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Citation: Wang, Y., Cai, G., Si Larbi, A., Waldmann, D., Tsavdaridis, K. D. & Ran, J. (2020). Monotonic axial compressive behaviour and confinement mechanism of square CFRP-steel tube confined concrete. *Engineering Structures*, 217, 110802. doi: 10.1016/j.engstruct.2020.110802

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1 **Monotonic axial compressive behaviour and confinement** 2 **mechanism of square CFRP-steel tube confined concrete**

3
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6
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18 19 **Abstract**

20 Steel tube confined concrete (STCC) is widely used in the vertical members of high-rise buildings
21 such as columns. The axial load is not directly resisted by the steel tube in STCC, but is resisted via
22 the interfacial frictional stress between steel tube and concrete core, which is different with that of
23 concrete filled steel tube (CFT) members and would effectively suppress the outward local buckling of
24 steel tube at early stage. Recently, fibre-reinforced polymer (FRP) confined STCC presents a potential
25 to enhance the ductility and durability of such vertical elements. This paper presents an experimental
26 study on monotonic axial compressive behaviour of carbon FRP (CFRP) confined STCC (CFRP-
27 STCC) stub column and an analytical study on the confinement mechanism of and the ultimate axial
28 bearing capacity of the elements. A three-stage confinement mechanism involving the different
29 contributions of the steel tube and the CFRP wrap in CFRP-STCC elements was proposed based on
30 the test results. A prediction model of the ultimate axial bearing capacity of CFRP-STCC stub
31 columns was developed subsequently. Results show that the presence of CFRP wrap enhances
32 effectively the load-bearing capacity and the ductility of steel tube confined plain concrete and
33 reinforced concrete elements, and significantly prevents the local buckling of the steel tubes in the

34 elements. The proposed prediction model of ultimate axial bearing capacity assesses test results with a
35 great agreement.

36 **Keywords:** FRP confined concrete; Steel tube confined concrete; Constitutive model; Confinement
37 mechanism; axial compressive behaviour

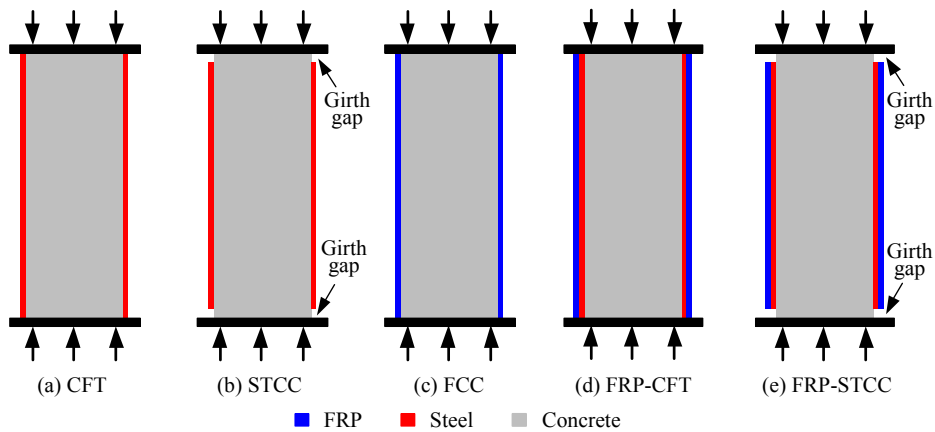
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39 **1. Introduction**

40 Reinforced concrete (RC) structures still are widely used in most of the earthquake-prone zones of the
41 world. Numerous studies have revealed that a sufficient confinement can significantly enhance the
42 ductility of RC elements subjected to seismic loads. To achieve an effective confinement, various
43 methods and technical provisions have been developed according to a series of experimental
44 laboratorial studies and earthquake field surveys. Among them, an effective and easily implemented
45 method at the early stage of the previous research is using steel stirrups or hoops with a smaller
46 spacing at the hinge zones of RC elements such as RC columns.

47 In order to further improve the bearing capacity and seismic performance of RC columns, concrete-
48 filled steel tube (CFT) column (Fig.1a) has been developed and widely applied in civil engineering
49 due to the effective confinement of steel tube in such elements [1]. However, the steel tube of CFT
50 must be thick to avoid its potential local buckling [2]. Steel tube confined concrete (STCC) column
51 (Fig. 1b) is an innovative type of composite columns [3-9], in which the main difference with CFT
52 column is that the steel tube is disconnected to both ends of the column (Fig. 1b). There are two main
53 benefits obtained from this difference of STCC columns. One is the construction simplification of
54 beam-column joints because that steel tube does not need to pass through the joint zone, which has
55 been illustrated by the literature [9]. Another is that the potential local buckling of steel tube can be
56 effectively avoided or delayed as STCC elements are under compressive load. This is because that the
57 steel tube in STCC does not resist directly axial load and mainly provides a confinement to concrete
58 core. It means the thickness of steel tube in STCC can be controlled compared with that of CFT in
59 order to archive the same load-bearing capacity. **The STCC elements have the potential of wide
60 applications in new construction.** It should be noted that, however, the steel tube in STCC still resists
61 certain axial load from compressive load via the interfacial friction between steel tube and concrete
62 core. But the interfacial friction can be reduced by smoothing the inner surface of steel tube (i.e. oil
63 treatment). However, the main concerns of CFT and STCC elements are the durability issues of
64 external steel tube (i.e. its resistance to corrosion) when they are subjected to aggressive environments.
65 **The conventional corrosion protection for steel tube is additional coating. However, some small**

66 defects could occur in the coating process or the use of steel tubes [2] such as cyclic loads or fatigue
 67 loads, which then can cause the pitting corrosion of the tube and then result in the subsequently large
 68 area corrosion of the steel tube. Therefore, it is desirable to explore alternative corrosion protection for
 69 steel tube.



70
 71 **Fig. 1.** Schematic diagram of different confined concrete columns.

72
 73 Fibre reinforced polymer (FRP) has been widely applied in civil engineering due to its high strength,
 74 light weight, good fatigue resistance, and especially excellent durability [10-17]. FRP confined
 75 concrete (FCC) column (Fig. 1c) is one of important applications of FRP material in civil engineering
 76 to improve the bearing capacity and ductility of concrete core [18-19]. FRP material provides a new
 77 choice for steel tube to resist corrosion by wrapping FRP layer on the outside of steel tube. To
 78 improve the durability of the outer steel tube of CFT and STCC elements under aggressive
 79 environments, and to avoid or delay the early age local buckling of steel tube of CFT elements, several
 80 researchers proposed using FRP wrap to confine CFT (FRP-CFT, Fig. 1d) [20-28] or STCC (FRP-
 81 STCC, Fig. 1e) [29] elements. FRP-CFT and FRP-STCC elements are two innovative composite
 82 elements, which benefit the advantages of both CFT and STCC. The outer FRP wrap/confining can
 83 effectively prevent the potential corrosion problem of outer steel tube under aggressive environments
 84 and enhance the bearing capacity of CFT/STCC. This means that the same bearing capacity still can
 85 be reached in the composite elements when the thickness of steel tube is reduced, which can reduce
 86 the manufacturing difficulty of thick steel tube. Meanwhile, it also can delay or even avoid the
 87 cracking of the welding seam of the steel tube because of the effective confinement of the outer FRP
 88 wrap. It should be admitted that the brittle fracture of FRP material at its ultimate state may lead to a
 89 sudden failure of FRP-STCC elements, however, the FRP wrap can provide the STCC higher
 90 confinement which could significantly improve the bearing capacity and the peak strain of the STCC

91 **elements.** Due to the large difference of thermal expansivity between FRP and steel, large temperature
92 difference is considered as a challenge for the interface adhesive in FRP-CFT and FRP-STCC
93 elements. This environment may cause the degradation of structural performance of the elements, thus
94 endangers the service life span of the structures. Therefore, **high toughness** adhesives are suggested to
95 fabricate the FRP wrap in FRP-CFT and FRP-STCC elements to delay the deterioration of their
96 structural behaviours caused by a large temperature difference. **Moreover, the balance between the**
97 **toughness of the adhesives and their glass transition temperatures should be considered, to avoid the**
98 **serviceability problems of the elements at higher service temperatures due to low glass transition**
99 **temperature.** On the other hand, the aging problem of external FRP wrap due to sunlight (mainly
100 Ultraviolet light) [30], temperature, and humidity is the main concern of the durability of FRP-
101 confined or -strengthened structures. To fix this issue, a surface treatment such as coating of FRP wrap
102 is suggested in practical application. **As new corrosion protection of steel, the cost of FRP wrap in**
103 **FRP-STCC elements is more expensive than those of the conventional corrosion protections of steel,**
104 **due to the high price of FRP materials and additional coating materials to resist the aging problems of**
105 **FRP. However, FRP wrap is also expected to improve the structural performance (the bearing capacity,**
106 **peak strain and local buckling, etc.) of STCC elements with the benefits of the material advantages.**

107 Compared to STCC and FCC elements, limited studies were conducted [2,29,31] to understand the
108 structural behaviour of FRP-STCC elements such as the effectiveness of FRP wrap to prevent the
109 failure provoked by local damage of steel tube. Lin [29] studied the structural behaviour of circular
110 glass FRP (GFRP) confined STCC (GFRP-STCC) columns to investigate the effects of the type of and
111 the number of layers of FRP wrap, stirrup ratio, and loading type. It was reported that FRP wrap, steel
112 tube, and reinforcements in STCC elements all can enhance significantly the axial load-carrying
113 capacity and the ductility of the elements [28]. Huang [31] experimentally investigated the cyclic
114 constitutive behaviour of circular GFRP-STCC columns and proposed a design model to predict the
115 compressive behaviour of the confined concrete. Xu *et al* [2] tested circular carbon FRP (CFRP)
116 confined STCC (CFRP-STCC) stub columns to investigate their eccentric compressive behaviour and
117 presented N - M interaction relationship by a plastic stress distribution method. However, up to now,
118 only a few parameters were studied to understand their effects of FRP wrap on the constitutive
119 behaviour of confined concrete [28,31] and no research was reported about square FRP-STCCs.
120 However, both constitutive behaviour and confinement mechanism are considered very important to
121 the structural analysis of FRP-STCC structures. To develop a more reliable analysis constitutive model,
122 more test studies on square FRP-STCC elements are needed to establish the stress-strain law of square
123 FRP-STCCs.

124 The main objectives of the paper are to study the monotonic axial compressive behaviour of square
125 CFRP-STCCs and to analyse the confinement mechanism of square steel tube and CFRP wrap in the
126 confined concrete stub columns. Although CFRP materials are more expensive and have a small
127 fracture strain and may cause potential galvanic corrosion issues, however, as a start of the study on
128 the confined STCC elements, CFRP was first selected among commonly used FRP materials (i.e.
129 CFRP, GFRP, aramid FRP, and basalt FRP). The main reasons are: (1) The elastic modulus of CFRP
130 materials is close to that of steel materials, which meaning it is easier to work together with the steel
131 tube, compared with the other FRP materials. (2) CFRP materials have a higher strength-weight ratio,
132 which means it has a high potential to effectively improve the confinement of the inside concrete in
133 STCC elements. (3) The basic research conclusions of CFRP-STCC are also applicable to those of the
134 STCC confined by other FRP materials due to the inherent linear elastic response of FRP materials.
135 Based on the experimental study, a calculation model was proposed to assess the axial bearing
136 capacity of CFRP-STCC stub columns. The investigation mainly includes failure modes, load-
137 deformation behaviour, the influence of main parameters (the number of layers of CFRP wrap, width-
138 to-thickness ratio of steel tube, corner radius at sectional corner), and confining stress analysis of
139 CFRP-STCCs.

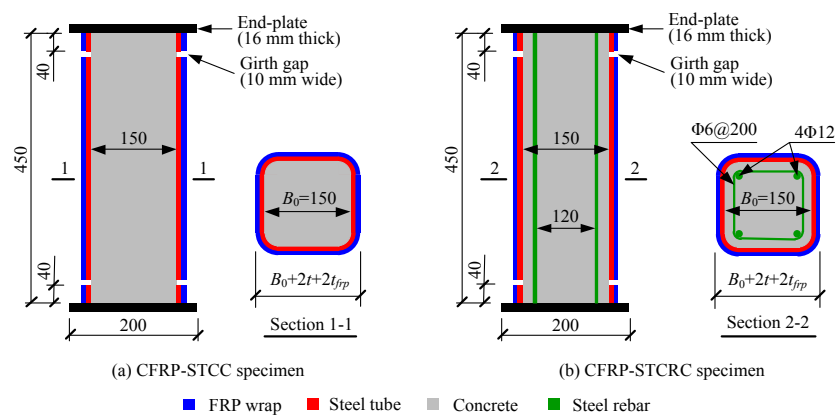
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141 **2 Test investigation**

142 2.1 Test specimens

143 In this study, total 23 specimens were prepared and tested, including 11 square CFRP-steel tube
144 confined plain concrete (CFRP-STCC) stub columns, 3 square steel tube confined plain concrete
145 (STCC) stub columns, 6 square CFRP-steel tube confined reinforced concrete (CFRP-STCRC) stub
146 columns and 3 square steel tube confined reinforced concrete (STCRC) stub columns. The height-to-
147 width ratio (H/B_0) of all specimens is 3.0. Fig. 2 gives the details of the test specimens. The volumetric
148 ratios of the longitudinal reinforcement ($4\Phi 12$) and steel stirrup ($\Phi 6@200$) of confined RC specimens
149 were 2.0% and 0.4%, respectively. The steel stirrups in the related specimens were only used to fix the
150 longitudinal reinforcements, and the hoop confinement of them to the concrete core was ignored in the
151 later analysis. In order to ensure that applied axial load was transferred uniformly to the internal
152 longitudinal reinforcement in the specimens, both ends of each longitudinal rebar were welded to the
153 bottom and top steel plates of each specimen (see Fig. 2b), respectively. In order to guarantee that the
154 steel tube does not directly bear axial load in each specimen, a ring with a length of 10 mm was cut
155 after casting from both ends of steel tube (40 mm from the ends), forming two girth gaps in each
156 specimen shown in Fig.2. A wet lay-up process was used to conduct CFRP wrap to steel tubes in the

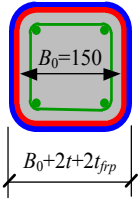
157 specimens. Before CFRP was wrapped, the floating rust and impurities on the surface of the steel
 158 tubes were removed with a fine sandpaper and using an alcohol treatment. CFRP sheets with the same
 159 height as that of the steel tube were then uniformly and tightly wrapped on the outer surface of the
 160 steel tube with an epoxy adhesive. The overlapping length of CFRP sheets was 120 mm according to
 161 the Chinese Code (GB 50608-2010) [32], which was arranged to cover one of the welding seams of
 162 steel tube (seen Fig. 3). The details of each specimen are listed in Table.1. The studied corner radiiuses
 163 of the steel tubes were 10 mm, 20 mm, 30 mm, as PC-D-2-2(10), PC-B-2-2 and PC-D-2-2(30)
 164 specimens listed in the table, respectively.



165
 166 **Fig. 2.** Details of test specimens (Units in mm).

167
 168 **Table.1** Details of test specimens

Types	Specimen no.	Steel tube		CFRP		R /mm	Cross section
		t /mm	B/t	n	t_{frp} /mm		
Confined plain concrete (PC)	PC-A-1-0	1	152	0	0	20	
	PC-A-1-1	1	152	1	0.167	20	
	PC-A-1-2	1	152	2	0.334	20	
	PC-A-1-3	1	152	3	0.501	20	
	PC-B-2-0	2	77	0	0	20	
	PC-B-2-1	2	77	1	0.167	20	
	PC-B-2-2	2	77	2	0.334	20	
	PC-B-2-3	2	77	3	0.501	20	
	PC-C-3-0	3	52	0	0	20	
	PC-C-3-1	3	52	1	0.167	20	
	PC-C-3-2	3	52	2	0.334	20	
	PC-C-3-3	3	52	3	0.501	20	
	PC-D-2-2(10)	2	77	2	0.334	10	
	PC-D-2-2(30)	2	77	2	0.334	30	

	RC-A-1-0	1	152	0	0	20	
	RC-A-1-2	1	152	2	0.334	20	
	RC-A-1-3	1	152	3	0.501	20	
Confined RC	RC-B-2-0	2	77	0	0	20	
	RC-B-2-2	2	77	2	0.334	20	
	RC-B-2-3	2	77	3	0.501	20	
	RC-C-3-0	3	52	0	0	20	
	RC-C-3-2	3	52	2	0.334	20	
	RC-C-3-3	3	52	3	0.501	20	

169 Note: B/t is the width-to-thickness ratio of steel tube; t and t_{frp} are the thickness of steel tube and CFRP
170 wrap, respectively; n is the number of layers of CFRP; R is the corner radius of steel tube.

171

172 2.2 Material properties

173 The elastic modulus, the yield load, and the ultimate tensile strength of the used steel tubes were
174 measured according to the Chinese Code, GB/T 228-2002 [33]. The test results are shown in Table 2.

175 The longitudinal rebars were HRB 335 rebars with a diameter of 12 mm, a measured yield strength of
176 378 MPa and an ultimate tensile strength of 540 MPa. A standard commercial concrete with a
177 maximum coarse aggregate size of 10.0 mm was used in all specimens which was supplied by a local
178 company. Three cylinders of $\varnothing 150 \times 300$ mm were tested under axial compression to define the

179 compressive strength of used concrete. The average compressive strength of unconfined concrete was

180 55.4 MPa. The related material properties of CFRP sheet (surface density: 300 g/m², provided by

181 Toray Co., Ltd, Japan), and of epoxy adhesive (provided by Dalian Kaihua New Technology

182 Engineering Co., Ltd, China), were provided by manufacturers and listed in Table 2. In order to avoid

183 potential galvanic corrosion between CFRP wrap and steel tube in practical application, a thin

184 insulating layer (i.e. Glass FRP) must be wrapped firstly before wrapping CFRP sheet on steel tube.

185 However, the insulating layer was not applied in the study considering the test is short-term without

186 such galvanic corrosion issue. **Although the CFRP-STCC elements proposed in this paper are relative**

187 **complex, consisting of steel rebars, concrete, steel tube, GFRP, CFRP, epoxy layers, and an additional**

188 **protection layer, it is one of the ways to effectively solve the corrosion problem of steel tube. And if**

189 **CFRP is replaced by GFRP in the elements, the additional insulating layer is not needed. Moreover, to**

190 **resist the steel corrosion, similar technologies using FRP wrap on steel tube had already been applied**

191 **in the structures with steel piles located in several harbours in China [31]. These projects preliminarily**

192 **proved the effectiveness of the FRP wrap to resist steel corrosion of the structures. Therefore, as one**

193 **of the treatments of durability and effective confinement methods, the proposed FRP-STCC elements**

194 **present the potential of wide applications in practical projects to address the corrosion problem of steel**

195 tube and improve the structural performance of the elements. In addition, to simplify the analysis, the
 196 axial compressive behaviour contributed from the thin GFRP insulating layer can be omitted due to
 197 the layer can be very thin in the practical application of CFRP-STCC elements.

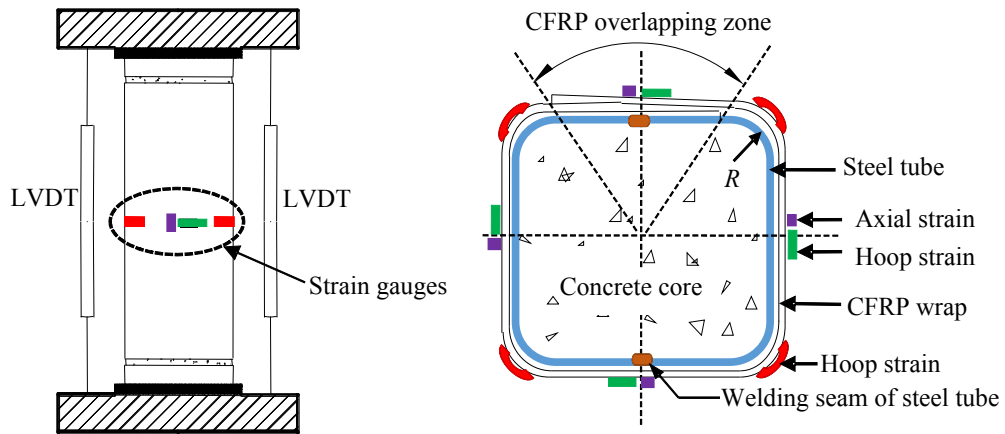
198 Table.2 Material properties of steel tube, CFRP sheet and epoxy adhesive

Materials	Nominal thickness /mm	Elastic modulus /GPa	Yield tensile strength /MPa	Ultimate tensile strength /MPa	Elongation /%
Steel #1	1.0	210	188	330	-
Steel #2	2.0	204	192	345	-
Steel #3	3.0	205	200	323	-
CFRP	0.167	245	-	4077	1.51
Epoxy	-	>2.5	-	>40	>1.80

199

200 2.3 Loading and measurement

201 The measurement and setup of the test are presented in Figs. 3 and 4. A monotonic axial compressive
 202 loading was applied on each specimen by a 5000 kN hydraulic compressive machine (see Fig. 4),
 203 which was controlled by vertical displacement with a rate of 0.5mm per minute referring to the
 204 literature [1]. The axial compressive load was measured by a load cell placed on the top of the
 205 specimens. Two linear variable displacement transducers (LVDTs) with a measurement range of
 206 50 mm were arranged symmetrically on the diagonal direction of the test specimens to measure the
 207 vertical displacement of stub columns, as shown in Figs. 3 and 4. Twelve strain gauges with a gauge
 208 length of 20 mm were installed on CFRP wrap to measure the axial and hoop strains of CFRP wrap
 209 and steel tube at the mid-height of the test specimens, as shown in Fig. 3. Since CFRP wraps were well
 210 bonded to steel tubes with epoxy adhesive, the inner steel tube was considered to work together with
 211 the outer CFRP wrap without interfacial slippage. Therefore, the strains of the inner steel tube were
 212 assumed to be the same as those of the outer CFRP wrap. The strain and load information were
 213 collected synchronously at an acquisition frequency of 1.0 Hz.



214
215

Fig. 3. Layout of LVDTs and strain gauges in the specimens.



216
217

Fig. 4. Test setup.

218 **3 Test observations and analyses**

219 **3.1 Failure modes**

220 The damage and failure modes of the steel tube confined concrete specimens and the CFRP-steel
 221 tube confined concrete specimens are shown in Fig. 5. In the steel tube confined concrete columns, the
 222 concrete cover at the ends of steel tube experienced sporadic crushing or spalling when approaching
 223 the peak loads of the columns. When the axial load dropped to around 70% of their peak load, the steel
 224 tube near the middle section suffered a significant outward local buckling. After removing the steel
 225 tubes, several obvious shear damages were observed in the steel tube confined plain concrete
 226 specimens, as shown in Fig. 5 (a), (b) and (c). On contrast, the shear failure was not pronounced in the
 227 steel tube confined RC specimens instead of evenly distributed cracks, as shown in Fig. 5 (f), (j) and
 228 (h), indicating that the installation of longitudinal reinforcements improved the axial compressive

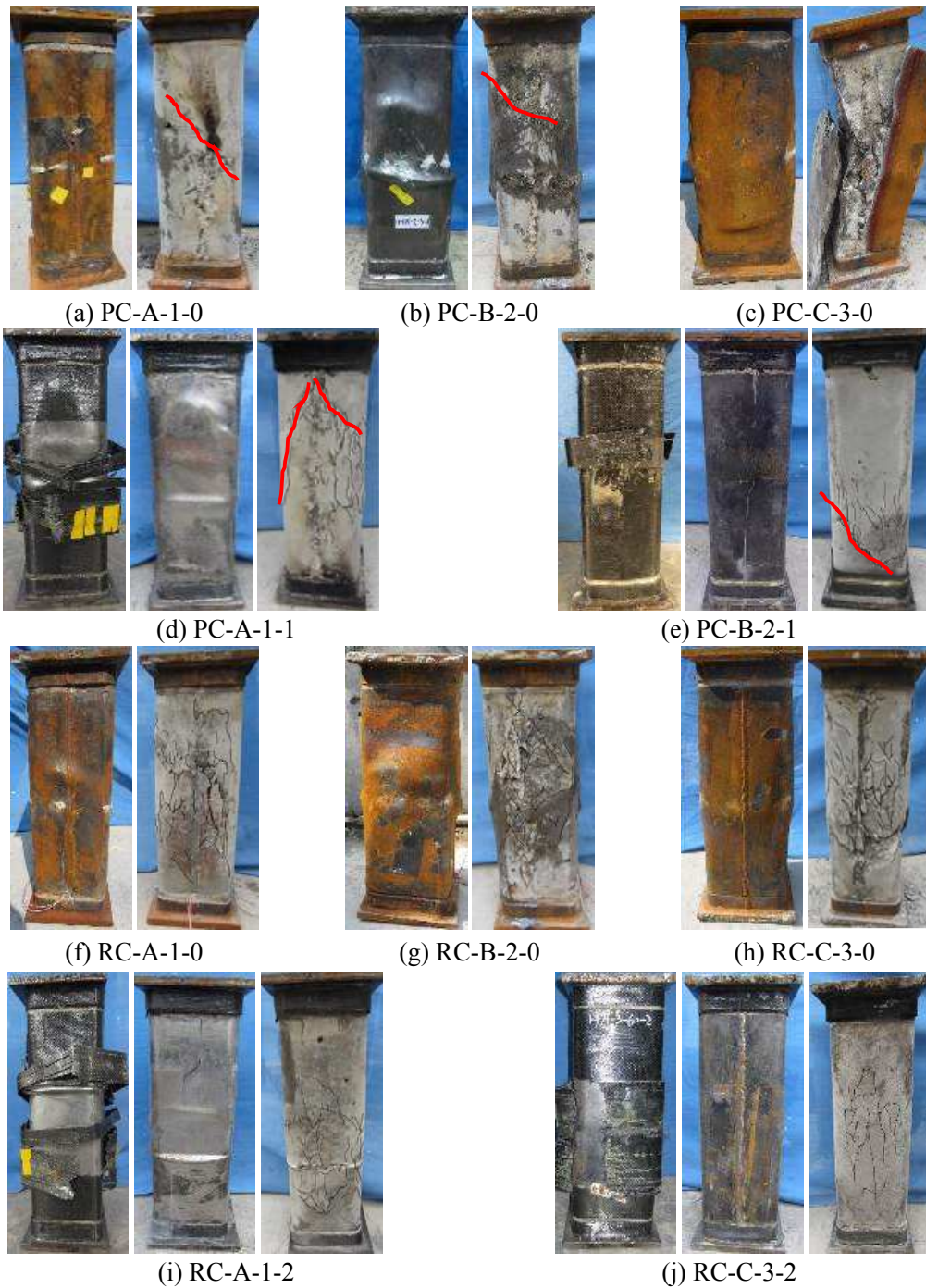


Fig. 5. Failure models of several representative confined concrete stub columns.

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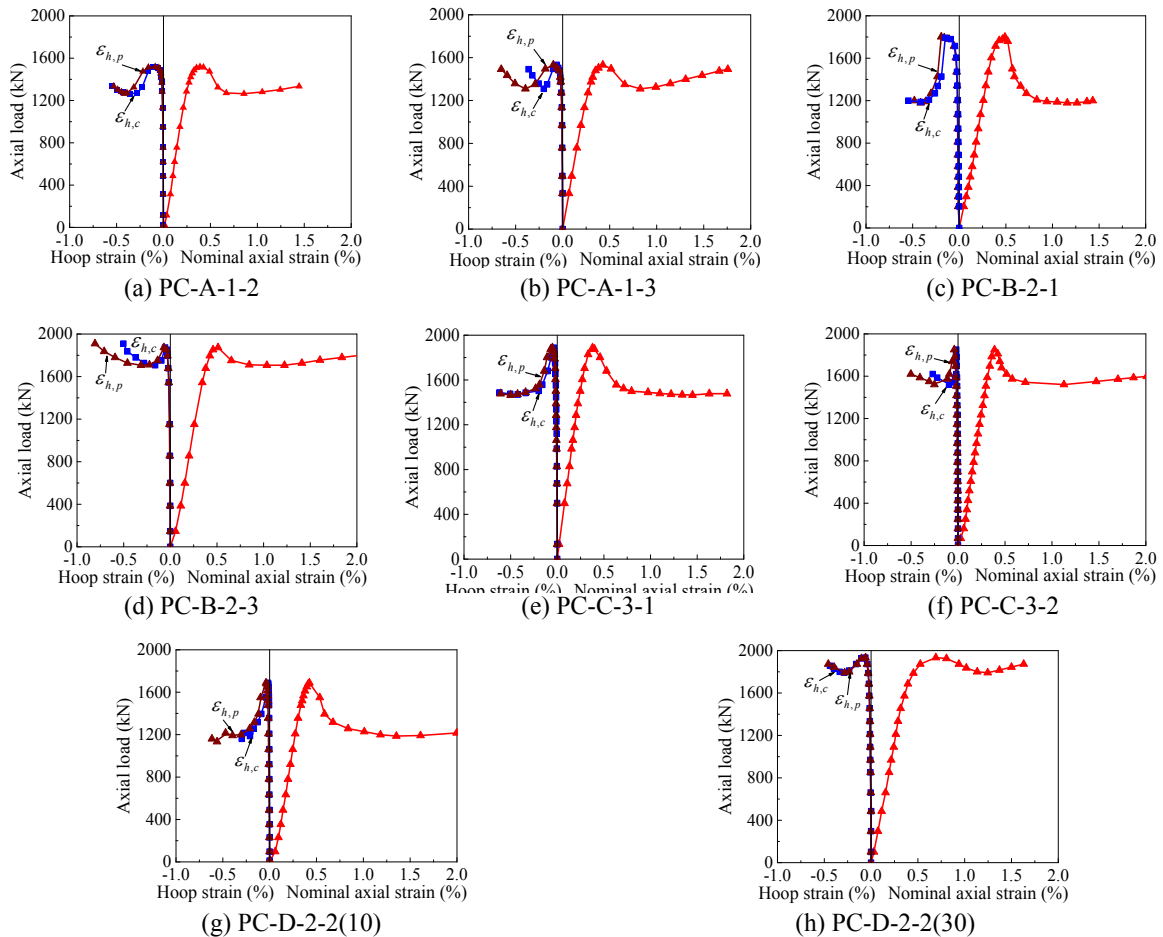
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For the CFRP-steel confined concrete specimens, their ultimate failure was dominated by the hoop rupture of CFRP wrap (see Fig. 5 (d), (e), (i) and (j)). After the fracture of CFRP wrap, the local

234 buckling of steel tube near specimens' mid-height section was observed and then the whole specimen
 235 failed. After removing the steel tubes, diagonal shear cracks still were observed in the surface of the
 236 concrete core in the specimens, shown in Fig. 5 (d) and (e). However, the shear failure was avoided in
 237 the CFRP-steel tube confined RC specimens (Fig. 5i and j), which confirms that the addition of
 238 longitudinal reinforcement can play a beneficial effect on the axial compressive behaviour of CFRP-
 239 steel tube confined concrete columns.

240 3.2 Axial load-strain behaviour

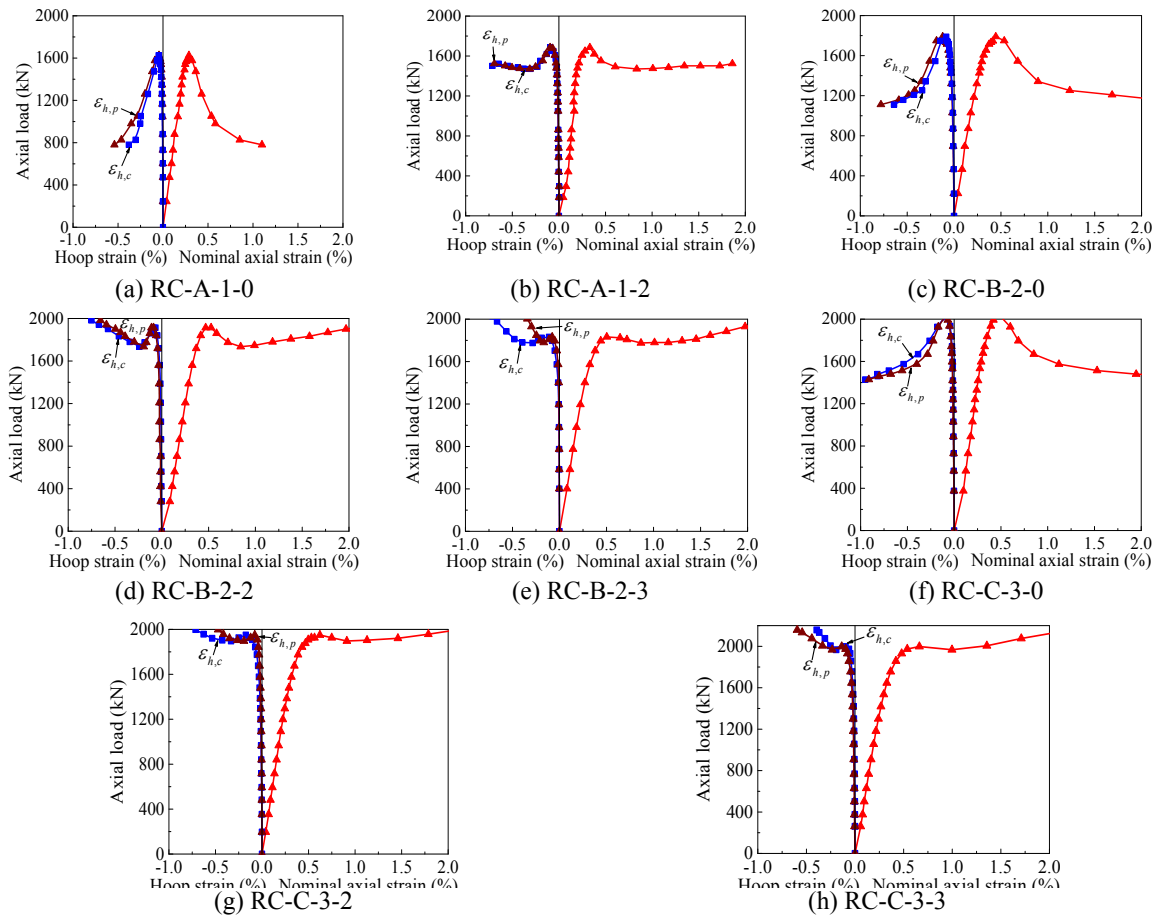
241 Figs. 6 and 7 depict the axial load-strain curves for several representative CFRP-steel tube
 242 confined plain concrete specimens. In this study, the nominal axial strain was calculated as a ratio of
 243 the axial shortening to the initial height of specimens, while the hoop strain was the average measured
 244 strain by four hoop strain gauges installed on the corners or middle sections.



245 **Fig. 6.** Axial load-strain curves of confined plain concrete specimens.

246

247 Results show that all confined plain concrete and confined RC specimens deformed elastically at
 248 the early stage. The axial deformation increased approximately linearly, and its increasing rate was
 249 much greater than that of the lateral deformation. With the increasing of axial deformation, the lateral
 250 deformation at the corners ($\epsilon_{h,c}$) was smaller than the deformation at the middle of steel tube side at
 251 the middle section ($\epsilon_{h,p}$). This indicates that the concrete deformation at the corners of the steel tubes
 252 was restrained well while the other deformations at the middle section are not well confined. The
 253 bearing capacity of steel tube confined concrete specimens rapidly decreased after the specimens
 254 reached their peak loads, and the axial load tended to stabilize when the peak load was reduced to a
 255 certain load ranging from 50% to 90% of corresponding peak load.



256 **Fig. 7.** Axial load-strain curves of confined reinforced concrete specimens.
 257

258 For both CFRP-steel confined plain concrete and confined RC specimens, their load carrying
 259 capacity started to decrease after the specimens reached their first peak load. The lower the number of
 260 layers of CFRP was, the larger the decrease of the bearing capacity was. When the curves decreased to

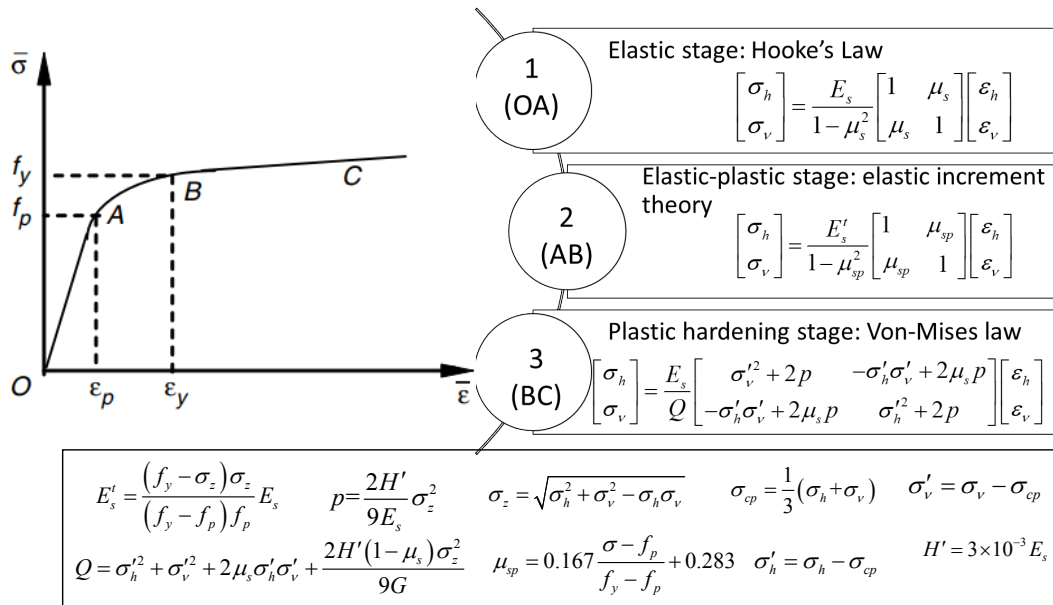
261 a certain extent, the hoop strain of the confined concrete started to increase and the curves began to
 262 slightly rise. The greater the number of layers of CFRP wrap used in the specimens, the higher the
 263 increase rate of the bearing capacity was. The softening phenomenon indicates that the confinement
 264 effectiveness of FRP-steel tube in square section concrete specimens was relatively weak. The
 265 softening phenomenon also occurred in CFRP-steel tube confined RC columns. However, the peak
 266 load of the curves in the second rising section was generally larger than that of the confined plain
 267 concrete specimens, e.g., PC-B-2-3 and RC-B-2-3 specimens. It shows that the deformability of
 268 confined concrete specimens was improved after reinforcing rebars were added to the columns. This
 269 improvement was more conducive to the development of the confinement effectiveness of the FRP-
 270 steel composite tube so that the load carrying capacity of the columns increased.

271 3.3 Stress-strain relationship of steel tube

272 The confinement of steel tube to concrete core can be understood by analysing the longitudinal and
 273 transverse stress of the steel tube. Referring to the literature [34], the stress of steel tube during loading
 274 was determined based on the hoop and axial strain in the middle of the specimen. This brings a better
 275 understanding of the confinement effectiveness of the steel tubes in the composite elements. Due to a
 276 thin-walled steel tube was used in this study, the force perpendicular to the wall of steel tubes is small
 277 and can be neglected. For this, the steel tube can be considered under the state of plane-stress [35]. Fig.
 278 8 demonstrates the main calculation method of stress analysis of the steel tube at three stages. At the
 279 elastic stage, the stress-strain relationship was assumed to obey the Hooke's law. An elastic increment
 280 theory [34] was used to determine the stress of steel tube at the elastic-plastic stage (AB). The Von-
 281 Mises yield criterion and the Prandtl-Reuss flow rule were adopted to analyse the behaviour of steel
 282 tube at the plastic hardening stage (BC) [36]. In Fig. 8, σ_h and ε_h are the hoop stress and strain of steel
 283 tube, σ_v and ε_v are the axial stress and strain of steel tube, σ_z is the equivalent stress of steel tube, μ_s is
 284 Poisson's ratio of steel in the elastic stage, E_s^t and μ_{sp} are the tangent modulus and Poisson's ratio of
 285 the steel in the elastoplastic stage, σ'_h , σ'_v and σ_{cp} are the hoop and axial deviatoric stress of steel and
 286 its mean stress, G is shear modulus of the steel, f_y and f_p are the steel yield strength and proportional
 287 limit ($0.8f_y$), ε_p and ε_y are the equivalent strain of steel corresponding to f_p and f_y , respectively. p , H'
 288 and Q are defined parameters for the calculation [34].

289 It should be noted that the transverse and axial strains used for the stress analysis of steel tubes are
 290 the strains at the middle of the mid-section of the steel tube. Fig. 9 shows the relationship between the
 291 axial load and the stress of steel tube developed in several specimens. The tensile stress was
 292 considered to have a negative sign in the stress analysis of steel tube. It was found that the axial stress

293 increased more quickly than the hoop stress at the early stage, and the growth rate gradually increased
 294 with the increase of axial load. The yielding of steel tubes of the specimens was confirmed around
 295 their first peak loads. After that point, the hoop stress of the steel tubes increased slowly, but in some
 296 cases, a negative evolution was observed such as PC-B-2-1 and PC-D-2-2 (10). In these specimens,
 297 the axial load decreased sharply too. This leads to the fact that the confinement of steel tube to
 298 concrete core was effectively confined anymore after the significant expansion of concrete, which then
 299 affected the bearing capacity of the specimens. In the CFRP-steel tube confined concrete specimens,
 300 the hoop stress of the steel tube increased after the first peak load, and the load carrying capacity of the
 301 specimens decreased slowly or increased slightly such as Specimen RC-C-3-3. This implies that the
 302 FRP wrap can not only confine the concrete core, but can also confine the steel tube, which increases
 303 the confinement effect of the steel tube on concrete core.



304
305 **Fig. 8.** Stress analysis of steel tube [34].
306

307 Besides, a similar test observation to that of the confined concrete specimens was confirmed in the
 308 confined RC specimens. The confinement effectiveness of the FRP-steel tube on the concrete core was
 309 stronger than those in the concrete specimens. For example, although the steel tube yielded in several
 310 specimens, their bearing capacity kept increasing (see RC-C-3-3). This implies that the CFRP-steel
 311 tube confined RC columns present better ductility and deformability compared to the confined plain
 312 concrete columns.

313

314

315

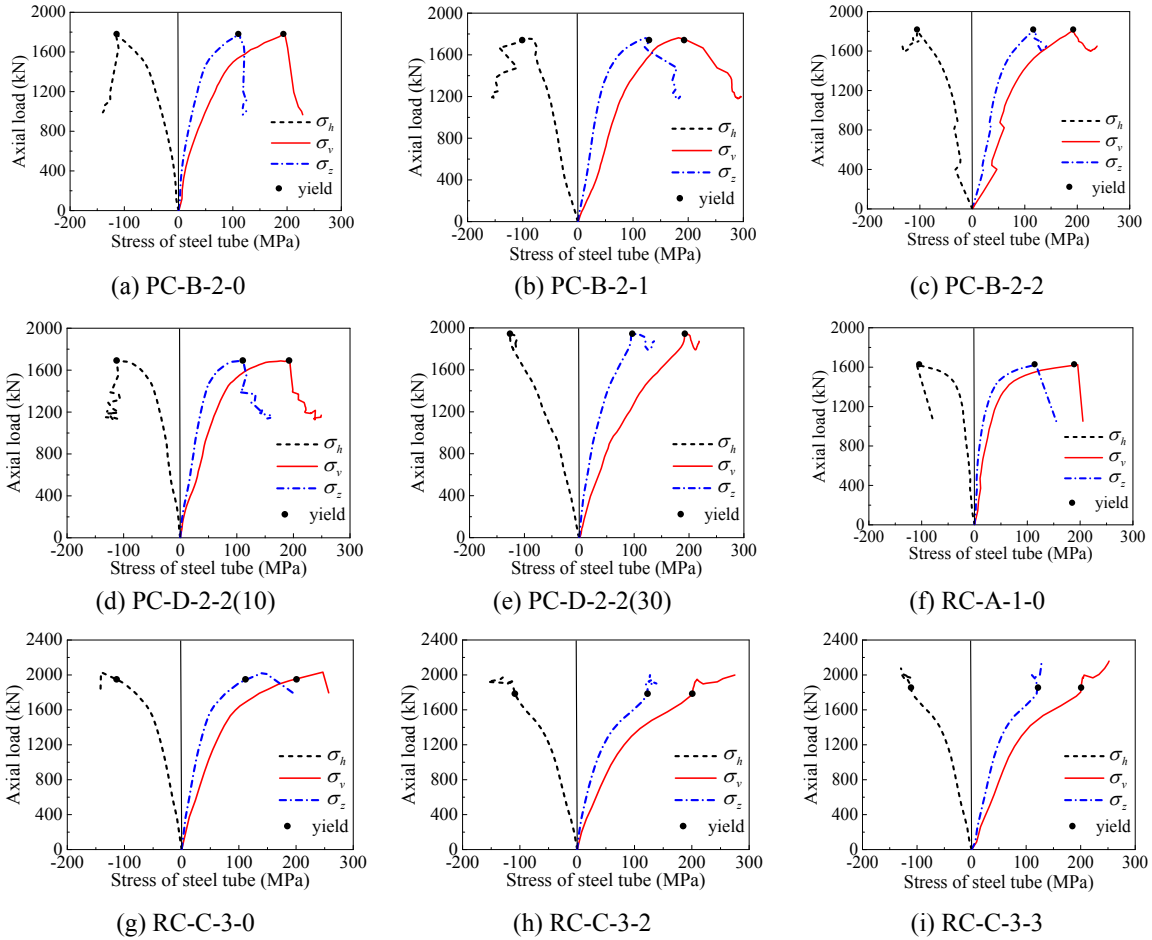


Fig. 9. Axial load-stress relationship of steel tube of representative specimens.

316

317 3.4 Stress-strain responses of confined concrete

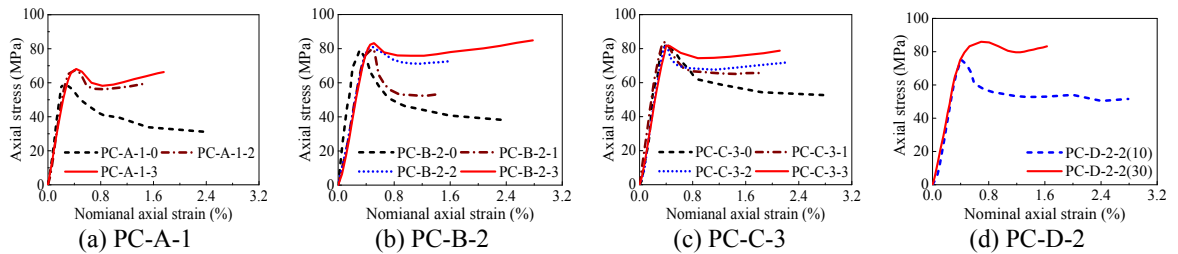
318 Applying the stress analysis of steel tube, the axial load resisted by steel tube can be discussed. In
319 addition, the main fibres of CFRP wrap are only oriented in the hoop direction, so that the stiffness of
320 the CFRP wrap in the direction perpendicular to the hoop direction is very small and can be ignored.
321 When the axial stiffness of CFRP wrap is ignored, the load supported by concrete core can be
322 calculated as the total load of the specimens deducted the load resisted by steel tube. Assuming the
323 compressive stress on the entire section of concrete core is uniformly distributed, the compressive load
324 of confined concrete can be calculated by dividing the deducted load by its cross-sectional area.
325 Moreover, for confined RC specimens, the axial bearing contribution of the longitudinal reinforcement

326 should be deducted from the load resisted by whole column. In summary, the axial stress of confined
 327 concrete can be obtained by,

$$328 \quad \sigma_c = \begin{cases} \frac{N - \sigma_v A_s}{A_c} & \text{for confined plain concrete} \\ \frac{N - \sigma_v A_s - f_a A_a}{A_c} & \text{for confined reinforced concrete} \end{cases} \quad (1)$$

329 where σ_c is the axial stress of confined concrete; N is the axial load resisted by whole column; σ_v is
 330 the axial stress of steel tube; f_a is the yield strength of longitudinal reinforcement in the columns; A_s ,
 331 A_a and A_c are the cross-sectional areas of the steel tube, the longitudinal reinforcement and the
 332 concrete core, respectively. Besides, the axial deformation of the confined concrete is believed to be
 333 identical to the nominal axial strain of the specimens. Table.3 lists a summary on the calculated results
 334 of the axial stress and measured strain of the concrete cores in the specimens, while Fig. 10 shows the
 335 stress-strain curves of the confined concrete.

336 Results plotted in Fig. 10 demonstrate that the initial elastic moduli of the confined plain concrete
 337 and RC are basically identical when compared within the same group. The first peak stress of the
 338 CFRP-steel tube confined plain concrete specimens in Groups PC-A and PC-B (or Groups RC-A and
 339 RC-B for confined RC specimens) were larger than those of the STCC specimens. The difference
 340 among the CFRP-steel tube confined concrete or RC specimens was small, especially in Groups PC-C
 341 and RC-C. This is explained by the fact that the B/t ratio of steel tube in Group A is large ($B/t = 152$)
 342 indicating that the confining stress of the steel tubes was much smaller than others for it is prone to be
 343 buckling failure. This also is the reason why the relatively weak confinement to suppress the
 344 expansion deformation of the concrete cores in the specimens. When FRP wrap was used, the wrap
 345 can not only restrain the lateral dilation of concrete core but also suppress the local buckling
 346 deformation of steel tube, so that steel tube can continue to exert its confinement effect.



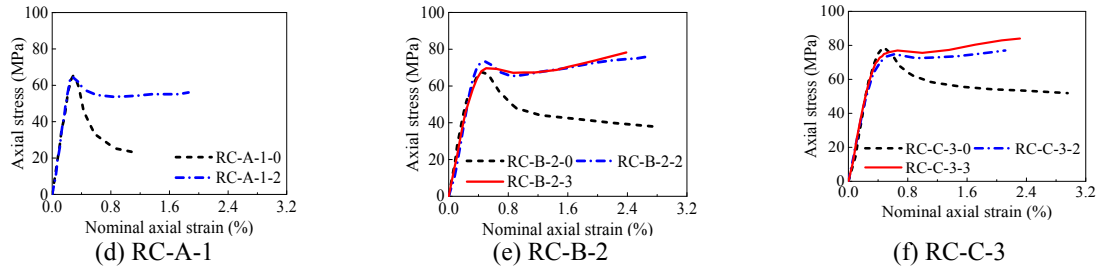


Fig. 10. Axial stress-strain curves of confined concrete.

Table 3. Summary of axial stress and axial strain of confined concrete.

Groups	Specimens	f_{cc1} /MPa	ε_{cc1} /%	f_{cc2} /MPa	ε_{cc2} /%
PC-A	PC-A-1-0	58.84	0.207	—	—
	PC-A-1-2	67.50	0.389	59.32	1.45
	PC-A-1-3	68.11	0.428	66.30	1.76
PC-B	PC-B-2-0	79.23	0.313	—	—
	PC-B-2-1	79.89	0.490	53.33	1.43
	PC-B-2-2	80.90	0.498	72.79	1.62
	PC-B-2-3	83.24	0.512	84.86	2.78
PC-C	PC-C-3-0	82.14	0.418	—	—
	PC-C-3-1	83.86	0.378	65.67	1.82
	PC-C-3-2	82.28	0.388	72.02	2.24
	PC-C-3-3	81.71	0.402	78.80	2.12
PC-D	PC-D-2-2 (10)	75.03	0.425	51.56	2.78
	PC-D-2-2 (30)	85.94	0.692	83.24	1.63
RC-A	RC-A-1-0	63.95	0.274	—	—
	RC-A-1-2	64.87	0.300	50.86	1.86
RC-B	RC-B-2-0	67.80	0.445	—	—
	RC-B-2-2	73.24	0.526	76.28	2.72
	RC-B-2-3	69.67	0.503	78.24	2.39
RC-C	RC-C-3-0	78.47	0.489	—	—
	RC-C-3-2	74.84	0.622	76.98	2.12
	RC-C-3-3	76.98	0.662	84.02	2.31

Note: f_{cc1} and ε_{cc1} are the first peak stress and corresponding nominal axial strain of confined concrete; f_{cc2} and ε_{cc2} are the ultimate stress and corresponding nominal axial strain of confined concrete at the rupture of FRP wrap.

In the confined plain concrete and RC specimens, following the first peak axial stress, the effective confining stresses of the steel tube and FRP wrap in the square section are relatively small. Similar to previous research, the confinement is effective only in a limited confinement area in square concrete. It cannot prevent the expansion deformation of concrete in the non-effective confinement area. This was the reason why the stress-strain curves of the concrete exhibited different degrees of softening. The softening segment was smaller as the number of CFRP layers increased, and the stress-strain curves of confined concrete after this stage increased with varying degrees. This indicates that the

360 lateral expansion deformation of the concrete core increased and the confining stress of CFRP wrap
361 increased, leading to an increase in confining stress to the concrete core. The axial stress of the
362 confined concrete increased until the hoop rupture of CFRP wrap. The slope of the secondary
363 ascending branch of the axial stress-strain curves increased with the number of layers of CFRP.
364 Besides, the corner radius of the steel tube has a significant influence on the stress-strain curves of
365 confined concrete, as shown in Fig. 10 (d). Results show that the strength and ductility of confined
366 concrete corresponding to a steel tube with a corner radius of 30 mm is significantly better than that of
367 the specimen with a corner radius of 10 mm.

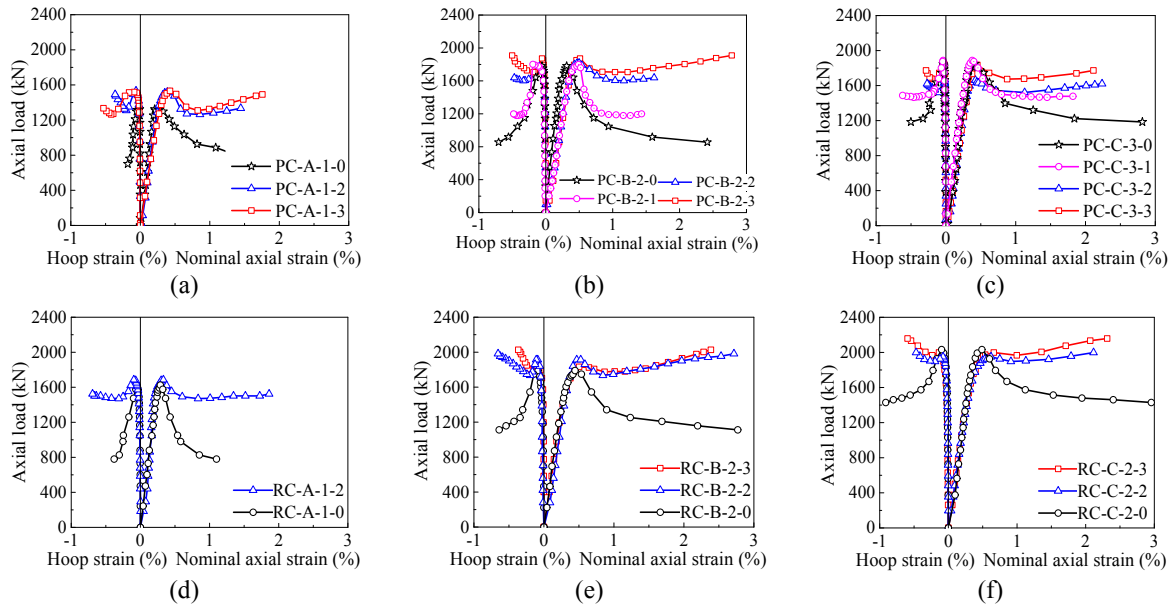
368 In addition, it is worth mentioning that the size effect also is an important affecting factor of the
369 composite confined columns especially for square columns. The hoop strain of CFRP wrap is non-
370 uniformly distributed along the circumferential direction. The hoop strain of CFRP wrap at the corners
371 varies with the sectional size of square columns, leading to a considerable influence on the
372 compressive behaviour of confined concrete. To the best of the authors' knowledge, the size effect in
373 square FRP-steel tube confined plain concrete or RC columns has not been understood well. However,
374 the study conducted by Wang et al. [37] on square FRP-confined RC columns can provide a
375 significant reference to this issue. The experimental results [37] revealed that the compressive strength
376 of square FRP-confined concrete decreased with cross-section size, while ultimate axial strain was
377 influenced little by section size. Therefore, the size effect also may have an important impact on the
378 axial compressive behaviour of square FRP-STCC elements, which deserves further concerns in the
379 future.

380 **3.5. Effects of test parameters**

381 (1) Effect of the number of CFRP layers

382 Fig. 11 depicts the effect of the number of CFRP layers on the axial load-strain behaviour of steel
383 tube confined concrete specimens and CFRP-steel tube confined concrete specimens, where the lateral
384 strain is the measured strain at the corners of the specimens. Results show that the number of CFRP
385 layers affects the first peak loads and corresponding axial strain. When the number of CFRP layers
386 increased, the degree of post-peak softening of the specimens decreased significantly. After the first
387 peak load, the curves of the CFRP-steel tube confined concrete specimens were much smoother than
388 those of the steel tube confined concrete specimens. The more CFRP layers were used, the more
389 gradual the curves exhibited and the higher the ultimate axial deformation of the specimens was. A
390 significant increase was confirmed in the axial load-strain responses of the specimens with 3-ply FRP
391 wrap after their softening stage, which is demonstrated by the fact that the bearing capacities of the

392 specimens even exceeded their first peak loads in some cases. This indicates that the CFRP wrap can
 393 work with steel tube together to provide an effective confinement to concrete core, where the steel
 394 tube can effectively prevent the local and sharp damage of FRP wrap while the FRP can confine the
 395 steel tube at large hoop deformations.



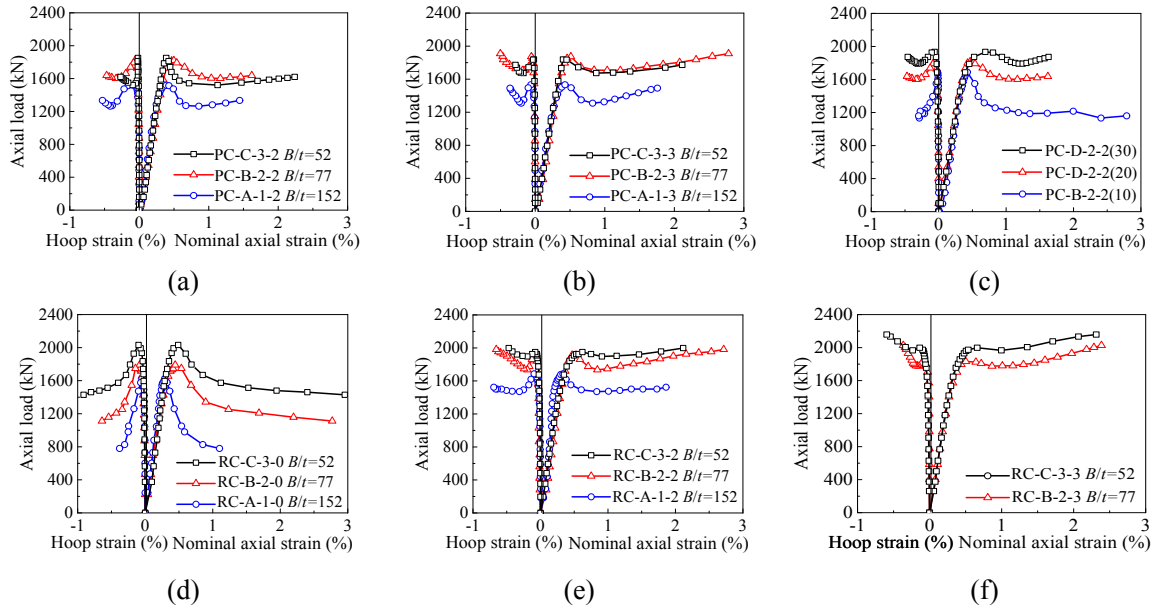
396 **Fig. 11.** Effect of the number of CFRP layers.

397
 398 For the CFRP-steel tube confined RC specimens, the elastic behaviour and first peak load of the
 399 specimens are not significantly affected by the number of CFRP layers. The first peak loads were
 400 slightly larger than those of steel tube confined specimens. After first peak load, the axial load-strain
 401 curves of the CFRP-steel tube confined RC specimens continued to rise until the rupture of CFRP
 402 wrap. The ultimate bearing capacities of the CFRP-steel tube confined RC specimens with 3-ply FRP
 403 wrap corresponding to the rupture of FRP wrap were larger than their first peak loads. This means that
 404 with the increase of the number of CFRP layers, the co-confinement effectiveness of CFRP-steel tube
 405 to the square concrete core is significantly enhanced.

406 (2) Effect of the width-to-thickness (B/t) ratio of steel tubes

407 As shown in Fig. 12, the specimens with higher B/t ratio present smaller bearing capacities.
 408 Compared to the load capacity of the specimens using a B/t ratio of 152.0, the first peak loads of both
 409 the specimens with B/t ratios of 52.0 and 77.0 were higher. This means that the B/t ratio of the steel
 410 tube has a significant influence on the bearing capacity of the CFRP-steel tube confined concrete
 411 specimens. This is similar to the cases of the steel tube confined concrete elements. Besides, the

412 smaller the B/t ratio was, the higher the load carrying capacity and ductility of the stub columns were.
 413 A similar result was found in the CFRP-steel tube confined RC specimens, but it seems that the B/t
 414 ratio has a slightly stronger influence on the first peak loads and on the ductility of the specimens.



415 **Fig. 12.** Effect of width-to-thickness on axial load-strain curves at different FRP layers.

416

417 (3) Effect of corner radius at sectional corners

418 The effects of three levels of the corner radius of steel tube were experimentally study, i.e., 10 mm,
 419 20 mm and 30 mm, respectively, as shown in Fig. 11 (c). The results show that the ultimate load of the
 420 specimens increases significantly with the increase of the corner radius. The softening behaviour of
 421 the curves after the first peak load was significantly reduced and slowed down as the radius increases.
 422 This presents the potential to improve the mechanical properties of square sectional confined plain
 423 concrete or RC columns by properly increasing the corner radius of column section. This is explained
 424 by the fact that more concrete core can be effectively confined in the columns, which is illustrated
 425 later in the study.

426

427 **4. Discussion on confinement mechanism**

428 **4.1 Effective confinement of steel tube and FRP in confined square section**

429 With reference to the cases in traditional square stirrup confined concrete, the effective

430 confinement mechanism of either steel tube confined concrete or FRP-steel tube confined concrete is
 431 presented in Fig. 13. In these sections, only the concrete in the area enclosed by four parabola lines
 432 with initial tangent lines 45° from the corresponding sides of the section (see Fig. 13 (a)) can be
 433 effectively confined. This is a significant difference compared to the cases in circular confined- plain
 434 concrete or RC. Pham and Hadi [38] proposed a confinement mechanism of the concrete in confined
 435 square columns, which is shown in Figs. 13 (b) and (c). The confining stress at the corners is much
 436 larger than that at the four sides since the curvature radius of sectional sides is much greater than that
 437 of the corners. The confining stress f_r at the corners is given as

$$438 \quad f_r = \frac{\sigma_{h,j}}{R} \quad (2)$$

439 where $\sigma_{h,j}$ is the hoop stress of a confining jacket at the corners; R is the corner radius.

440 According to Section 3.3, the confining stress provided by the steel tube $f_{r,s}$ is expressed as

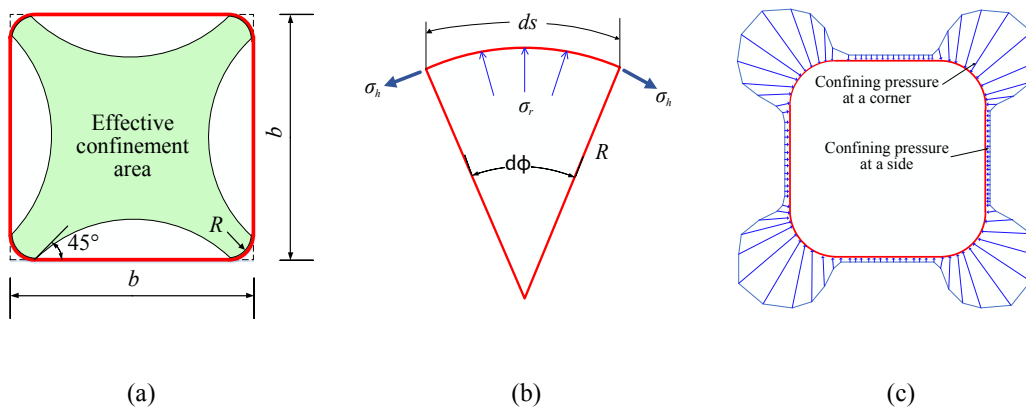
$$441 \quad f_{r,s} = \frac{\sigma_h}{R} \quad (3)$$

442 where σ_h is the hoop stress of steel tube at the corners.

443 Therefore, according to Fig. 13 (c), the confining stress of FRP wrap $f_{r,frp}$ is given as

$$444 \quad f_{r,frp} = \frac{\sigma_{h,frp}}{R+t} = \frac{E_{frp}\varepsilon_{f,c}t_{frp}}{R+t} \quad (4)$$

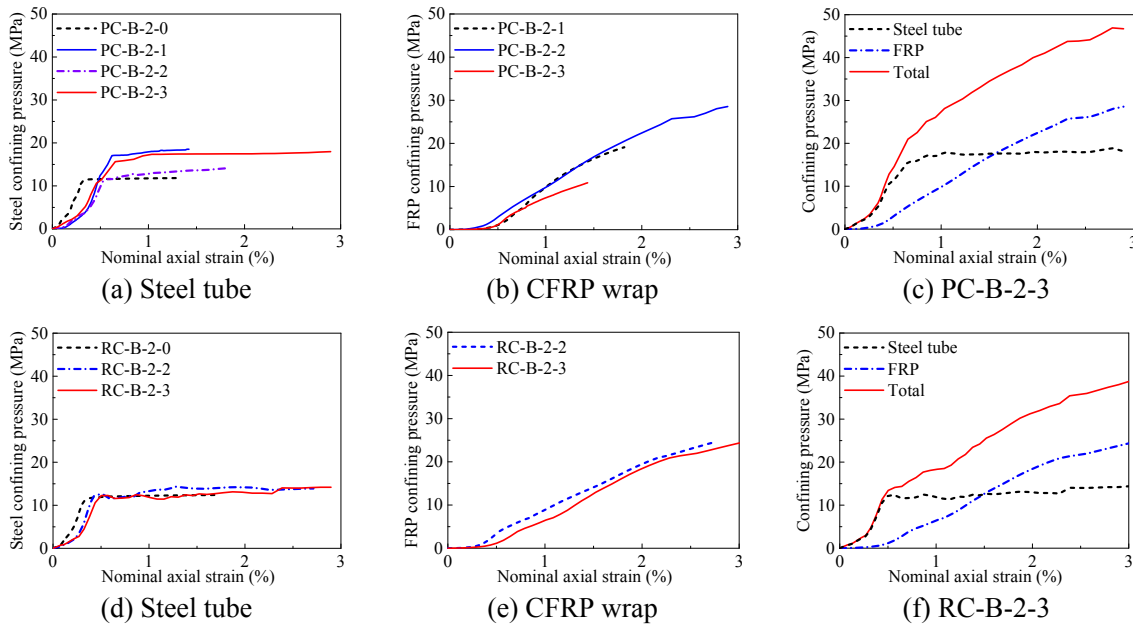
445 where $\sigma_{h,frp}$ and $\varepsilon_{f,c}$ are the hoop stress and hoop strain of the FRP wrap at corners, respectively;
 446 E_{frp} and t_{frp} are the Young's modulus and thickness of FRP wrap, respectively.



447 **Fig. 13.** The confinement of square confined concretes: (a) effective confining area of confined concrete;
 448 (b) stress distribution; and (c) confinement mechanism of FRP confined concrete [38].

449

450 Fig. 14 shows the evolution of the confining pressure of the steel tube and the CFRP wrap in the
451 specimens, as well as the total confining pressure with the increasing nominal axial strain of the stub
452 columns. Results show that the confining pressure of the steel tube increases rapidly at the initial stage
453 of loading, and then increases slowly or almost remains constant during the later period. This indicates
454 that the confining pressure of steel tube to the concrete core is limited after the yielding of the steel
455 tube. On the other hand, the confining pressure provided by CFRP wrap was not high at the initial
456 loading. Due to the increase of the lateral deformation of the steel tube, the FRP wrap started to
457 provide a higher confining stress, for example, from an axial strain of 0.004 to 0.006. After that, the
458 confining pressure of the CFRP wrap increased until the rupture of the FRP wrap. No obvious
459 difference was found between the CFRP-steel tube confined plain concrete and RC specimens.



460 **Fig. 14.** Confining pressure provided by the steel tube and the CFRP wrap.

461

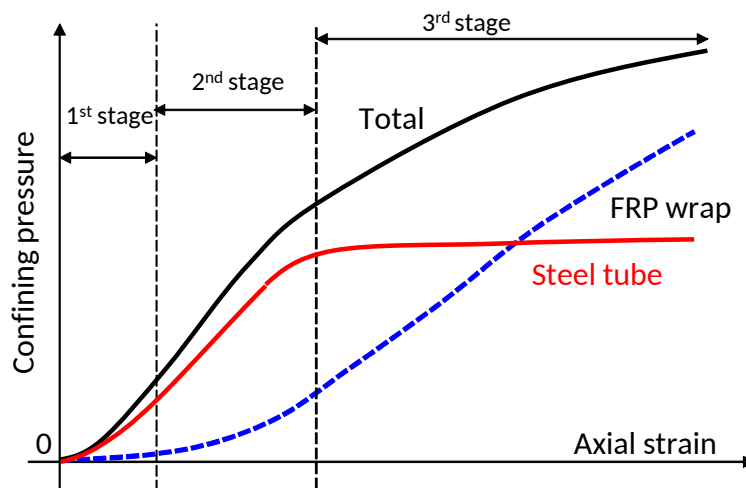
462 4.2 Confinement mechanism of square FRP-steel tube confined concrete/reinforced concrete

463 Based on the above analysis, Fig. 15 shows an ideal evolution of various confining pressures in
464 FRP-steel tube confined plain concrete and RC columns, which explains the confinement mechanism
465 of the composite tube to concrete core. The evolution of the confining pressure provided by steel tube
466 and FRP wrap in the composite columns is similar to that observed in FRP-confined CFT specimens
467 reported by Hu *et al.* [1]. However, the confinement mechanism of the specimens still is different from
468 that in FRP-confined CFT specimens for the steel tube does not directly carry the axial load.

469 According to Fig. 15, the confinement actions in FRP-steel tube confined plain concrete and RC
470 columns can be divided into three stages as follows,

471 (1) 1st stage – steel tube confinement stage

472 In this stage, the confining pressure of the concrete core comes mostly from the confinement of
473 steel tube, while the confinement from FRP wrap can be nearly neglected. This is because the test
474 specimens are only subjected to a small axial compression load, resulting in a very small lateral
475 expansion in the concrete core at this stage. There are few obvious differences between the confined
476 plain concrete and the confined RC columns as the stirrups were limited and only to erect the
477 longitudinal reinforcements in the study. Therefore, it is believed that the stirrups only provide a quite
478 small confinement to the concrete core. The small lateral deformation induced by a small axial strain
479 in the concrete core does not need the confinement action of FRP wrap. Therefore, if the potential
480 deformation of the confined plain concrete or RC columns remains at this level, the additional FRP
481 confinement is not necessary from the point of view of the mechanical performance of the elements.



482

483 **Fig. 15.** Ideal confinement in FRP-steel tube confined concrete columns.

484

485 (2) 2nd stage – FRP-steel tube co-confinement stage

486 The second stage can be considered as a co-confinement stage consisting of both the confining
487 pressures from steel tube and FRP wrap. However, as shown in Fig. 15, the two types of confining
488 pressures increase at different rates depending primarily on their hoop stiffness. This stage is similar to
489 the case in FRP-confined CFT columns [1]. The total confining pressure increases rapidly in this stage,
490 as the lateral deformation of concrete core starts to rapidly increase. Based on the experimental
491 investigation in the present study, the second stage can be delimited to a nominal axial strain of around

492 0.006. The FRP and steel tube work together in this stage and delay their respective fracture or local
493 buckling due to the contribution of each partner.

494 (3) 3rd stage – FRP-dominated confinement increasing stage

495 The third stage of the confinement of FRP-steel tube confined concrete is dominated by FRP
496 confinement. In this stage, the increasing total confining pressure to inner concrete comes mainly from
497 the increasing confinement of FRP wrap, as the confinement of the steel tube keep almost a constant
498 level after its yielding. The high strength feature of FRP materials becomes apparent at this stage. At
499 the same time, the behaviour of the FRP material itself still is highly elastic, and the confining
500 pressure of the FRP wrap can keep a similar increasing rate to that of the second stage. Therefore, at
501 this stage, the increasing rate of the total confining pressure of onfined concrete or RC columns at this
502 stage becomes smaller than that of the second stage, which is similar to the previous research results of
503 FRP-confined CFT columns [1].

504 **5. Proposal for predicating axial bearing capacity of composite square stub columns**

505 Referring to previous research [39, 40], the superposition principle was used to predict the axial
506 bearing capacity of CFRP-steel tube confined plain concrete or RC stub columns (N_u), which is given
507 as

$$508 \quad N_u = f_{CFS}A_c + f_a A_a \quad (5)$$

509 where A_c and A_a are the cross-sectional areas of concrete core and longitudinal reinforcement,
510 respectively; f_a is the yield strength of longitudinal reinforcement; and f_{CFS} is the compressive
511 strength of CFRP-steel tube confined concrete.

512 Based on the test results reported in this paper, a superposition calculation method is applied to
513 predict the axial bearing capacity of CFRP-steel tube confined plain concrete or RC stub columns,
514 consisting of the contribution of steel tube and FRP wrap. The discussion on the steel tube, FRP and
515 FRP-steel tube confined concrete is presented in the following sections.

516 **(1) For steel tube confined concrete**

517 According to the literature, the calculation model for steel stirrup-confined concrete strength f_{cc}
518 proposed by Mander et al. [41] is given as

$$519 \quad f_{cc} = f_{co} \left(1 + 2.254 \sqrt{1 + \frac{7.94f_r}{f_{co}}} - 2\frac{f_r}{f_{co}} - 2.254 \right) \quad (6)$$

520 where f_{co} is the compressive strength of unconfined concrete, and f_r is the confining pressure provided
521 by steel stirrups.

522 Referring to this model, the ultimate compressive strength of steel tube confined concrete (f_{CS}) is
 523 given as

$$524 \quad f_{CS} = f_{co} \left(1 + 2.254 \sqrt{1 + \frac{7.94 f_{r,s}}{f_{co}}} - 2 \frac{f_{r,s}}{f_{co}} - 2.254 \right) \quad (7)$$

525 where $f_{r,s}$ is the confining pressure provided by steel tube calculated based on a static equilibrium,
 526 which is given as

$$527 \quad f_{r,s} = \frac{2\sigma_h t}{B - 2t} \quad (8)$$

$$528 \quad \sigma_h = \beta f_y \quad (9)$$

529 where σ_h is the hoop stress of the steel tube corresponding to the peak load of confined concrete
 530 columns; B and t are the width and thickness of square steel tube, respectively; β is a reduction factor
 531 related to the yielding strength of steel f_y . Previous studies [39, 40] proposed a similar prediction
 532 model and suggested the factor β , which is influenced by the width-thickness ratio of steel tube
 533 ranging from 50 to 100. However, based on the test results in this study, an average value of 0.62 was
 534 taken for the simplification of the calculations.

535 (2) For FRP-confined concrete

536 Based on the model proposed by Lam and Teng [42], the ultimate strength of square FRP-confined
 537 concrete (f_{CF}) is suggested as

$$538 \quad f_{CF} = f_{co} \left[1 + k_1 k_{s1} \left(\frac{f_{r,FRP}}{f_{co}} \right) \right] \quad (10)$$

539 In this equation, $f_{r,FRP}$ is the confining pressure provided by FRP wrap to an equivalent circular
 540 column [42], and the confinement effectiveness coefficient $k_1 = 3.3$, same as defined in Lam and Teng
 541 model [43] for uniformly confined concrete. Referring to Ref. [42], k_{s1} is defined as a shape factor
 542 calculated as

$$543 \quad k_{s1} = 1 - \frac{2 (B_0 - 2R)^2}{3B_0^2 - (4 - \pi)R^2} \quad (11)$$

544 where R is the corner radius of inner concrete. Referring to the literature [38, 44], the confinement
 545 effectiveness is reduced at the corner of concrete [45]. Therefore, the confining pressure of FRP to
 546 concrete ($f_{r,FRP}$) is expressed as

547
$$f_{r,FRP} = \frac{n t_{frp} k_c k_r E_{frp} \varepsilon_{h,rup}}{D} \quad (12)$$

548 where n is the number of layers of FRP wrap; D is an equivalent diameter which is taken as $\sqrt{2}B_0$ in
 549 this paper; t_{frp} is the thickness of FRP wrap; E_{frp} and $\varepsilon_{h,rup}$ are the elastic modulus and the hoop
 550 rupture strain of FRP wrap. Referring to the method introduced by Hadi et al. [44], a corner-effect
 551 coefficient k_c was introduced to reduce the stronger confining stress at the corner. The factor was
 552 defined as the ratio of the sum of the corner length to the sectional perimeter and given as

553
$$k_c = \frac{\pi R}{2B_0 - (4 - \pi)R} \quad (13)$$

554 Besides, to consider the effect of the large curvature of the corners on FRP wrap leading to a stress
 555 concentration of the FRP wrap, the reduction factor k_r is introduced. Based on the literature [45], the
 556 factor is taken as

557
$$k_r = \left(1 - 0.2121 \times \frac{\sqrt{2}}{2}\right) \frac{2R}{B_0} + 0.2121 \times \frac{\sqrt{2}}{2} \quad (14)$$

558 The FRP efficiency factor (k_ε) is defined as the ratio of recorded hoop rupture strain of FRP ($\varepsilon_{h,rup}$)
 559 to the ultimate tensile strain of FRP obtained from flat coupon tests (ε_{frp}), which is shown in Eq. (15)
 560 and taken as 0.33 based on the test results of the study.

561
$$k_\varepsilon = \varepsilon_{h,rup} / \varepsilon_{frp} \quad (15)$$

562 **(3) For FRP-steel tube confined concrete**

563 The steel tube confinement is generally regarded as an active confinement because the confining
 564 pressure provided by steel tube almost remains constant after the yielding of steel tube. On contrast,
 565 the FRP confinement is generally considered as a passive confinement because the confining pressure
 566 provided by FRP wrap increases continuously with the lateral dilation of concrete. Therefore, the FRP-
 567 steel composite confinement might be a confinement type between active confinement and passive
 568 confinement. Theoretically, the steel tube-FRP composite confinement in the study can be regarded as
 569 one integral confinement since the two confining materials are well bonded based on the tests in the
 570 study. However, up to now the theoretical model of FRP-steel composite confined concrete is not
 571 researched well. In the present study, a simplified superposition calculation method was used based on
 572 the understanding of steel-confined concrete and FRP-confined concrete. As a start, the simplified
 573 method is relatively rough but easier to be understood by structural engineers.

574 Based on the superposition principle, the ultimate strength of square FRP-steel tube confined

575 concretes can be calculated as a total strength consisting of the contribution components of FRP wrap
 576 and steel tube, which is given as

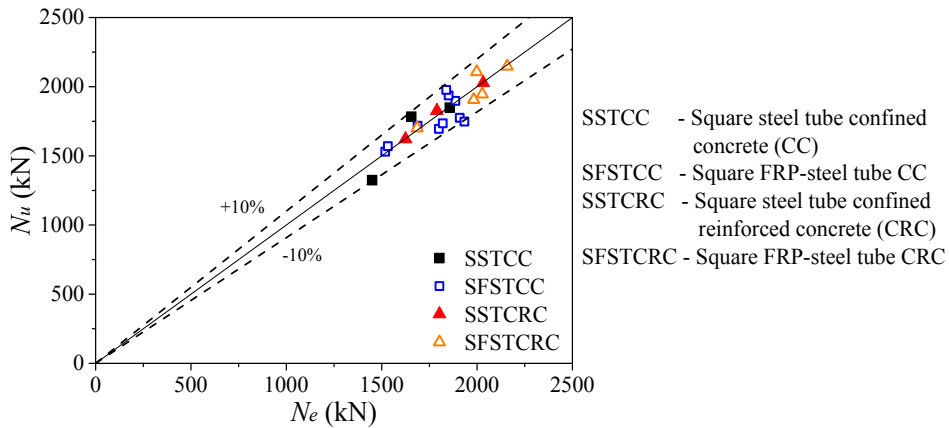
$$577 \quad f_{CFS} = f_{co} \left[1 + \left(2.254 \sqrt{1 + \frac{7.94f_{r,s}}{f_{co}}} - 2\frac{f_{r,s}}{f_{co}} - 2.254 \right) + k_1 k_{s1} \left(\frac{f_{r,FRP}}{f_{co}} \right) \right] \quad (16)$$

578 Taking Eqs. (7) and (16) into Eq. (5), the axial bearing capacities of steel tube confined concrete
 579 stub columns and FRP-steel tube confined concrete stub columns are expressed as

$$580 \quad N_u = \begin{cases} f_{co} \left(1 + 2.254 \sqrt{1 + \frac{7.94f_{r,s}}{f_{co}}} - 2\frac{f_{r,s}}{f_{co}} - 2.254 \right) A_c + f_a A_a \\ f_{co} \left[1 + \left(2.254 \sqrt{1 + \frac{7.94f_{r,s}}{f_{co}}} - 2\frac{f_{r,s}}{f_{co}} - 2.254 \right) + k_1 k_{s1} \left(\frac{f_{r,FRP}}{f_{co}} \right) \right] A_c + f_a A_a \end{cases} \quad (17)$$

581 Fig. 16 compares the prediction results of proposed model with the experimental results in this
 582 study. Regardless of the confinement types, the proposed model evaluates the ultimate bearing
 583 capacities of these confined plain concrete and RC columns with a great agreement.

584



585

586 **Fig. 16.** Comparisons between calculated and experimental results.

587

588 In addition to the axial bearing capacity, ultimate axial strain of composite stub columns is a very
 589 important parameter. For square STCC specimens, as shown in Table 3, the strain capacity increases
 590 with the thickness of steel tube because a thicker steel tube usually can provide a larger confinement to
 591 concrete core. Moreover, the installation of longitudinal reinforcements also can improve strain
 592 capacity. For square FRP-STCC specimens, the strain capacity generally increases with the thickness
 593 of steel tube, the number of layers of FRP wrap and the installation of longitudinal reinforcements.
 594 Therefore, the confinements from steel tube and FRP wrap as well as the advantageous effects of
 595 longitudinal reinforcement should be considered when predicting the strain capacities of square STCC
 596 stub columns and square FRP-STCC columns, which is expected to be studied in the future.

597

598 **6. Concluding remarks**

599 This paper presented an experimental study to understand the monotonic axial compressive behaviour
600 and confinement mechanism of square CFRP-steel tube confined concretes. The confinement from
601 steel tube and CFRP wrap enhances the ultimate strength and ductility of core concrete. CFRP
602 wrapping effectively constrains the deformation of steel tube, which delays its outward local buckling
603 and constrains the continuous dilation of core concrete at the stage of large deformation. Based on this
604 study, the following conclusions can be drawn:

605 1. The CFRP-steel tube confinement is highly effective in improving the bearing capacity and ductility
606 of concrete columns, especially for plain concrete. The number of layers of CFRP wrap has a
607 significant effect on the failure of the confined reinforced concrete columns. The width-to-thickness
608 ratio of the steel tube is also a key factor affecting the axial bearing capacity of confined concrete
609 columns.

610 2. The post-peak softening phenomenon of square confined concretes was observed in the specimens.
611 However, the softening degree of the columns was improved by using a thicker CFRP wrap. The
612 effect of the CFRP wrap is more pronounced for the CFRP-steel tube confined concrete columns with
613 a larger width-to-thickness ratio of steel tube.

614 3. Through a detailed stress analysis, the stress-strain curves of the concrete core confined by
615 composite action of steel tube and CFRP wrap were provided. The mechanical properties of the
616 concrete core was greatly improved by the composite confinement. The study explained the
617 confinement mechanism of the steel tube and the FRP wrap in confined plain or reinforced concrete
618 columns, and the role of steel tube and CFRP wrap in each load stage, which provides a basis for the
619 establishment of a calculation model of the bearing capacity for the columns. The three stages of the
620 confinement mechanism include a steel tube confinement stage which is similar to steel tube confined
621 concrete, and a CFRP-steel tube co-confinement stage in which the total confinement pressure
622 increases rapidly due to the effective co-confinement from steel tube and CFRP wrap, and a FRP-
623 dominated confinement increasing stage when FRP wrap keeps an effective confinement to steel tube
624 and concrete core to resist axial compressive load.

625 4. Based on previous studies and discussion on the strength models for confined concrete, through a
626 superposition principle considering the confinement of steel tube and CFRP wrap, this paper proposed
627 a simplified calculation model to predict the axial bearing capacity of CFRP-steel tube confined plain
628 concrete and reinforced concrete stub columns. Comparing with test results, the accuracy and

629 reliability of proposed model was confirmed.

630 Compared with CFRP, GFRP wrap may be more suitable to work together with the steel tube than
631 CFRP in FRP-STCC elements, because of GFRP materials' low cost, greater fracture strain. The
632 potential galvanic corrosion issues also will be eliminated. In the future, the axial compressive
633 behaviour of GFRP-STCC elements will be investigated.

634

635 Acknowledgements

636 The authors of the paper appreciate the support from the National Key R&D Program of China (No.
637 2017YFC0703000), the National Natural Science Foundation of China (Nos. 51778102 and
638 51978126), the Fundamental Research Funds for the Central Universities (No. DUT18LK35), and the
639 Natural Science Foundation of Liaoning Province of China (No. 20180550763).

640

641

642 Notation

643	A_a	cross-sectional area of longitudinal reinforcement
644	A_c	cross-sectional area of concrete core
645	A_s	cross-sectional areas of steel tube
646	B	width of steel tube
647	B_0	width of concrete core
648	D	equivalent diameter
649	E_{frp}	elastic modulus of FRP
650	E_s	elastic modulus of steel
651	E_s^t	tangent modulus steel in the elastoplastic stage
652	H	height of the specimen
653	f_a	yield strength of longitudinal reinforcement
654	f_y	yield strength of steel tube
655	f_p	proportional limit of steel tube
656	f_{co}	compressive strength of unconfined concrete
657	f_r	confining pressure
658	$f_{r,s}$	confining pressure provided by steel tube
659	$f_{r,FRP}$	confining pressure provided by FRP wrap
660	f_{CF}	compressive strength of FRP-confined concrete
661	f_{CS}	compressive strength of steel tube confined concrete
662	f_{CFS}	compressive strength of FRP-steel tube confined concrete
663	f_{cc1}	first peak stress of confined concrete
664	f_{cc2}	ultimate stress of confined concrete corresponding to the rupture of FRP wrap
665	G	shear modulus of the steel
666	k_1	confinement effectiveness coefficient
667	k_{s1}	shape factor
668	k_c	corner-effect coefficient

669	k_r	reduction factor considering stress concentration at corner
670	k_ε	FRP efficiency factor
671	n	the number of FRP layer
672	N	axial load resisted by the composite column
673	N_u	axial bearing capacity of the composite column
674	R	corner radius
675	t	thickness of steel tube
676	t_{frp}	thickness of FRP wrap
677	β	reduction factor
678	μ_s	Poisson's ratio of steel in the elastic stage
679	μ_{sp}	Poisson's ratio of steel in the elastoplastic stage
680	σ_h	hoop stress of steel tube
681	σ_v	axial stress of steel tube
682	σ_c	axial stress of confined concrete
683	$\sigma_{h,j}$	hoop stress of a confining jacket
684	σ_z	equivalent stress of steel tube
685	ε_p	equivalent strain of steel tube corresponding to f_p
686	ε_y	equivalent strain of steel tube corresponding to f_y
687	ε_h	hoop strain of steel tube
688	ε_v	axial strain of steel tube
689	ε_{frp}	ultimate tensile strain of FRP coupon
690	$\varepsilon_{h,rupt}$	hoop rupture strain of FRP wrap
691	ε_{cc1}	nominal axial strain of confined concrete corresponding to f_{cc1}
692	ε_{cc2}	nominal axial strain of confined concrete corresponding to f_{cc2}
693		

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Declaration of Competing Interest

We declare that we do not have any commercial or associative interest that represents a conflict of interest in connection with the work submitted.

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Yanlei Wang: Conceptualization, Funding acquisition, Supervision, Writing - original draft, Writing - review & editing. **Gaochuang Cai:** Conceptualization, Supervision, Writing - original draft, Writing - review & editing. **Amir Si Larbi:** Methodology, Writing - review & editing. **Danièle Waldmann:** Methodology, Validation, Writing - review & editing. **Konstantinos Daniel Tsavdaridis:** Methodology, Validation, Writing - review & editing. **Jianghua Ran:** Data curation, Investigation, Methodology, Validation.