12915	2656	1.20	1.48	1.91	Yes
139.7×6.3-0.55-8-r	22.30	12918	2671	1.20	1.49	1.91	Yes
168.3×12.5-0.35-8	14.06	16395	5887	-	-	-	Yes
168.3×12.5-0.40-8	13.93	16324	5930	1.19	2.12	1.57	Yes
168.3×12.5-0.45-8	14.07	16423	5895	1.29	2.53	1.60	Yes
168.3×12.5-0.50-8	14.20	16426	5827	1.30	2.64	1.56	Yes
168.3×12.5-0.55-8	14.06	16393	5890	1.23	2.99	1.45	Yes

Table 9: Comparison of measured yield loads with strength predictions by various design codes for CFST stub columns infilled with conventional concrete.

Specimen label	P_y/P_{AISC}	P_y/P_{ACI}	P_y/P_{AIJ}	P_y/P_{EC}
88.9×5.0-0.35-0	1.25	1.30	1.11	0.91
88.9×5.0-0.35-0-r	1.22	1.27	1.09	0.89
88.9×5.0-0.40-0	1.20	1.25	1.06	0.87
88.9×5.0-0.55-0	1.23	1.26	1.05	0.85
139.7×5.0-0.35-0	1.36	1.44	1.25	1.01
139.7×5.0-0.40-0	1.28	1.34	1.16	0.94
139.7×5.0-0.55-0	1.33	1.38	1.16	0.92
139.7×6.3-0.35-0	1.25	1.32	1.14	0.93
139.7×6.3-0.40-0	1.26	1.32	1.13	0.92
139.7×6.3-0.55-0	1.26	1.30	1.10	0.87
139.7×6.3-0.55-0-r	1.30	1.35	1.13	0.90
168.3×12.5-0.35-0	-	-	-	-
168.3×12.5-0.40-0	1.27	1.30	1.09	0.91
168.3×12.5-0.55-0	1.32	1.35	1.10	0.91
Mean	1.27	1.32	1.12	0.91
COV	0.037	0.038	0.046	0.044

Table 10: Comparison of measured yield loads with strength predictions by various design codes for CFST stub columns infilled with eco-concrete.

Specimen label	P_y/P_{AISC}	P_y/P_{ACI}	P_y/P_{AIJ}	P_y/P_{EC}
88.9×5.0-0.35-8	1.24	1.29	1.10	0.91
88.9×5.0-0.40-8	1.14	1.20	1.03	0.84
88.9×5.0-0.45-8	1.22	1.27	1.08	0.89
88.9×5.0-0.45-8-r	1.25	1.30	1.10	0.90
88.9×5.0-0.50-8	1.21	1.26	1.06	0.87
88.9×5.0-0.50-8-r	1.22	1.26	1.07	0.88
88.9×5.0-0.55-8	1.24	1.29	1.09	0.88
139.7×5.0-0.35-8	1.40	1.47	1.28	1.04
139.7×5.0-0.40-8	1.28	1.35	1.18	0.96
139.7×5.0-0.45-8	1.29	1.36	1.17	0.95
139.7×5.0-0.50-8	1.31	1.37	1.18	0.95
139.7×5.0-0.50-8-r	1.30	1.37	1.18	0.95
139.7×5.0-0.55-8	1.25	1.31	1.12	0.90
139.7×5.0-0.55-8-r	1.28	1.34	1.15	0.92
139.7×6.3-0.35-8	1.38	1.45	1.25	1.02
139.7×6.3-0.40-8	1.25	1.32	1.15	0.93
139.7×6.3-0.45-8	1.29	1.35	1.16	0.94
139.7×6.3-0.45-8-r	1.27	1.33	1.14	0.92
139.7×6.3-0.50-8	1.24	1.29	1.11	0.90
139.7×6.3-0.55-8	1.23	1.28	1.09	0.88
139.7×6.3-0.55-8-r	1.23	1.28	1.09	0.88
168.3×12.5-0.35-8	-	-	-	-
168.3×12.5-0.40-8	1.21	1.25	1.05	0.88
168.3×12.5-0.45-8	1.31	1.35	1.12	0.94
168.3×12.5-0.50-8	1.31	1.35	1.12	0.94
168.3×12.5-0.55-8	1.24	1.27	1.05	0.88
Mean	1.26	1.32	1.13	0.92
COV	0.043	0.045	0.054	0.049