

STRESS-STRAIN MODELS FOR CONCRETE IN SQUARE HYBRID MULTITUBE CONCRETE COLUMNS

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Abstract: This paper presents the development of stress-strain models for the confined concrete in square fibre-reinforced polymer (FRP)-concrete-steel hybrid multitube concrete columns (MTCCs) subjected to uniaxial compression. A square MTCC consists of a square FRP outer tube and multiple inner steel tubes, with concrete filling the spaces inside all tubes. In comparison to traditional square concrete columns, square MTCCs have a number of advantages, such as ample ductility and excellent durability. The compressive behaviour of square MTCCs has been experimentally investigated to demonstrate its structural advantages in the existing studies. The experimental results confirmed that the concrete in square MTCCs is well confined despite its square cross-section. However, the complex confinement mechanism of square MTCCs is challenging to be completely understood experimentally due to the difficulties associated with the measurement of the nonuniform distributions of stresses across the cross-section. With the employment of the finite element (FE) method, the complex stress distribution and the interactions between the three components can be captured to fully explore the confinement mechanism of square MTCCs. In this paper, the development of three-dimensional FE models for square MTCCs is first presented. A parametric study using the validated FE models is then presented, which was used to generate a database for the establishment of stress-strain models for the confined concrete in MTCCs.

Keywords: Finite element analysis; Hybrid columns; Confinement; Fibre-reinforced polymer (FRP); Steel; Concrete.

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33 1.0 INTRODUCTION

34 In the last three decades, fibre-reinforced polymer (FRP) composites have become increasingly popular in
35 civil engineering structures due to their high strength-to-weight ratio and excellent corrosion resistance.
36 One prominent application of FRP is to be used in combination with concrete (and steel) to form novel
37 hybrid tubular columns, in which a filament-wound FRP tube is typically used as a confining device and a
38 protective skin against corrosion (e.g., Fam and Rizkalla 2001; Yu et al. 2017; Huang et al. 2017; Deng et
39 al. 2024; Zhang et al. 2024). While both square and circular hybrid columns have been investigated, the
40 existing studies (e.g., Fam et al. 2005; Mirmiran et al. 1998; Chan et al. 2021a; Li and Wu 2023) have
41 shown that the confinement effectiveness of FRP is much more significant in circular columns than in
42 square columns.

43 Due to aesthetics and other reasons, square columns may be preferred in some applications. To enhance
44 confinement effectiveness, rounded corners are generally adopted in square FRP-confined concrete
45 columns (e.g., Mirmiran et al. 1998). However, this approach still results in highly nonuniform confinement
46 over the cross-section, with the concrete near the flat sides being barely confined due to the low flexural
47 stiffness of the thin tube (Huang et al. 2017). More recently, the authors' research group has explored the
48 use of additional confinement from embedded steel section to improve the performance of square hybrid
49 columns (e.g., Yu et al. 2016; Huang et al. 2017, 2018; Chan et al. 2018). Examples include the FRP-
50 confined concrete-encased cross-shaped steel columns (Huang et al. 2017) and the square FRP-concrete-
51 steel multitube concrete columns (MTCCs) (Yu et al. 2017; Chan et al. 2018).

52 A square MTCC consists of a square outer tube made of FRP and a number of circular steel inner tubes,
53 with the space inside all tubes filled with concrete. In square MTCCs, the combination of circular steel
54 tubes and square FRP tube leads to a larger effective confined area (Figure 1) than normal square FRP-
55 confined concrete columns where the concrete near the flat sides is not effectively confined (Pei et al. 2021;
56 Li et al. 2024). Similar to its circular counterparts [i.e., circular MTCCs (Chan et al. 2025)], this column
57 form facilitates the use of standard small tubes readily available in the market to construct large-scale

58 structures. In square MTCCs, the concrete inside the circular steel tubes is well confined. The multiple
59 small concrete-filled steel tubes (CFSTs) also form a stiff “wall” that provides additional confinement to
60 the concrete core surrounded by them. As a result, the behaviour of concrete in MTCCs is significantly
61 superior to that in the corresponding square FRP-confined columns without steel tubes, as demonstrated by
62 Chan et al.’s (2018; 2021b) experimental tests. Building on this concept, recent work by other research
63 groups has explored MTCCs with alternative cross-sectional geometries (e.g., Fang et al. 2019; Wang et al.
64 2025) for diverse engineering applications, underscoring the versatility of the MTCC.

65 Two experimental studies have been conducted on the compressive behaviour of square MTCCs (Chan et
66 al. 2018; 2021b), involving the testing of small-scale and large-scale specimens. These studies have
67 confirmed the excellent load capacity and ductility of square MTCCs and have clarified the effects of a
68 number of parameters on the overall behaviour of the columns. However, these studies do not allow the
69 complex confinement mechanism in square MTCCs to be thoroughly examined due to the challenges in
70 measuring the highly nonuniform distributions of stresses and strains in the columns. The stress-strain
71 behaviour of various parts of the concrete in MTCCs has also not been clarified.

72 Against the above background, this paper first presents three-dimensional (3D) finite element (FE)
73 modelling on the compressive behaviour of square MTCCs. Special attention is given to the constitutive
74 modelling of concrete and the interaction between the three components (FRP, steel, and concrete) in
75 MTCCs, based on existing studies on similar column forms (e.g., Yu et al. 2010a; Abdelkarim and
76 ElGawady 2015; Lin and Teng 2017; Huang 2019). The FE models are used to investigate the confinement
77 mechanism and the stress-strain behaviour of the concrete in square MTCCs, after being validated using
78 the test results presented in Chan et al.’s (2018; 2021b) studies. An FE parametric study is then presented,
79 based on which stress-strain models for the concrete in square MTCCs are developed.

80 **2.0 EXISTING EXPERIMENTAL STUDIES**

81 The experimental studies on square MTCCs presented by Chan et al. (2018) and Chan et al. (2021b) covered
82 a wide range of parameters, including the steel volume ratio (4.38 % to 9.68%), configuration of steel tubes
83 (1-tube to 8-tube configurations), side length of the cross-section (b) (171 mm and 500 mm) and the
84 confinement stiffness of FRP. The details of the test specimens in these two studies are summarised in
85 Table 1. In this table, f_{co} and ε_{co} are the compressive strength and the axial strain at the compressive
86 strength of unconfined concrete, respectively; $\varepsilon_{rup,f}$ is the average ultimate lateral strain of FRP at the
87 middle of flat side obtained from test results; D_{st} and t_{st} are the outer diameter and thickness of inner steel
88 tubes, respectively; n_{st} is the number of inner steel tubes; ρ_{st} , $\rho_{c,in}$ and $\rho_{c,out}$ are the volume ratios of the
89 steel section, the concrete inside the steel tubes and the concrete outside the steel tube in percentage,
90 respectively. The equivalent FRP confinement ratio proposed by Lam and Teng (2003) for square FRP-
91 confined concrete columns is adopted herein, which can be expressed by the following equation:

$$\rho_{K,eq} = \frac{2E_{frp}t_{frp}}{\left(\frac{f'_{co}}{\varepsilon_{co}}\right)D_{eq}} \quad (1)$$

92 where E_{frp} and t_{frp} are the elastic modulus and the thickness of the FRP outer tubes, respectively; f'_{co} and
93 ε_{co} are the compressive strength and the axial strain at the compressive strength of unconfined concrete,
94 respectively; $D_{eq} = \sqrt{2}b$ where b is the side length of the square column.

95 With this definition, the equivalent FRP confinement ratio of the specimens presented in Chan et al. (2018)
96 and Chan et al. (2021b) ranges from 0.0190 to 0.0381. For ease of reference, the specimens are renamed
97 herein. The new names consist of the following parts in sequence: two letters (i.e., “SS” and “LS”) to
98 represent the specimen size (‘SS’ for small-scale specimen and ‘LS’ for large-scale specimen); a digital
99 number followed by a letter “T” to represent the number of steel tubes in a specimen; three letters ‘FRP’
100 followed by a digital number (e.g., 0.52) to represent the thickness of FRP tube in the unit of millimetre
101 and another two letters “SV” followed by a digital number (e.g., 9.86) to represent the volume ratio of steel

102 in percentage. For example, SS-8T-FRP0.52-SV9.68 refers to the small-scale MTCC specimen with eight
103 inner steel tubes, an FRP thickness of 0.52 mm and a steel volume ratio of 9.68%

104 **3.0 FINITE ELEMENT MODELS**

105 3.1 General

106 The 3D FE models of square MTCCs in the present study are developed using the general-purpose software
107 ABAQUS (2016), which was used in many existing studies to model the behaviour of hybrid columns
108 incorporating FRP (e.g., Teng et al. 2015; Labibzadeh M. 2015; Huang et al. 2023). As the FE models are
109 developed for the concentric compressive behaviour of square MTCCs, they consist of one layer of
110 elements to simulate the behaviour of the section at the mid-height of the specimens. Such FE models have
111 also been adopted in numerous existing studies (e.g., Yu et al. 2010a; Huang 2023) for similar problems.
112 Furthermore, due to the symmetry of the cross-section and the loading, only a quarter of the cross-section
113 of square MTCCs is modelled, as shown in Figure 2.

114 3.2 Element type, constitutive models and contact properties

115 In the FE models, the FRP outer tube was modelled using shell elements (i.e. Element S4R), while the inner
116 steel tubes and the concrete infill were modelled using solid elements (i.e. Element C3D8R). Based on a
117 mesh convergence study, the element sizes of 2.0 mm for FRP, 2.5 mm for steel and 2.0 mm for concrete
118 were adopted for the FE analysis in this study.

119 The FRP outer tube of the MTCCs was modelled with specified tensile properties, while the compressive
120 stress was set to always be zero. The general plasticity model based on J_2 flow theory in ABAQUS was
121 adopted to model the behaviour of steel. Yu et al.'s (2010b) constitutive model, which is based on the
122 theoretical framework of the Concrete Damage Plastic model (CDPM) in ABAQUS (2011) and takes due
123 consideration of the unique properties of confined concrete, was used to model the confined concrete in
124 MTCCs. In the present study, Jiang and Teng's model (2007) was used to generate the basic material
125 parameters for Yu et al.'s (2010b) model.

126 The interactions between FRP and concrete and those between steel and concrete were simulated by the tie
127 constraint and surface-to-surface contact in ABAQUS, respectively. Other details of the FE models, such
128 as the process of selecting element types, information of the material constitutive models, boundary
129 conditions, are similar to those in the authors' work on the FE modelling of FRP-confined concrete column
130 (Chan 2020; Huang et al. 2023; Chan et al. 2025).

131 3.3 Validation of finite element models

132 The existing experimental results from Chan et al. (2018, 2021b) were used to validate the 3D FE models
133 developed in the present study, as shown in Table 1. For the FE model of each test specimen, the calculation
134 was terminated when the lateral strain of FRP at the flat sides reached the average ultimate lateral strain
135 ($\epsilon_{rup,f}$) of FRP obtained from the test (see Table 1). This approach aligns with experimental observations,
136 where FRP rupture consistently occurred at the flat sides. FRP rupture near flat sides has also been reported
137 in other types of square FRP-steel-concrete columns (e.g., Huang et al. 2017). Figure 3 compares the FE
138 predictions and the test results of four typical specimens in terms of the axial load-axial strain curve,
139 demonstrating good agreement. Figure 4 compares axial strain-lateral strain curves, showing that the FE
140 models reasonably predict the majority of lateral-axial strain curves at the flat side region, where FRP
141 rupture commonly occurred in tests. For the corner region, the FE models provide accurate predictions for
142 large-scale specimens [Figures 4(d)] but are less accurate for others, possibly due to localised deformation
143 (e.g. caused by the heterogeneity of concrete) near the corner region. Such localised deformation may not
144 have occurred within the gauge length (i.e. 20 mm) of the discrete strain gauges. It should, however, be
145 noted that even for these specimens, the axial strain-lateral strain curves for the flat side region and the axial
146 load-axial strain curves can both be generally well predicted by the FE models.

147 Based on the above verifications and the discussions, it can be concluded that the developed FE models can
148 provide reasonable predictions for the behaviour of square MTCCs subjected to concentric compression.

149 4.0 CONFINEMENT MECHANISM OF MTCCS

150 4.1 General

151 The developed FE models of square MTCCs have been validated using the test results in the previous
152 section. This section discusses the fundamental confinement mechanism for the concrete in square MTCCs
153 based on these models. For ease of reference, the concrete in a square MTCC is divided into three regions:
154 (1) concrete inside the steel inner tubes (CI), (2) concrete surrounded by the steel inner tubes (CO-I), and
155 (3) concrete between the FRP outer tube and steel inner tubes (CO-O). Figure 5 illustrates the locations of
156 CI, CO-I, and CO-O in a square MTCC with eight steel inner tubes. The compressive behaviour of these
157 three concrete regions (i.e., CI, CO-I and CO-O) is discussed to illustrate the confinement mechanism in
158 the following three aspects: (1) comparisons of the behaviour of the three concrete regions in MTCCs; (2)
159 effects of the FRP outer tube on the behaviour of three concrete regions; and (3) effects of steel inner tubes
160 on the behaviour of the three concrete regions.

161 Three numerical specimens are used in this section: (1) a typical square MTCC specimen (SS-8T-
162 FRP0.520SV9.68), (2) an MTCC specimen without an FRP outer tube, and (3) a square CFFT (MTCC
163 without steel tubes). The only difference between the MTCC specimen without FRP and the typical MTCC
164 specimen is the presence of the FRP outer tube in the latter. Similarly, the only difference between the
165 square CFFT specimen and the typical MTCC specimen is the presence of steel inner tubes in the latter. It
166 should also be noted that for ease of comparison, the concrete in the CFFT specimen is divided into four
167 regions (corresponding to CI, CO-I, CO-O and steel tubes) in the same way as the MTCC specimens. All
168 curves in this section are terminated when the lateral strain of FRP at the middle of the flat side reaches
169 0.015 for consistency.

170 4.2 Behaviour of CI, CO-I and CO-O

171 The average stress-strain curves of the three concrete regions (i.e., CI, CO-I and CO-O) in the typical MTCC
172 specimen are shown in Figure 6, in which the stress is obtained by dividing the axial load by the respective
173 cross-section area of the concrete. Three key numerical observations can be made:

174 (1) The three curves start to diverge when the concrete stress reaches around the unconfined concrete
175 strength (indicated by Line A in Figure 6);

176 (2) Both the CI and CO-I curves exhibit a monotonically ascending trend, with the CI curve generally higher
177 than the CO-I curve. In contrast, the CO-O curve, which is the lowest among the three, shows a descending
178 branch after Line A;

179 (3) After Line A, the slope of CI curve is significantly steeper than that of the CO-I curve between Line A
180 and Line B, particularly near Line A. However, the difference in slope between the two curves reduces as
181 the axial strain increases.

182 The first observation is attributed to the minimal lateral expansion of concrete in MTCC before Line A,
183 resulting in negligible lateral confinement from the outer and inner tubes. The second observation indicates
184 that in MTCCs, CI is most effectively confined, CO-I is less effectively confined than CI, and CO-O is not
185 well confined. This is because CI benefits from the effective confinement provided by the circular steel
186 inner tubes in addition to the FRP outer tube, while CO-I and CO-O are mainly confined by the FRP outer
187 tube, with the majority of CO-O located in the weakly confined region [see Figure 1(b)]. The third
188 observation can be explained by the average hoop stress-axial strain curves of two steel tubes, one at the
189 corner and the other at the middle of the flat side in the typical MTCC, shown in Figure 7. Between Line A
190 and Line B, the confinement from the steel inner tubes increases rapidly, while after Line B, the confinement
191 from the steel tube decreases with the axial strain due to the yielding of steel and confinement from the FRP
192 tube. This explains why the stress of CI increases significantly faster than the other two parts of concrete
193 after Line A and why the increasing rate tends to decrease with the axial strain (Figure 6).

194 4.3 Confinement contribution from FRP

195 To study the effect of FRP confinement on the behaviour of CI, CO-I and CO-O in MTCCs, comparisons
196 of the average axial stress-strain curves of these three regions of the typical MTCC (SS-8T-FRP0.52-
197 SV9.68) and the MTCC without FRP are presented in Figure 8. The latter has a similar column

198 configuration to the former, except for the absence of the FRP tube. It should be noted that the ultimate
199 axial strain of the MTCCs without FRP is assumed to be the same as the typical MTCCs for comparison
200 purposes. Two key numerical observations can be made:

201 (1) There is little difference between the CI curve of the typical MTCC specimen and that of the MTCC
202 specimen without FRP before Line B (defined as at an axial strain of around 0.008), after which the former
203 gradually becomes larger than the latter; and

204 (2) Both the CO-I and CO-O curves of the MTCC without FRP have a descending branch after the peak
205 stress, and they are both significantly lower than the corresponding curves of the typical MTCC specimen.

206 The first observation indicates that the effect of the FRP confinement on CI is negligible before a certain
207 strain (e.g. around 0.008 in Figure 8). This is primarily because, for CI in MTCCs, the lateral confinement
208 stiffness of the steel inner tubes is usually much larger than that of the FRP outer tube before the steel
209 yields, and thus, the steel confinement dominates the behaviour of CI until the FRP confinement becomes
210 sufficiently strong. The second observation clearly indicates that, compared to CI, the stress-strain
211 behaviour of CO-I and CO-O in MTCCs is much more significantly affected by the FRP outer tube. This
212 is not difficult to understand, as the confinement for CO-I and CO-O in MTCCs is largely provided by the
213 FRP outer tube.

214 4.4 Confinement contribution from steel

215 Comparisons of the average axial stress-strain curves for the three concrete regions (i.e., CI, CO-I and CO-
216 O) in the typical MTCC specimen and the three corresponding regions of the CFFT specimen are shown in
217 Figure 9 to demonstrate the effect of steel confinement. Key numerical observations include:

218 (1) The ultimate axial strain of the CFFT specimen is significantly smaller (by approximately 50%) than
219 the typical MTCC specimen;

220 (2) The CI curve and the CO-I curve of the CFFT specimen are remarkably lower than the two
221 corresponding curves of the typical MTCC specimen;

222 (3) The CO-O curve of the CFFT specimen is also lower than that of the typical MTCC specimen, although
223 the difference is not as pronounced as those of CI and CO-I.

224 To explain the first observation, a comparison of the lateral strain-axial strain curves of FRP at the middle
225 of flat side of the CFFT specimen and the typical MTCC specimen is presented in Figure 10. At the same
226 axial strain, the FRP lateral strain of the typical MTCC specimen is significantly smaller, resulting in FRP
227 rupture at a larger axial strain compared to the CFFT specimen. This is because the concrete in the typical
228 MTCC specimen expands less significantly due to the additional confinement from the steel inner tubes.
229 The second and third observations indicate that the steel inner tubes in MTCCs significantly affect the
230 compressive behaviour of CI and also impact CO-I and CO-O. To further examine such effects, the
231 distributions of the effective lateral confining pressure ($\sigma_{l,eff}$) on the concrete of the CFFT specimen and
232 the typical MTCC specimen at their ultimate states are compared in Figure 11. $\sigma_{l,eff}$ is defined by the
233 following equation (Yu et al. 2010b) for concrete under nonuniform lateral confinement:

$$\sigma_{l,eff} = \frac{2(\sigma_2 + 0.039 f'_{co})(\sigma_3 + 0.039 f'_{co})}{(\sigma_2 + \sigma_3 + 0.078 f'_{co})} - 0.039 f'_{co} \quad (2)$$

234 where σ_2 and σ_3 are the two principal lateral stresses acting on the concrete and f'_{co} is the unconfined
235 concrete strength.

236 Figure 11 shows that, compared to the CFFT specimen, the effective confining pressure in CI, CO-I and
237 CO-O of the typical MTCC is significantly higher. It should be noted that since both specimens have the
238 same FRP outer tube, the FRP confinement is identical at their ultimate states. Therefore, the difference
239 between the distribution of $\sigma_{l,eff}$ in Figures 11(a) and (b) is solely due to the effect of the steel inner tubes
240 in the typical MTCC specimen. Based on Figures 9 and 11, it can be concluded that the steel inner tubes in

241 MTCCs not only provide direct and effective confinement to the CI but also enhance the confinement of
242 CO-I and CO-O through the composite action among the three components (FRP, concrete, and steel).

243 **5.0 Stress-Strain Models for Confined Concrete**

244 5.1 General

245 The FE modelling has been employed to thoroughly demonstrate the confinement mechanism of square
246 MTCC, revealing that the three parts of concrete (CI, CO-I and CO-O) in square MTCCs exhibit different
247 behaviours, as shown in Figure 6. The FRP confinement significantly influences the behaviour of confined
248 concrete in square MTCCs. Compared to circular MTCCs, the effect of steel volume ratio is more
249 pronounced in square MTCCs due to the additional steel confinement for the weakly confined region. This
250 section presents the development of stress-strain models for the three parts of confined concrete in square
251 MTCCs. The three-segment equations proposed by Huang (2019) for modelling the confined concrete in
252 FRP-confined concrete-encased cross-shaped steel columns are employed to describe the stress-strain
253 behaviour of three parts of concrete in square MTCCs. The performance of the three-segment equations is
254 shown in Figure 12 for a typical MTCC specimen (i.e. Specimen SS-8T-FRP0.52-SV9.68), in which the
255 four key parameters (i.e. ε_{t2} , ε_{cu} , E_2 and f_i) of the stress-strain curves are directly extracted from the FE
256 results. Figure 12 demonstrates that the selected equations accurately describe the stress-strain behaviour
257 of all three concrete regions in the specimen, with four preset parameters. In the following sections, the
258 equations for the four independent parameters are formulated through the regression of numerical results
259 obtained using the proposed FE model. Among these parameters, ε_{t2} and ε_{cu} are the same for the three
260 parts of the concrete in square MTCC, while E_2 and f_i are various for different parts of concrete in square
261 MTCC.

262 To identify the parameters that significantly affect the stress-strain behaviour of the concrete in square
263 MTCC, a parametric study is conducted to investigate the effects of five key column parameters (i.e., steel
264 tube configuration, concrete cover thickness, corner radius, steel volume ratio and FRP confinement

265 stiffness) on the behaviour of the three concrete parts (i.e., CI, CO-I and CO-O) in square MTCCs.
266 Corresponding to the five key column parameters, five groups of numerical specimens (i.e., Groups A, B,
267 C, D and E) are considered, as listed in Table 2. All the numerical MTCC specimens in Table 2 have the
268 cross-sectional side length of 171 mm and unconfined concrete strength of 31.8 MPa, which is the same as
269 that of the experimental specimens in Chan et al. (2018). The FE analysis of all numerical MTCC specimens
270 in this parametric study are terminated when the lateral strain of FRP at the middle of flat side reaches
271 0.015; the axial strain and stress corresponding to the rupture strain are referred to as the ultimate axial
272 strain and stress. Other key information of these numerical specimens, including specimen names, is also
273 listed in Table 2.

274 5.2 Effect of key parameters

275 5.2.1 Steel tube configuration

276 The steel tube configuration discussed in this study refers to the number of steel inner tubes that form the
277 steel section in MTCCs. To investigate this effect, a total of four numerical specimens are simulated, which
278 are collectively referred to as Group A in Table 2. The number of steel inner tubes in the four numerical
279 specimens are four, eight, twelve and sixteen, respectively, while their steel volume ratios are all the same.
280 The maximum number of steel inner tubes is chosen to be sixteen for the following reasons: (1) for MTCCs
281 of the same outer dimensions, a larger number of steel tubes means a smaller steel tube diameter and thus
282 a larger slenderness ratio of steel tubes, which are more prone to potential overall buckling; (2) in the
283 experimental study of Chan et al. (2021b), overall buckling of steel inner tubes was observed in MTCC
284 specimens with a 16-tube configuration.

285 Figure 13 compares the average axial stress-strain curves of the three parts of concrete in the four numerical
286 specimens, while Figure 14 shows the effective confining pressure (Eq. 2) distributions on the concrete of
287 these four specimens at the ultimate state. It can be seen in Figure 13 that for all three concrete parts, the
288 effect of the steel tube configuration on the average axial stress-strain behaviour is marginal (by less than

289 2%). It is also shown in Figure 14 that at the ultimate state, although the area and patterns of the three
290 concrete parts vary with the steel tube configuration, the distribution of effective confining pressure on each
291 concrete part is only slightly affected. Based on these observations, it can be concluded that the variation
292 of steel tube configuration in square MTCCs in the selected range (i.e., from 4-tube to 16-tube), which is
293 believed to be large enough to cover most of the reasonable cases in practice, has only minor effects on the
294 compressive behaviour of the concrete in MTCCs. Therefore, to achieve a balance between simplicity and
295 representativeness, numerical MTCC specimens with eight steel inner tubes (Figure 5) are used in the
296 following discussions.

297 5.2.2 Round corner radius

298 Existing studies confirm that in square CFFTs, the variation of the round corner radius (r) of the FRP outer
299 tube can significantly affect the confinement effectiveness of the FRP outer tube (Mirmiran et al. 1998;
300 Lam and Teng 2003; Wang and Wu 2008). To clarify this effect, a parametric study including three
301 numerical specimens (as listed in Group B of Table 2) is presented in this section. In this parametric study,
302 the ‘round corner radius-to-side length ratio’ (r/b) is termed as round corner ratio (R_c), and the three
303 numerical specimens have round corner ratios of 1/10, 1/8 and 1/6, respectively. This range of R_c is selected
304 based on two considerations: (1) to ensure the confinement efficiency of the FRP outer tube ($>1/10$); and
305 (2) to keep the geometry feature (i.e., the ‘square’ cross-sectional shape) of square columns ($<1/6$).

306 Figure 15 shows the average stress-strain curves of the three parts of concrete in the three numerical
307 specimens in Group B. It can be seen in this figure that the variation of R_c in the selected range hardly
308 affects the curves of CI and CO-I, but has a small effect on the CO-O curves (e.g., at the ultimate state, the
309 average axial stress of CO-O of the specimen C-RC1/6 is larger than that of the specimen C-RC1/10 by
310 7%). Figure 16 shows the distribution of the $\sigma_{l,eff}$ on the concrete of the three numerical specimens at the
311 ultimate state. It can also be seen from Figure 16 that the variation of R_c affects the distribution of $\sigma_{l,eff}$
312 for CO-O at both the flat side region and the round corner region while hardly affects the distribution of

313 $\sigma_{l,eff}$ for CI and CO-I. It should also be noted that the area of CO-O in MTCCs depends on the thickness
314 of concrete cover, and is generally much smaller than those of CO-I and CI.

315 Based on the above discussions, it can be concluded that the variation of R_c in the selected range (i.e., 1/10-
316 1/6) has a marginal effect on the stress-strain behaviour of the concrete in square MTCCs.

317 5.2.3 Thickness of concrete cover

318 The thickness of concrete cover (t_{cover}) in a square MTCC is defined as the minimum distance between the
319 external surface of steel tubes and the internal surface of FRP tube at the flat side region. It is easily
320 understood that an increase in the thickness of concrete cover generally leads to an increase in the area of
321 weakly confined concrete near the flat side region, which is detrimental to the structural performance of
322 MTCCs. However, the presence of a concrete cover is beneficial for fire resistance of MTCCs and allows
323 additional flexibility in identifying steel tubes of suitable sizes from the market to fit a given FRP outer
324 tube (e.g., Yu et al. 2017). In this section, a parametric study with three numerical specimens (Group C in
325 Table 2) is presented to examine the effect of concrete cover thickness. The three specimens in Group C
326 have the same steel volume ratio of 9.86%, and the controlling parameter t_{cover} varies from 0 to 25 mm,
327 which makes the value of ρ_{cover} (i.e., t_{cover}/b) vary from 0 to 0.146. The range of ρ_{cover} (i.e., 0 to 0.146)
328 adopted in this study is believed to be large enough since a relatively small thickness of concrete cover is
329 generally preferred in practice to ensure a relatively high material efficiency of the steel inner tubes when
330 MTCCs are subjected to lateral loads.

331 Figure 17 shows the average axial stress-strain curves of the three parts of concrete in the three numerical
332 MTCC specimens in Group C. It can be seen from Figure 17 that the increase in concrete cover thickness
333 has little effect on the curves of both CI and CO-I (e.g., for the same axial strain, the difference in axial
334 stress is generally less than 1%), which is not surprising. By contrast, the increase of concrete cover
335 thickness from 0 mm to 25 mm results in an increase of 35% in the average axial stress of CO-O at the
336 ultimate strain.

337 To further examine this phenomenon, the distributions of effective confining pressure on the concrete of
338 the three specimens at their respective ultimate states are compared in Figure 18. It is evidently seen in
339 Figure 18 that for these three specimens, the increase of concrete cover thickness only slightly affects the
340 distribution of confining pressure in CI and CO-I, while substantially increasing the area of the effectively
341 confined portion (the round corner region) of CO-O, which leads to the observations in Figure 17.

342 Figure 19 shows the comparison of the average axial stress-strain curves of the whole concrete section of
343 the three specimens. It can be seen in this figure that a larger concrete cover thickness leads to a smaller
344 ultimate strain and a lower final linear segment of the axial stress-strain curves. This is because when
345 considering the concrete section in MTCC as a whole, the weakly confined portion (e.g., that near the
346 middle of flat sides) tends to increase with the concrete cover thickness, as shown in Figure 18.

347 5.2.4 Steel volume ratio

348 As discussed in Section 4, steel inner tubes can significantly affect the behaviour of the concrete in MTCCs
349 (especially the CI part). Thus, it is necessary to study the effect of steel volume ratio on the behaviour of
350 confined concrete in MTCCs. In this section, a parametric study with three numerical specimens (Group D
351 in Table 2) is conducted to investigate such effects. As shown in Table 2, the three numerical specimens
352 have the same concrete cover thickness and round corner ratio, and the steel inner tubes in these specimens
353 have the same outer diameter but different inner diameters, which makes the steel volume ratio of the three
354 MTCC specimens vary from 4.92% to 14.2%. This range is selected based on the following two
355 considerations: (1) according to the standard sizes of circular steel tubes listed in existing standards [e.g.,
356 AS1163 (2016)], the steel volume ratio of MTCCs with no/thin concrete cover is generally larger than 5%;
357 (2) the steel volume ratio of 14.2%, which is around 10 times of that of typical RC columns, is believed to
358 be large enough to cover most of the cases in practice.

359 Figure 20 shows the stress-strain curves of the three parts of concrete in the three numerical specimens in
360 Group D. The following two observations can be obtained from this figure: (1) the variation of steel volume

361 ratio has a significant effect on the ultimate strain of the concrete in MTCCs (e.g., the increase of steel
362 volume ratio from 4.92% to 14.2% leads to an increase of 28% in the ultimate axial strain); (2) for a given
363 axial strain, the steel volume ratio only has a slight (by less than 1%) effect on the average axial stress of
364 CO-I and CO-O, while has a greater effect (up to 7%) on that of CI. The first observation is that an increase
365 in steel volume ratio leads to an increase in steel confinement, which makes the concrete (especially CI) in
366 MTCCs better confined and thus reduces the overall expansion of MTCCs. The reason for the second
367 observation is that in MTCCs, CI is directly confined by the circular steel inner tubes. Thus, the behaviour
368 of CI, among the three parts of concrete, is most significantly affected by the variation in steel volume ratio.
369 Despite the observed difference in the stress-strain curves of CI, it is interesting to note that after a certain
370 axial strain, the effect of the steel volume ratio on the behaviour of CI becomes minimal. This is believed
371 to be due to the yielding of steel.

372 5.2.5 FRP confinement stiffness ratio

373 The confining FRP outer tube is essential for the excellent structural performance of square MTCCs as
374 demonstrated in Chan et al.'s (2018) experimental study. This section presents a parametric analysis with
375 three numerical specimens (i.e., Group E in Table 2) to investigate the effect of FRP confinement stiffness
376 on the compressive behaviour of square MTCCs. The FRP tube thickness is the only difference between
377 the three specimens in Group E. According to Eq. 2, the equivalent FRP confinement ratio ($\rho_{k,eq}$) of the
378 three normal MTCC specimens in Group E varies from 0.0151 to 0.0452, as listed in Table 2. The minimum
379 value of $\rho_{k,eq}$ (i.e., 0.0151) is selected to ensure that the linear final segment of the stress-strain curves of
380 CI and CO-I is non-descending. Moreover, the confinement provided by the steel inner tubes in MTCCs is
381 expected to be more effective in the MTCC with relatively weak FRP confinement (e.g., $\rho_{k,eq}$ of less than
382 0.03). The maximum value of $\rho_{k,eq}$ (i.e., 0.0452) is selected to maximise the advantages of the column form
383 of MTCCs based on existing test results on MTCCs and related column forms (e.g., Fanggi and
384 Ozbakkaloglu 2015; Huang et al. 2017).

385 The average stress-strain curves of CI in the three MTCC specimens in Group E are compared in Figure
386 21(a), and those of CO-I and CO-O are compared in Figure 21(b). The following observations can be
387 obtained from these figures: (1) the FRP confinement has a minor effect on the separation point (represented
388 by $\epsilon_{s,CI}$, $\epsilon_{s,CO-I}$ and $\epsilon_{s,CO-O}$ in Figure 21) of the stress-strain curves of the three parts of concrete; (2) the
389 increase of FRP tube thickness leads to a higher axial stress-strain curve for all of CI, CO-I and CO-O after
390 the separation point, while such effects are more significant for CI and CO-I, especially the latter.

391 The first observation is due to the fact that the FRP confinement is not active, or is small compared to that
392 provided by the steel tubes, in the early stage, so that its effect on the stress-strain behaviour of confined
393 concrete is minor, as discussed previously in this paper. For the second observation, the reason is that most
394 of CO-O is in the weakly confined region (i.e. close to the flat sides), while CI and CO-I are in the
395 effectively confined region as illustrated in Figure 1(a). Furthermore, CI is confined by both the FRP outer
396 tube and the steel inner tubes, while the confinement for CO-I is mainly provided by the FRP outer tube,
397 which makes the behaviour of CO-I more significantly affected by the variation of FRP confinement.

398 5.3 Ultimate axial strain

399 It has been shown from the previous sections that the ultimate axial strain of square MTCCs is mainly
400 dependent on three parameters, which are the equivalent FRP confinement ratio ($\rho_{K,eq}$), the steel volume
401 ratio (ρ_{st}) and the concrete cover ratio (ρ_{cover}). In addition, it has been well established that the rupture
402 strain of FRP plays an important role in the ultimate state of FRP-confined columns. Therefore, a numerical
403 parametric study of square MTCCs with equivalent FRP confinement ratios of 0.0151 to 0.0452, steel
404 volume ratios of 4.92%- 14.6%, concrete cover ratios of 0- 0.146, and FRP rupture strain of 0.01-0.02 were
405 conducted using the developed FE models. The specimens in the numerical parametric study had the same
406 dimensions as the specimens in Tables 1 and 2. It has been confirmed in the existing studies (e.g., Huang
407 2019), for normal strength concrete, the variation of unconfined concrete strength (f'_{co}) (from 30 MPa to 50
408 MPa) does not have a significant effect on the ultimate axial strain of FRP-confined concrete column. The

409 unconfined concrete strength is thus not taken as a variable in the parametric study here. The details of the
410 numerical specimens in the parametric study are summarised in Table 3.

411 The effect of FRP confinement ratio on the ultimate axial strain (normalised by ε_{co}) of square MTCCs is
412 shown in Figure 22, in which the ultimate axial strain corresponds to the assumed GFRP rupture strain of
413 0.015 at the middle of flat side of square cross-section. Figure 22 shows that the relationship between the
414 normalised ultimate axial strain and FRP confinement ratio is approximately linear. Figure 22 also shows
415 that the steel volume ratio and concrete cover ratio have considerable effects on the ultimate axial strain,
416 especially when the FRP confinement ratio is small. Furthermore, the FRP rupture strain is shown to have
417 a significant effect on the ultimate axial strain as expected (Figure 23).

418 Based on the above observations, the following equation is proposed for the ultimate axial strain (ε_{cu}) of
419 square MTCCs:

$$\frac{\varepsilon_{cu}}{\varepsilon_{co}} = A\rho_{\varepsilon}^B \rho_{K,eq} + C\rho_{\varepsilon} + D + E(\rho_{st} - 0.0492) - F\rho_{cover} \quad (3)$$

420 where ρ_{ε} is the strain ratio given by $\varepsilon_{h,rupt}/\varepsilon_{co}$; $\rho_{K,eq}$ is the equivalent FRP confinement ratio (Eq. 1); ρ_{st}
421 is steel volume ratio; and ρ_{cover} is the concrete cover thickness-to-column side length ratio, while the six
422 coefficients (A, B, C, D, E and F) are determined to be 6.4, 1.8, 0.6, 1.9, 30 and 0.15, respectively, through
423 a regression analysis of the results of numerical parametric study (Table 3).

424 5.4 Axial strain at second transition point

425 Huang (2019) indicates that the three-segment expression is not sensitive to the variation of axial strain at
426 the second transition point (ε_{t2}), implying the possibility of using an approximate value for simplicity. The
427 examination of FE results of all square MTCC specimens in the present study shows that the axial strain at
428 the second transition point of the three parts of concrete varies from 0.006 to 0.009, depending on the
429 location of concrete (i.e., CI, CO-I and CO-O), steel volume ratio and FRP confinement ratio. To examine
430 the effect of variation of ε_{t2} , the stress-strain curves generated using the three-segment expression with ε_{t2}
431 values of 0.006, 0.0075 and 0.009 are compared in Figure 24. It is evident that the effect of the selected

432 range of ε_{t2} values on the stress-strain curves are minor. Therefore, a constant value of 0.0075 for ε_{t2} is
433 adopted in the present study to simplify the problem.

434 5.5 Concrete inside steel inner tubes (CI)

435 In square MTCCs, before a certain axial strain (i.e. the second transition point), CI is mainly confined by
436 the steel tubes and the stress-strain behaviour of CI up to the second transition point is generally dominated
437 by the steel volume ratio (ρ_{st}). After the second transition point, due to the expansion of concrete, the FRP
438 confinement starts to dominate the stress-strain behaviour of CI. Based on the discussion in Section 5.2, the
439 slope (E_2) of the third segment is mainly affected by the FRP confinement ratio ($\rho_{K,eq}$) [see Figure 21(a)]
440 while the intercept stress (f_i) is mainly affected by the steel volume ratio (see Figure 20). The equations of
441 the other two key parameters (E_2 and f_i) of stress-strain curves of CI are formulated through the regression
442 analyses of FE results and are given by:

$$\frac{E_2}{E_c} = 0.49\rho_{K,eq} - 0.0059 \quad (4)$$

$$\frac{f_i}{f'_{co}} = 1.25 + 0.41(\rho_{st} - 0.049) \quad (5)$$

443 The performance of the proposed model for predicting the stress-strain behaviour of CI of MTCCs with
444 steel volume ratios of 4.92% and 9.68%, and different FRP confinement ratios is shown in Figure 25. It can
445 be seen that the proposed model produces reasonable predictions of the stress-strain behaviour of CI in
446 square MTCCs with different FRP confinement ratios and steel volume ratios.

447 5.6 Concrete surrounded by steel inner tubes (CO-I)

448 From the confinement mechanism of square MTCCs, the CO-I is largely confined by FRP tube and is
449 independent of other column parameters examined in Section 5.2. Therefore, the following equation is
450 proposed to consider the effect of FRP confinement ratio ($\rho_{K,eq}$):

$$\frac{E_2}{E_c} = 0.62\rho_{K,eq} - 0.0014 \quad (6)$$

$$\frac{f_i}{f'_{co}} = 1 + 4.1 \rho_{K,eq} \quad (7)$$

451 Figure 26 shows the comparison between the predictions generated using the proposed model and FE
 452 results. The comparison shows that the proposed model produces reasonable predictions of the CO-I in
 453 square MTCCs with different FRP confinement ratios.

454 5.7 Concrete between FRP outer tube and steel inner tubes (CO-O)

455 The stress-strain behaviour of CO-O in square MTCCs is mainly affected by two parameters, which are the
 456 concrete cover ratio (ρ_{cover}) and the FRP confinement ratio ($\rho_{K,eq}$) [see Figures 17 and 21(b)]. Both
 457 parameters contribute significantly to the stress-strain behaviour of CO-O in square MTCCs in different
 458 ways. The former controls the proportion of weakly confined areas of concrete in CO-O (Figure 18), while
 459 the latter controls the level of confinement.

460 The stress-strain curves of CO-O generated from FE models of MTCCs with two different concrete cover
 461 ratios (ρ_{cover} of 0 and 0.0731) and five different FRP confinement ratios ($\rho_{K,eq}$ of 0.0151 to 0.0452) are
 462 shown in Figure 27. For $\rho_{K,eq}$ of less than 0.0227, the axial stress after the transition zone decreases
 463 dramatically due to the relatively weak confinement. For these cases, the stress-strain model of unconfined
 464 concrete may be adopted for conservative predictions. For MTCCs with $\rho_{K,eq}$ value higher/ equal to 0.0227,
 465 the following equations are proposed to predict the stress-strain behaviour of CO-O:

$$\frac{E_2}{E_c} = -0.62\rho_{cover}^2 + 0.11\rho_{cover} - 0.018 \quad (8)$$

$$\frac{f_i}{f'_{co}} = 1 + 3.1 \rho_{K,eq} + 1.2 \rho_{cover} \quad (9)$$

466 Comparisons between predictions generated using the proposed model and FE results are shown in Figure
 467 28. The comparison shows that the proposed model can produce reasonably accurate predictions for axial
 468 strains of up to around 0.02, while it underestimates the axial stress afterwards. To accurately predict the
 469 whole stress-strain curve of CO-O, a more complex form of expression is needed to capture the stress

470 increase in the late stage. However, the area of CO-O in square MTCCs is typically much smaller compared
471 to the other two parts of concrete, and the use of overcomplex expressions for more accurate predictions
472 may not be necessary. Therefore, Eqs. 8 and 9 are recommended for conservative predictions of the stress-
473 strain behaviour of CO-O.

474 5.8 Performance of the proposed models

475 A comparison of ultimate axial strain between the prediction of Eq. 3 and FE/experiment results is shown
476 in Figure 28. The FE results are from all numerical specimens in Table 4, with the assumed rupture strain
477 of 0.015. It can be seen that the proposed model can predict the ultimate axial strains of FE specimens well.
478 For the test specimens, the model generally provides reasonably accurate or conservative predictions of the
479 ultimate axial strain. The inaccuracy of Eq. 3, as shown in Figure 28, is due to the differences between the
480 predictions of the developed FE models and the test results, as discussed in Section 3.3. Because of the
481 relatively large scatter of the experimental ultimate axial strain (Chan et al. 2018) and the conservative
482 nature of Eq. 3, it is believed that it is still acceptable for design use.

483 Additionally, Figure 3 compares the axial load-strain curves of typical MTCC specimens predicted by the
484 proposed models with both experimental and FE results. In this comparison, the confined concrete in CI,
485 CO-I, and CO-O were predicted using the proposed models, while the steel tubes' load contribution was
486 assumed to exhibit elastic-perfectly plastic behaviour, based on the elastic modulus and yield stress data
487 from material tests. It can be seen from Figure 3 that the proposed model closely aligns with the
488 experimental and FE results up to an axial strain of approximately 0.01. Beyond this point, the model tends
489 to provide conservative predictions, primarily due to the simplified models for the steel tubes and CO-O.
490 Overall, the proposed model strikes a good balance between accuracy and simplicity and can be adopted
491 for design use.

492 6.0 CONCLUSIONS

493 This paper has been mainly concerned with the stress-strain behaviour of the three parts of concrete in
494 square MTCCs and the modelling of their behaviour using simple stress-strain models. To this end, 3D FE
495 models were first developed for the concentric compressive behaviour of square MTCCs and verified with
496 the existing experimental results. The FE models were then used to examine the confinement mechanism
497 of concrete in square MTCCs and to conduct FE parametric studies. The FE study showed that the three
498 parts of concrete in square MTCCs behave quite differently from each other: the concrete inside steel tubes
499 (CI) receives the effective confinement from both the FRP tube and the steel tubes so that its behaviour is
500 significantly superior to the behaviour of other parts of concrete in square MTCCs; the concrete surrounded
501 by steel tubes (CO-I) is largely and effectively confined by FRP tube, while the concrete between the FRP
502 tube and steel tubes (CO-O) is mostly located in the weakly confined region close to the flat sides of the
503 square FRP tube, and thus has the lowest stress-strain curve among the three parts of concrete. Therefore,
504 three independent stress-strain models were proposed to model the behaviour of concrete in square MTCCs.
505 Comparisons with the FE results have demonstrated that the proposed stress-strain models provide
506 reasonably accurate and conservative predictions for all three parts of concrete in square MTCCs.

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512 **DATA AVAILABILITY STATEMENT**

513 Some or all data, models, or code that support the findings of this study are available from the corresponding
514 author upon reasonable request.

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