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Behaviour of circular SSC-FST beams and columns subjected to short-term static loading

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Abstract: The research presented in this paper is aimed to assess both flexural and axial compressive behaviour of circular steel slag concrete-filled steel tube (SSC-FST) members subjected to short-term static loading. The tests of circular SSC-FST beams and columns were first performed with different replacement ratio of steel slag aggregate (SSA) and slenderness ratio, followed by finite element (FE) modelling to replicate the behaviour of circular SSC-FST beams as well as columns with various slenderness ratio. The results indicate that, both beam and column specimens show good deformability and load-carrying capability, and three phases are observed in the measured moment (load) vs. deformation diagrams. At the end of tests, several symmetrically distributed mild local bulges of steel tube and tiny tensile cracks together with inconspicuous compressive crushing of concrete core were observed for the beam specimens, while one major and a few minor tube local bulges and severe compressive crushing of concrete core for the column specimens were observed. In general, the SSC-FST specimens possess a superior capacity and ductility as well as a lower flexural stiffness than the reference CFST specimens, and the axial compressive capacity and ductility of SSC-FST column specimens show a decreasing trend when λ increases. In the end, simplified formulae to compute the flexural capacity and axial compressive capacity of circular SSC-FST members were proposed.

Keywords: Circular steel slag concrete-filled steel tube (SSC-FST); Beams; Columns; Finite element (FE) modelling; Capacity; simplified formulae.

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1. Introduction

Steel slag is one of the largest solid wastes generated in iron and steel industry, and its main components include SiO_2 , Al_2O_3 , MnO , CaO and a small amount of metal oxides such as Cr_2O_3 , TiO_2 , among others [1, 2]. At present, the disposal of steel slag in China is about 15% of crude steel production, and the utilization rate is only less than 40% [3, 4], which leads to land occupation and environmental pollution due to the accumulation of steel slag wastes, and that in Japan, America and Europe countries has reached more than 85% [4]. In China, it is an impressing problem to enable efficient regeneration and recycling of steel slag, and it is a good solution to use steel slag as concrete aggregates or admixture. Using steel slag in concrete production can not only efficiently consume a great deal of accumulated waste to facilitate its resource utilization, but also alleviate the increasing shortage of natural material supply to a large extent, so as to achieve green and sustainable development of building materials industry [1-8].

To produce steel slag concrete (SSC), [part or all](#) of natural aggregates or cement in normal concrete (NC) can be replaced by steel slag particles or steel slag powder, respectively [2]. Compared with NC, the introduction of steel slag [particles or powder](#) can enhance the properties of SSC, reduce the engineering cost, and relieve the environmental pollution owing to stacking of wastes [3, 4]. However, the free oxides in the steel slag [particles or powder](#) have a poor soundness and are transformed into swelling substance when meeting water, which may cause excessive internal stress during cement hydration, resulting in the volume instability and easy cracking of SSC that endanger the safety of structures [3]. In view of the above defects, the researchers, e.g. Yu et al. [9], propose to pour SSC into steel tube, that is, to form steel slag concrete-filled steel tube (SSC-FST). [Similarly with](#) conventional concrete-filled steel tube (CFST) [10], the SSC-FST also has superior mechanical properties through the interaction between steel tube and its core SSC, that is, the behaviour of the latter is improved by limiting its deformation from the confinement of the former, and simultaneously the local buckling of the former is avoided or delayed due to the presence of the latter [9, 11, 12].

Nowadays, the researches on the behaviour of SSC-FST members are still inadequate, and existing

attempts mainly cover the tests of interfacial bonding property and bond strength prediction method [13, 14], the tests, numerical simulation and bearing capacity calculation of axially compressed stub and slender columns [9, 11, 12, 15-18], the tests and finite element (FE) modelling on flexural performance of beams [16], the tests of beam-columns under constant axial compression and lateral cyclic loading [19, 20], and the tests of stub and intermediate columns after exposure to elevated temperatures [21]. In the available specimen tests, the steel slag aggregate (SSA) was used to individually substitute one kind of natural aggregate [9, 11, 12, 15-18, 20, 21] or replace both coarse and fine aggregate in the production of the filled SSC [9, 13, 14, 16, 17], and the steel slag powder was also used as an admixture [19]. The above experimental results indicated that, the deformation development during loading process and eventual failure patterns of the SSC-FST specimens were similar to those of the conventional CFST specimens, and the former had comparable bond strength, stiffness, bearing capacity, ductility and energy dissipation capability to the latter. Additionally, the potential volume instability of core SSC was generally eliminated by using the tubular sections, considering that the steel tube offered a reliable restraint. It should be pointed out that, the replacement ratio of steel slag particles and powder has a significant impact on the constitutive model of SSC [16]; however, in previous numerical simulation [9, 12, 13, 16-19] most researchers did not consider the above facts. Only our research group proposed a constitutive model for core SSC in the steel tube considering the effect of the replacement ratio of SSA, which had been successfully adopted in the FE simulation on static behaviour of SSC-FST short columns and beams [16, 17].

It is well known that, the SSC-FST structural members are often subjected to combined axial compression and bending moment in reality, and a prerequisite for design of SSC-FST members is to offer accurate simplified correlation curve of axial force (N) vs. bending moment (M), as schematically depicted in Fig. 1, in which M_u and N_u are flexural capacity and axial compressive capacity, respectively. This approach has been adopted by many design codes; however, none is available for this type of new structural members. To depict a complete $N - M$ correlation curve, it is necessary to first know its intersection points with two coordinate axes, namely, M_u and N_u .

84 However, existing studies only involve the limited tests of circular SSC-FST columns with varied
85 slenderness ratio while subjected to axial compression [15, 18] and square SSC-FST beams [16], and
86 there is a lack of systematic studies on the flexural performance and simplified flexural capacity of
87 circular SSC-FST beams, as well as axial compressive performance and simplified axial compressive
88 capacity of SSC-FST columns under varying slenderness ratio.

89 According to the above introduction, it is clear that the research on the practical method of
90 determining critical control points on $N - M$ correlation curve of SSC-FST members is rare. Thus,
91 this paper aims to study the static behaviour and design calculation method of circular SSC-FST
92 beams and axially compressed columns via standard tests and comprehensive FE modelling. In this
93 study, the effect of replacement ratio of SSA and slenderness ratio on the performance of circular
94 SSC-FST specimens was first studied experimentally. Moreover, FE models were built to replicate
95 the static responses of circular SSC-FST members. In the end, simplified formulae capable of well
96 predicting the capacity of circular SSC-FST beams and axially compressed columns were developed.

97 **2. Experimental investigation**

98 ***2.1. Fabrication of specimens***

99 Twelve circular specimens, including 5 simply supported beams and 7 columns with both ends
100 hinged, were designed and fabricated, and each type of specimens contained a reference one filled
101 with NC. The experimental parameters included replacement ratio of SSA (S_c/S_f) and slenderness
102 ratio (λ), and S_c and S_f equal to the percentage of coarse and fine SSA mass to that of total coarse
103 and fine aggregate mass, respectively, whilst λ of column specimens equals to $4L/D$, in which L
104 is the physical length of the specimen, and D is the outer diameter of the circular steel tube. The
105 specimen details are listed in Table 1, where t and f_y denote the wall thickness and yield strength
106 of the steel tube respectively, and f_{cu} is the compressive cube strength of the concrete, while in the
107 static loading tests of the composite specimens. In the labels, 'B' and 'C' stand for the beams and
108 columns, respectively, the two hyphenated numbers following the initial letter are associated with the

109 parts of S_c and S_f respectively, and the number in the brackets represents the slenderness ratio of
110 column specimens.

111 Each circular steel tube was fabricated by first rolling a steel sheet into a cylinder and then welding
112 its gap with a butt weld, and both ends of the finished tube were milled flat. For each specimen, two
113 identical square endplates with a side length of $(D+20)$ mm and a thickness of 16 mm were produced
114 in advance. Moreover, the column specimens were provided with four pairs of stiffeners to avoid
115 local damage at both ends. One endplate was first welded to tube end using fillet weld, and then the
116 concrete was poured into the vertically placed steel tube from upper open end. Two weeks later, the
117 upper end (including both steel tube and concrete core) of the specimens was grinded flat, and then
118 the welding of the other endplate to steel tube was performed. Finally, welding of the stiffeners to the
119 steel tube and endplate was performed for the column specimens.

120 Table 2 summarizes the measured properties of steel via standard tensile test of three plate coupons,
121 and all results are the average value of the indicators, where f_u , E_s , μ_s , δ are tensile strength, elastic
122 modulus, Poisson's ratio and elongation after fracture, respectively.

123 In this study, the steel slag employed was the main by-product of converter steelmaking and had
124 undergone aging for 2 years to eliminate the amount of harmful components (mainly free oxides) as
125 much as possible from the freshly produced steel slag, thereby improving the volume stability. After
126 manual screening, the steel slag particles with a size of 5~20 mm and 0.15~4.75 mm were prepared
127 to substitute natural coarse and fine aggregate, respectively. The measured grading, chemical
128 compositions and physical properties of the SSAs had been reported in the previous studies [16, 17].
129 Two groups of concrete (G-B and G-C) were prepared for filling the steel tubes of the specimens, and
130 each group contained a variety of SSC with varied S_c and/or S_f as well as a reference NC. To
131 guarantee full absorption of water and uniform mixing of all components, the SSC had 30 to 45 s
132 longer mixing time than the NC as the former had a higher water absorption rate. The concrete mixture
133 proportion is summarized in Table 3. Other materials used in the production of concrete included
134 ordinary Portland cement (P.O42.5), fly ash (Grade I), limestone rubble as natural coarse aggregate

(NCA), river sand as natural fine aggregate (NFA), tap water and water reducer (polycarboxylic acid superplasticizer). It should be noted that the manufacturer of the water reducer in the G-B concrete is different from that in the G-C concrete, and the water reducing efficiency of the water reducer in the G-B concrete is higher, thus resulting in a lower usage of the water reducer in the G-B concrete. The concrete properties, including main workability (i.e., slump and spread), cube compressive strength at 28 days ($f_{cu,28}$) and elastic modulus (E_c), are also presented in Table 3. It is shown that, the workability of two groups of SSC is generally similar to that of the reference NC [1], which is attributed to the reasonable mixing process and the addition of superplasticizer. However, the former has higher $f_{cu,28}$ and E_c than the latter considering that the mechanical properties of SSAs in the former are better than those of natural aggregates in the latter, as observed in previous studies of our research group [16, 17] and other groups [4, 5, 22, 23].

2.2. Test set-up, measurement and loading scheme

A four-point bending test set-up, as shown in Fig. 2(a), was designed to evaluate the flexural behaviour of circular SSC-FST beam specimens. The vertical concentrated forces in mid-span applied by a hydraulic jack were distributed equally between the two quarter points through a spreader beam, and a load cell between the jack and the spreader beam was used to record the force variation. In addition, to ensure that the forces were reliably transferred, and the deformation of the specimen occurred in the vertical plane, a total of four steel auxiliary force-transfer devices (AFD), two upright and two upside-down, were arranged at both supports and two quarter points, respectively. The bottom surface of the AFD was in contact with the roller, and the top surface of the AFD was connected with a half steel tube, namely, the inner diameter of the AFD was in harmony with the diameter of the specimen. The effective span (L_e , i.e. the distance between the supports on the reaction block) of all the beam specimens was equal to 1000 mm.

A column test set-up using a compression-testing machine, as depicted in Fig. 2(b), was designed to measure responses of circular SSC-FST column specimens with both ends hinged. To ensure that the deflection shape and boundary conditions of the column specimen meet the expectations, a knife

161 hinge (KH) fixed to the platen of testing machine and a loading plate (LP) with several V-grooves
162 fitted to the front of the KH were arranged at both ends of the column specimen. Simultaneously, to
163 achieve the centroid coaxial between the column specimen and the LP, a tenon with diameter of 20
164 mm and length of 10 mm was welded to the center of both endplates, and in the position
165 corresponding to the tenon a circular groove with diameter of 21 mm and depth of 13 mm was
166 machined on both loading plates.

167 The change in global displacements and localized strains of the specimens was traced continuously
168 until the end of the tests, as demonstrated in Fig. 2. For the beam specimens, five vertical displacement
169 transducers (DTs) and four pairs of strain gauges in mid-span section were installed. For the column
170 specimens, three horizontal DTs together with four vertical DTs on the lower platen, as well as four
171 pairs of strain gauges in mid-height section were arranged.

172 A loading scheme using both force and displacement control was employed in the tests. During the
173 force control phase, the force of each level was equal to 10% of the estimated capacity until the
174 applied force reached 90% of the estimated capacity and the levels were held for 2 to 3 minutes.
175 During the subsequent displacement control phase, the displacement recorded by the DT in mid-span
176 section of beam specimen or that in mid-height section of column specimen was equal to 5 mm at
177 each level and was also held for 2-3 min.

178 **2.3. Experimental results and analyses**

179 *2.3.1. Failure behaviours*

180 Experimental observation showed that, good load-carrying capability and deformability were attained
181 for all the composite specimens, and the eventual deflection shape was similar to a thick arc.
182 Simultaneously, the deformability of beam specimens was better than that of column specimens due
183 to the second-order effect in the latter, leading to a faster failure after reaching the capacity. Fig. 3(a1)
184 exhibits the global pattern of beam specimens after finishing the tests. The failure modes of all five
185 specimens with various types of concrete core are generally similar, that is, several mild local bulges
186 with symmetrical distribution relative to the mid-span section, pointed by the arrows, are formed on

187 the concave side of steel tube within the two quarter points. Fig. 3(b1) shows the global pattern of
188 column specimens after finishing the tests. Except for specimen C50-0(15), there are one major and
189 one or two minor local bulges on the concave side of steel tube, still indicated by the arrows, and the
190 major bulge does not always occur to the mid-height section; however, all the bulges appear within
191 the range of one half the length, i.e. they are asymmetrically distributed about the mid-length section.
192 These can be explained so that the failure of axially compressed column specimens always happens
193 at the section/area with a weaker bearing capacity caused by the random distribution in the material
194 defects and the geometric imperfections. In general, the failure modes of specimen C50-0(15) with
195 $\lambda=15$, including two local bulges along the circumference and certain oblique shear-slip steel tube,
196 are similar to those of the axially compressed circular SSC-FST stub specimens [17]. This may be
197 because the existing defects and initial imperfections are small enough to keep the specimen under a
198 more ideal concentric compression. Moreover, when λ is the same, the difference in the positions,
199 quantity and peak of the bulges for the specimens with different concrete core is produced, and the
200 specimens with coarse SSA and a larger λ value lead to a larger deflection due to their lower E_c
201 value and more serious second-order effect, respectively.

202 Failure modes of concrete core are indicated in Figs. 4(a1) and 4(b1). For the beam specimens, tiny
203 tensile cracks with depth of approx. $0.6D$ appear on the convex side of concrete core within two
204 quarter points, and inconspicuous compressive crushing occurs to the concave side of concrete core
205 at the positions with tube bulge. However, compared with the beam specimens, the column specimens
206 show obviously different failure modes of the concrete core, that is, severe compressive crushing
207 takes place at the positions with tube bulge on the concave side and no visible cracks appear on the
208 convex side except for specimen C50-0(35), which has the most severe compressive crushing at the
209 positions with the most remarkable tube bulge, as well as tiny tensile cracks with the depth of approx.
210 $0.3D$ on the opposite side of crushing positions, due to its more significant second-order effect. In
211 addition, a good integrity of concrete core is produced for all the specimens as the steel tube can
212 provide a reliable restraint throughout loading process.

2.3.2. Development of *loading and deformations*

Fig. 5 exhibits the diagrams of the measured bending moment (M) vs. mid-span displacement (u_{ms}) and it can be seen that M of all the specimens experiences a similar development as u_{ms} increases. There are three major phases noticed on the $M - u_{ms}$ diagrams: approx. elastic, elastic-plastic and plastic strengthening. In approx. elastic phase each specimen with SSC has similar $M - u_{ms}$ diagram as its counterpart with NC; however, in the subsequent two phases, the former generally has a better resistance to bending as its core SSC has a higher compressive strength. These performances are essentially consistent with those of square SSC-FST beam specimens [16]. Moreover, in the later stages of loading, the $M - u_{ms}$ diagrams fluctuate significantly, which may be caused by the sudden separation of steel tube and concrete core due to the tensile cracking of concrete core and the local bulge of steel tube at different positions.

For the column specimens, the load (N) vs. axial displacement (u_a) curves as well as the load (N) vs. lateral displacement in mid-height section (u_{mh}) curves are shown in Figs. 6(a) and 6(b), respectively. It can be observed that, the $N - u_a(u_{mh})$ curves generally include approx. elastic, elastic-plastic and post-peak descending stage; however, both the $N - u_a$ and $N - u_{mh}$ curve of specimen C50-0(15) demonstrate a trend of decreasing first after the peak and then rising slowly, considering that axial shortening becomes the primary mode of deformation as its damage process and failure modes [see Fig. 3(b1)] are similar to a stub column under uniform axial compression [17], and in post-peak stage the local contact between bulged steel tube and stiffeners may be the reason for the increase of load-carrying capacity. When $\lambda=25$, the slope of $N - u_a(u_{mh})$ curve of specimen with coarse SSA is close to that of specimen with natural aggregates and higher than that of specimen with fine SSA; however, in the post-peak stage, with the increase of u_a and u_{mh} , the decline rate of load in specimen C0-50(25) is the fastest, while that of specimen C0-0(25) is the slowest, meaning that the interfacial properties between SSAs and hydration products are weaker than those between natural aggregates and hydration products. Furthermore, for the column specimens with SSA, the larger the λ value, the smaller the slope before the peak, the larger the displacement

239 of the peak and the slower the dropping of load after the peak, which are generally observed in
240 previous studies on various composite columns [18, 24, 25].

241 The measured distribution of displacements (solid lines) along the length of typical circular SSC-
242 FST specimens together with the corresponding half-sine wave curves (dashed lines) having the same
243 displacement in half-length section are shown in Fig. 7, in which, for the beam specimens, x is
244 distance to fixed support, m ($=M/M_{ue}$) is the bending level, M_{ue} is the flexural capacity defined
245 later, and u_s stands for the displacements at the measuring points; while for the column specimens,
246 y is the distance from the bottom endplate, n ($=N/N_{ue}$) denotes the level of the axial load and N_{ue}
247 is the axial compressive capacity (presented in Table 4), defined as the peak load on the $N - u_a(u_{mh})$
248 curves, and u_h denotes the lateral displacements at the measuring points. Until achieving the
249 capacity, the measured distribution of displacements and the half-sine wave curve have good
250 consistency; however, after reaching the capacity, the measurements deviate slightly from the half-
251 sine wave curve, exhibiting certain asymmetric characteristics. These may be caused by the random
252 distribution of material defects, the initial eccentricity of the loading device or the size deviation of
253 the specimens. Moreover, the curvature of mid-span section can be firstly obtained after confirming
254 that the measured distribution of displacements matches the half-sine wave curve, and then the
255 flexural stiffness (K_{ie}) of beam specimens can be determined by the moment-to-curvature ratio when
256 the moment reaches $0.2M_{ue}$ [16, 26], as listed in Table 4.

257 Fig. 8 displays the typical moment (M) vs. longitudinal strain (ε_L) curves in the mid-span section
258 of the beam specimens as well as load (N) vs. longitudinal strain (ε_L) curves in the mid-length section
259 of the column specimens. It can be observed from Fig. 8(a) that, ε_L on the convex side and the
260 concave side of beam specimens are always positive (in tension) and negative (in compression)
261 respectively, and under the same moment the absolute value of ε_L on the convex side is larger than
262 that on the concave side, considering that the neutral axis moves towards the concave side after
263 cracking of concrete core in tensile region, which is consistent with the result of similar tests [16, 26].
264 In general, the variation in the replacement ratio of SSA has no evident effect on the development of

265 $M - \varepsilon_L$ curves. Taking the suggestions in [16, 26] as reference, the flexural capacity (M_{ue}) of beam
 266 specimens is defined as the moment when ε_L on the convex side reaches 0.01, and the detailed
 267 results are also given in Table 4. As can be observed in Fig. 8(b), in approx. elastic stage, the
 268 compressive ε_L on the concave and convex side of column specimens is very close and generally
 269 increases linearly with the increase of load. In elastic-plastic stage, the compressive ε_L of both sides
 270 gradually ‘separates’, that is, with the increase of load, the growth rate of ε_L on the concave and
 271 convex side increases and decreases, respectively. After reaching N_{ue} , with the aggravation of the
 272 second-order effect of axial compression, the growth rate of compressive ε_L on the concave side
 273 further increases, while the ε_L on the convex side rapidly changes from compression to tension and
 274 gradually enlarges with the decrease of load. Overall, S_c and S_f have no obvious impact on the
 275 development of $N - \varepsilon_L$ curves, while λ has no coherent impact on the $N - \varepsilon_L$ curve before N_{ue}
 276 is achieved, and mainly has an obvious effect on the post-peak phase of $N - \varepsilon_L$ curve, namely, a
 277 larger λ leads to a smaller growth rate of ε_L as a more evident second-order effect is produced.
 278 Furthermore, the compressive ε_L on the concave side corresponding to N_{ue} decreases with the
 279 increase of λ , which means that the state of steel tube changes from the elastic-plastic one to elastic
 280 one.

281 The longitudinal strain (ε_L) vs. transverse strain (ε_T) relationships at the recorded positions is shown
 282 in Fig. 9. It is shown in Fig. 9(a) that, generally, there is little difference in the $\varepsilon_L - \varepsilon_T$ relationships
 283 of the beam specimens, i.e. in the initial phase the steel tube and concrete core independently bear the
 284 bending moment, and the $|\varepsilon_T/\varepsilon_L|$ value is very close to μ_s , and then on the concave side the
 285 transverse deformation of steel tube under longitudinal compression and transverse tension is
 286 subjected to the ‘outward movement’ effect caused by the volume expansion of the concrete, resulting
 287 in that the $|\varepsilon_T/\varepsilon_L|$ value quickly exceeds μ_s ; however, on the convex side the transverse
 288 deformation of steel tube under longitudinal tension and transverse compression is restricted by the
 289 ‘rigid’ concrete core, causing that the $|\varepsilon_T/\varepsilon_L|$ value is lower than μ_s . It can be observed from Fig.
 290 9(b1) that, the development of $\varepsilon_T/\varepsilon_L$ on the concave side of column specimens is similar to that of

291 beam specimens [Fig. 9(a)], and when $\lambda=25$ the $|\varepsilon_T/\varepsilon_L|$ value of column specimens with SSC is
 292 larger than that of their counterparts with NC, indicating that the core SSC produces a greater
 293 ‘outward movement’ effect. In addition, still on the concave side, the circular SSC-FST column
 294 specimens with a larger λ generally have a smaller $|\varepsilon_T/\varepsilon_L|$ value, and while λ is the same, the
 295 difference between the column specimen with coarse SSA and that with fine SSA cannot be clearly
 296 found as the transverse SGs were prematurely damaged in the tests. Simultaneously, Fig. 9(b2) shows
 297 that, in the initial phase the development of $\varepsilon_T/\varepsilon_L$ on the convex side is basically similar to that on
 298 the concave side, that is, the $|\varepsilon_T/\varepsilon_L|$ value is close to μ_s , then in the subsequent elastic-plastic phase
 299 the $|\varepsilon_T/\varepsilon_L|$ value on the convex side is closer to μ_s compared with that on the concave side, and in
 300 the post-peak phase, with the decrease of ε_L caused by the gradually increased second-order effect,
 301 the $|\varepsilon_T/\varepsilon_L|$ value is getting smaller and smaller than μ_s , producing a similar development as on the
 302 convex side of beam specimens [Fig. 9(a)]. Moreover, still on the convex side, there is no obvious
 303 difference in the development of $\varepsilon_T/\varepsilon_L$ for the column specimens with $\lambda=25$ and containing
 304 different concrete, and for the circular SSC-FST column specimens λ has no consistent effect on the
 305 development of $\varepsilon_T/\varepsilon_L$, which may be due to the deviation between the actual position of SGs and
 306 the designed consideration.

307 The experimental results indicated that, until achieving the capacity, the distribution of longitudinal
 308 strain (ε_L) along the diameter of half-length section of all the specimens generally conformed to the
 309 assumption of plane sections remaining plane, as typically depicted in Fig. 10, where z is the
 310 distance between the position of strain gauges and the outermost point of convex side. It is shown
 311 that, ε_L of three gauging points generally present a linear distribution; however, the three-point
 312 collinearity features of beam specimens are evidently better than those of column specimens, which
 313 may be due to the subtle fluctuation of larger compressive loads on the column specimens, causing
 314 that ε_L of the centroidal axis is deviated from the exact value. In addition, after the load ratio (m
 315 and n) is equal or greater than 0.6, there is obvious difference for the specimens with the same
 316 replacement ratio of SSA and different type of SSA. This may be caused by the discrepancy in the

sequence and progress of steel tube bulging as well as concrete core cracking.

2.3.3. Mechanical index

Table 4 summarizes the obtained mechanical indexes of the specimens. Fig. 11(a) exhibits the variation in M_{ue} and K_{ie} of the beam specimens. Based on Fig. 11(a) and values in Table 1, M_{ue} of SSC-FST specimens with coarse SSA is slightly lower or equal to that of the reference CFST specimen, and M_{ue} of SSC-FST specimens having 50% coarse SSA and 50% coarse and fine SSA is 4.2% and 4.8% higher than that of the counterpart CFST specimen respectively, meaning that replacing NFA by fine SSA is better for improving the flexural capacity of composite beams with SSC. Moreover, compared with the relevant CFST specimen, K_{ie} of all the SSC-FST specimens shows varying degrees of reduction, the specimen with 50% coarse SSA has the largest reduction of up to 8.4%, while the specimen with 50% coarse and fine SSA has the smallest reduction of up to 1.9%, which may be due to the weaker empty micropores within the SSC [27].

For the column specimens, the ductility factor (DF) is defined as $u_{mh,-0.85}/u_{mh,p}$ [17], where $u_{mh,-0.85}$ and $u_{mh,p}$ denote the lateral displacements on $N - u_{mh}$ curve when N in post-peak phase equals to $0.85N_{ue}$ and the capacity (N_{ue}) is reached, respectively. The calculation results of the DF are listed in Table 4. The variation in N_{ue} and DF of column specimens is displayed in Fig. 11(b), where DF of specimen C50-0(15) is not provided as its load does not drop to $0.85N_{ue}$ in the post-peak phase. According to Fig. 11(b) and values in Table 4, when $\lambda=25$, the SSC-FST specimens possess a larger N_{ue} than the relevant CFST specimen, and N_{ue} respectively increases by 27.9% and 0.1% when $S_f=50\%$ and $S_c=50\%$, considering that the two kinds of SSC have a higher f_{cu} than the reference NC. In addition, similar to the previous findings [18, 24], N_{ue} of SSC-FST specimens decreases when λ increases due to the intensification of the second-order effect of axial compression, and while $S_c(S_f)=50\%$ N_{ue} of the specimens having λ of 25 and 35 is 4.4% (4.3%) and 5.0% (12.6%) lower than that of the specimens with $\lambda=15$, respectively. It can also be observed from Fig. 11(b) that, in general, DF shows a decreasing trend with the increase of λ under the same S_c and S_f , as the load in post-peak phase drops rapidly under the augmented second-order effect, and

when $\lambda=25$, DF of circular SSC-FST column specimen with $S_f=50\%$ and $S_c=50\%$ is 51.8% and 32.2% higher than that of the relevant circular CFST column specimen, respectively, considering that the coarser surface of SSA retards the damage of the interface between aggregates and hydration products in the core SSC.

3. FE simulation

3.1. FE models

Numerical simulation on static behaviour of circular SSC-FST beams and columns was performed employing the FE package ABAQUS [28], and the available test results were used to validate the accuracy of the FE modelling.

The classical metal plasticity model [28] was selected to simulate the material of circular steel tube, and the results of μ_s and E_s in Table 2 were identified as elastic property. Moreover, to describe the plastic property of the circular steel tube, the data pairs of true stress and plastic strain respectively converted from engineering stress (σ_s) and engineering strain (ε_s) were input into the FE package. The $\sigma_s - \varepsilon_s$ relationship in [29] was adopted, as expressed in the following equations:

$$\sigma_s = \begin{cases} E_s \cdot \varepsilon_s & (\varepsilon_s \leq \varepsilon_e) \\ -c_0 \cdot \varepsilon_s^2 + c_1 \cdot \varepsilon_s + c_2 & (\varepsilon_e < \varepsilon_s \leq \varepsilon_y) \\ f_y & (\varepsilon_y < \varepsilon_s \leq \varepsilon_h) \\ f_y \cdot \left(1 + 0.6 \frac{\varepsilon_s - \varepsilon_h}{\varepsilon_u - \varepsilon_h}\right) & (\varepsilon_h < \varepsilon_s \leq \varepsilon_u) \\ 1.6f_y & (\varepsilon_s > \varepsilon_u) \end{cases} \quad (1)$$

where, $\varepsilon_e=0.8 f_y/E_s$, $\varepsilon_y=1.5\varepsilon_e$, $\varepsilon_h=10\varepsilon_y$, $\varepsilon_u=100\varepsilon_y$, $c_0 = 0.2 f_y/(\varepsilon_y - \varepsilon_e)^2$, $c_1 = 2c_0 \cdot \varepsilon_y$, and $c_2 = 0.8f_y + c_0 \cdot \varepsilon_e^2 - c_1 \cdot \varepsilon_e$.

To simplify the analysis and guarantee the convergence, the endplates and stiffeners (if any) on the specimens, which generally have limited influence on the performance of composite beams and columns, were modelled as elastic materials that will not easily deform, and their Poisson's ratio and elastic modulus were taken as 1.0×10^{-10} and 1.0×10^{10} N/mm², respectively.

The concrete damaged plasticity (CDP) model [28] was specified to capture the complicated feature of the filled SSC. The Poisson's ratio (μ_c) was set at 0.2 [30], and E_c was taken as

366 $4730\sqrt{f'_{SSC}}$ [31], f'_{SSC} is the compressive cylinder strength of SSC and it is transformed from the
 367 compressive cube strength in terms of stipulation in [32] when there is no measured result. The plastic
 368 parameters in CDP model were determined by referring to the previous data [16, 17], as detailed in
 369 Table 5, and the formula in [33] was chosen to obtain compressive damage factors. Additionally, the
 370 input compressive stress vs. inelastic strain relationship was converted from existing compressive
 371 stress (σ_c) vs. strain (ε_c) model of core SSC [16, 17], which had been certified to be good at modelling
 372 the performance of plain SSC and SSC-FST members, and the equations are as follows:

$$373 \quad y = \begin{cases} 2x - x^2 & (x \leq 1) \\ \frac{x}{k \cdot (x-1)^2 + x} & (x > 1) \end{cases} \quad (2)$$

374 where, $x = \varepsilon_c / \varepsilon_{cp}$, $y = \sigma_c / f'_{SSC}$, $\varepsilon_{cp} = (800\xi_s^{0.2} + 12.5f'_{SSC} + 1300) \times 10^{-6}$, $k = 1.25\sqrt{f'_{SSC}} \times$
 375 $(2.36 \times 10^{-5})^{[0.25 + (\xi_s - 0.5)^7]} \geq 0.12$, $\xi_s (= \alpha \cdot f_y / f_{ssck})$ is the confinement factor of SSC-FST,
 376 f_{ssck} is 67% of the compressive cube strength of SSC. The measured SSC strength should be used if
 377 experimental result is available; otherwise, the SSC strength can be acquired using the regression
 378 equations in [16, 17]. In addition, S_c or S_f is used in calculation when coarse SSA and fine SSA are
 379 individually adopted, and the average value of S_c and S_f is used in calculation when both coarse
 380 and fine SSA are adopted.

381 Based on the previous findings of our research group [16, 17], the plastic properties of core SSC
 382 in tension could be well replicated by the cracking criterion using fracture energy, and similarly the
 383 values of stress at cracking and fracture energy were $0.1f'_{SSC}$ and 100 N/m, respectively.

384 Circular steel tube was modelled by the 4-node reduced-integration shell elements (S4R), and there
 385 were 9 integral points along their thickness direction. The core SSC, two endplates and stiffeners (if
 386 any) were simulated by the 8-node reduced-integration three-dimensional continuum elements
 387 (C3D8R). The FE model of circular SSC-FST beams had three types of parts, including circular steel
 388 tube, core SSC and endplates, whilst the FE model of circular SSC-FST columns had one more type
 389 of parts (i.e. stiffeners) than that of circular SSC-FST beams. The structured meshing techniques were
 390 used for each type of parts in the FE model, and to ensure the accuracy, computational efficiency and

391 convergence of the simulation, the consistent meshing with element size of $D/12$ was considered for
392 circular steel tube and core SSC, while the mesh size of endplates was $1/10$ of **their** width and the
393 mesh size of stiffeners was 5 mm. Moreover, necessary cutting was performed to ensure the alignment
394 of meshing nodes of different parts. The meshing of the FE models is shown in Fig. 12.

395 The interaction between various parts was simulated by setting contact formulation. For the contact
396 area between core SSC and circular steel tube, the normal direction was defined as ‘hard contact’,
397 and the tangent directions were characterized by the Coulomb friction model, setting the friction
398 coefficient to 0.6 [16, 17]. Simultaneously, the inner wall of circular steel tube and the core SSC
399 surface in contact with it were identified as the master and slave surface, respectively. The contact
400 interface between core SSC and endplates was also treated as ‘hard contact’. The interaction between
401 endplates and circular steel tube was set as ‘shell-to-solid coupling’ to replicate the welded connection
402 between them. Furthermore, for the circular SSC-FST columns, the interaction between stiffeners and
403 circular steel tube together with endplates was defined as ‘Tie’ constraint.

404 For circular SSC-FST beams, the boundary conditions of FE model, displayed in Fig. 12(a),
405 conform to the tested specimens in this study. Four RPs (reference points) corresponding to the two
406 loading positions and two supports, which were respectively situated at the vertex of upper and lower
407 semi-arc, were defined, and the coupling between each RP and the outer surface of upper and lower
408 semi-arc on circular steel tube was built at the specific range. The width of the coupling range was
409 equal to $1.5D$, which was a good way to make sure **that** the FE simulation was efficient and accurate.
410 For the RP representing fixed and rolling support, the setting of boundary conditions was
411 ‘ $U_X=U_Y=U_Z=U_{R_X}=U_{R_Z}=0$ ’ and ‘ $U_X=U_Y=U_{R_X}=U_{R_Z}=0$ ’ respectively, in which U_X , U_Y and U_Z are the
412 translational DoFs (degrees of freedom) in three directions respectively, and U_{R_X} and U_{R_Z} are the
413 rotational DoFs with respect to the X- and Z-axis, respectively. A vertical downward displacement
414 (U_Z) of 70 mm was applied to the two quarter points. For circular SSC-FST columns with hinged
415 ends, the boundary conditions of FE model are exhibited in Fig. 12(b). Two reference lines, which
416 **are** $L/1000$ (initial eccentricity e_i) from the centroidal axis along the negative X-axis, were set on

both the upper and lower endplate. For the reference line denoting lower immovable hinge, all translational DoFs (U_X , U_Y and U_Z) and two rotational DoFs (UR_X and UR_Z) were restricted, and for the reference line denoting the upper movable hinge, two translational DoFs (U_X and U_Y) together with two rotational DoFs (UR_X and UR_Z) were restricted. A vertical downward displacement (U_Y) of 20 mm was applied to the upper reference line on the composite columns.

3.2. Validation of FE models

The simulated overall failure modes of circular SSC-FST beam and column specimens are compared with the tested results of this study in Fig. 3. Generally, the global deflection of all the specimens, the slight bulges under compression of beam specimens and the relatively evident bulges under compression of column specimens predicted by the FE models generally agree well with the tested phenomena. Moreover, the simulated and tested damage are mainly concentrated in a certain range symmetric about the half-length section of the specimens; however, the observed failure forms of some column specimens are different from the simulated results. Figs. 4(a2) and 4(b2) demonstrate the simulated failure modes of concrete core. Within a certain range symmetric about the half-length section, crushing and cracking of concrete core respectively occur at the concave side with the local bulges of the tube and the convex side, which are close to the tested phenomena of the beam specimens [Fig. 4(a1)] and they are different from the tested phenomena of part of the column specimens [Fig. 4(a2)].

Fig. 13 presents the comparison of $M - u_{ms}$ curves of circular SSC-FST beam specimens. The FE-simulations generally conform to the measured curves from this study, except that a slightly lower plastic strengthening phase is produced in the former, considering that the rolling support between beam specimen and the spreader beam obviously moves inward with the quick increase of u_{ms} , leading to an extra bending moment in the specimens; however, in the FE simulation the rolling support is treated as a fixed RP. The contrast between simulated and tested $N - u_a(u_{mh})$ curves of columns is demonstrated in Fig. 14. The available tested $N - u_a$ curves from this study as well as $N - u_{mh}$ curves from this study and reference [18] generally accord with the FE-simulations,

although there are some differences between simulated and tested results of part of the column specimens. The simulated $M - \varepsilon_L$ and $N - \varepsilon_{L(T)}$ curves are compared with the tested results in Fig. 15. As can be observed, the simulated evolution trend of M and N with the variation of ε_L and ε_T generally matches with the tested results, and good agreement in elastic and elastic-plastic phase between them is obtained, but the simulated plastic phase of $M - \varepsilon_L$ curves and post-peak phase of $N - \varepsilon_{L(T)}$ curves deviate from the tested results, due to the difference in their positions of tube bulges and forms of concrete cracking.

Fig. 16 presents the contrast between simulated capacities ($M_{u,fe}$ and $N_{u,fe}$) and measured ones (M_{ue} and N_{ue}) in this study and the references [15, 18], where $M_{u,fe}$ and $N_{u,fe}$ denote the simulated flexural capacity of the beams and axial compressive capacity of the columns, respectively. Overall, $M_{u,fe}$ and $N_{u,fe}$ are close to M_{ue} and N_{ue} , leading to difference within 5% and 10%, respectively. The mean and Cov of $M_{u,fe}/M_{ue}$ are 0.977 and 0.019, and for $N_{u,fe}/N_{ue}$ the results are 0.969 and 0.056, indicating that the capacity of circular SSC-FST members can be well predicted by the FE models.

Based on the aforementioned comparisons in Figs. 13-16, it is demonstrated that the FE models presented in this study can effectively replicate the static behaviour of circular SSC-FST members. Nevertheless, it should also be noted that there is certain discrepancy between the simulated and tested results. The reason is that, due to the limitation of the capacity of the FE analysis method, the FE models developed in this study is difficult to reasonably reproduce the impact of the factors with random characteristics in the tests, such as the deviation of the actual steel tube shape and the sizes of the specimens from the design considerations, the difference in the characteristics of the steel tube and core SSC in the specimens from the measured material properties, and the ever-present errors of the loading and measuring equipment.

4. Simplified formulae

Based on the validated FE models, the effect of parameters, such as cross-sectional steel ratio (α), strength of materials (f_y and f'_c), replacement ratio of SSA (S_c and S_f) and slenderness ratio (λ), on

the key coefficients related to the capacity of circular SSC-FST members was further investigated. Finally, practical simplified formulae for the capacity prediction were proposed. The basic parameters for the numerical examples included: $D = 400$ mm, $\alpha = 0.10$, $f_y = 355$ MPa, $f'_c = 60$ MPa, $S_c(S_f) = 50\%$ and $\lambda = 40$. The details of the parameters in the additional FE models are presented in Table 6.

For the composite beams, the impact of α , f_y , f'_c and $S_c(S_f)$ on the relationship between dimensionless coefficient (γ_b) and longitudinal tensile strain at the outermost point of the steel tube in mid-span section ($\varepsilon_{L,op}$) is presented in Fig. 17, where $\gamma_b = M_{fe} / (W_{scm} \cdot f_{scy})$, M_{fe} is the bending moment predicted by the FE model, $W_{scm} (= \pi D^3 / 32)$ is composite section modulus, and f_{scy} is the characteristic value of the composite axial compressive strength, which can be determined using the formulae in [17], namely $f_{scy} = (1.02\xi_s + 1.14) \cdot f_{ssck}$. Generally, the $\gamma_b - \varepsilon_{L,op}$ diagram of circular SSC-FST beams changes obviously with the variation of α , f_y and f'_c and changes very little as S_c and S_f vary.

Using the proposal of CFST [26], the coefficient of flexural capacity ($\gamma_{u,b}$) of circular SSC-FST beams is defined as:

$$\gamma_{u,b} = \frac{M_{u,fe}}{W_{scm} \cdot f_{scy}} \quad (3)$$

where, $M_{u,fe}$ is the numerical value of the flexural capacity when $\varepsilon_{L,op}$ equals to 0.01.

An improvement of $\gamma_{u,b}$ is achieved with the increase of α and f_y and the decrease of f'_c , which represents an enlargement in ξ_s [16], as shown in Fig. 18. Therefore, the simplified formula for $\gamma_{u,b}$ can be reached using the regression analysis of a sufficient number of parameterized modelling results, and it is expressed by:

$$\gamma_{u,b} = 1.28 + 0.35 \ln(\xi_s + 0.1) \quad (4)$$

By putting Eq. (4) into Eq. (3), the simplified formula for flexural capacity (M_u) is obtained, namely:

$$M_u = \gamma_{u,b} \cdot W_{scm} \cdot f_{scy} \quad (5)$$

To build the relationship between stability capacity and available sectional capacity [17], the stability coefficient (φ_c) of axially compressed circular SSC-FST columns is defined as [24]:

$$\varphi_c = \frac{N_{cr,fe}}{N_{0,fe}} \quad (6)$$

where, $N_{cr,fe}$ is the numerical value of the axial compressive capacity while considering the effect of λ , and $N_{0,fe}$ is the numerical value of the sectional capacity under axial compression.

Fig. 19 presents the impact of α , f_y , f'_c and $S_c(S_f)$ on $\varphi_c - \lambda$ curves. Generally, α , f_y and f'_c have an evident impact on the $\varphi_c - \lambda$ curves, while S_c and S_f have a moderate effect. Based on the analysis of a large number of numerical results, it is found that the form of simplified formulae for stability coefficient of axially compressed CFST columns in [24] is also applicable to circular SSC-FST columns, namely, the simplified formulae of φ_c can be expressed by:

$$\varphi_c = \begin{cases} 1.0 & (\lambda \leq \lambda_{ep}) \\ a \cdot \lambda^2 + b \cdot \lambda + c & (\lambda_{ep} < \lambda \leq \lambda_e) \\ d/(\lambda + 35)^2 & (\lambda > \lambda_e) \end{cases} \quad (7-1)$$

$$d = \left[13000 + 4657 \ln \left(\frac{235}{f_y} \right) \right] \cdot \left(\frac{35.5}{f'_c + 12} \right)^{0.3} \cdot \left(\frac{\alpha}{0.1} \right)^{0.05} \quad (7-2)$$

$$a = \frac{1 + (35 + 2\lambda_e - \lambda_{ep}) \cdot e}{(\lambda_e - \lambda_{ep})^2} \quad (7-3)$$

$$b = e - 2a \cdot \lambda_e \quad (7-4)$$

$$c = 1 - a \cdot \lambda_{ep}^2 - b \cdot \lambda_{ep} \quad (7-5)$$

$$e = \frac{-d}{(\lambda_e + 35)^3} \quad (7-6)$$

where, λ_e and λ_{ep} are the limit slenderness ratios when circular SSC-FST columns experience elastic and elastic-plastic instability respectively, and they can be expressed as:

$$\lambda_e = 1743 / \sqrt{f_y} \quad (8)$$

$$\lambda_{ep} = \pi \sqrt{\frac{420\xi_s + 550}{(1.02\xi_s + 1.14) \cdot f_{ssck}}} \quad (9)$$

in which, the unit for f_y and f_{ssck} is MPa.

The simplified $\varphi_c - \lambda$ curves (shown by dashed lines) are compared with the numerical results (shown by solid lines) in Fig. 19, and generally there is a good accordance between simplified and numerical $\varphi_c - \lambda$ curves. Therefore, according to Eqs. (6) to (9) as well as the simplified equation of sectional capacity in [17], the formula for the axial compressive capacity (N_u) can be obtained:

$$N_u = \varphi_c \cdot (1.02\xi_s + 1.14) \cdot f_{ssck} \cdot A_{sc} \quad (10)$$

In Fig. 20, the capacity ratios of simplified flexural capacity (M_{us}) and axial compressive capacity

(N_{us}) over their measured results (M_{ue} and N_{ue}) are demonstrated. Overall, the discrepancy between simplified and measured capacities is less than 20%. The statistical results show that, the mean and Cov of M_{us}/M_{ue} are 0.986 and 0.012, and for N_{us}/N_{ue} they are 0.904 and 0.084, indicating that the simplified formulae can accurately compute the capacity of circular SSC-FST members.

The application range for the simplified formulae is: $\alpha=0.05-0.15$, $f_y=235-420$ MPa, $S_c/S_f=0-100\%$, $f'_c=25-75$ MPa, and $\lambda=10-120$.

5. Conclusions

The main conclusions of this study are as follows:

(1) Both beam and column specimens show good load-bearing capacity and the deformability of beams is superior compared to that of columns. The failure modes of beam specimens include several symmetrically distributed mild local bulges of steel tube, and tiny cracks with depth of approx. $0.6D$ on the convex side as well as inconspicuous crushing on the concave side of concrete core. The failure modes of column specimens include one major and a few minor local bulges of steel tube, and severe crushing on the concave side of concrete core.

(2) Three major phases of approx. elastic, elastic-plastic and plastic strengthening are recorded in the moment vs. deformation diagram of beam specimens, whilst three successive stages of approx. elastic, elastic-plastic and post-peak descending are included in the load vs. deformation diagram of column specimens. Until reaching the capacity, the distribution of displacements of beam and column specimens is generally close to the half-sine wave curve, and the strain distribution along the diameter of half-length section generally conforms to the assumption of plane sections remaining plane.

(3) Compared to the reference CFST beam specimen, the SSC-FST beam specimens with coarse SSA have a similar flexural capacity (M_{ue}), while those with fine SSA result in a 4.2~4.8% higher M_{ue} ; however, the beam specimens with SSA have a 1.9~8.4% reduction in the flexural stiffness (K_{ie}). For the column specimens, the axial compressive capacity (N_{ue}) and ductility factor (DF) of SSC-FST specimens with λ of 25 is 0.1~27.9% and 32.2~51.8% higher than that of the reference CFST specimen, respectively, and when $S_c(S_f)=50\%$, N_{ue} of SSC-FST column specimens with λ of 25

546 and 35 is 4.4% (4.3%) and 5.0% (12.6%) lower than that of SSC-FST column specimens with λ of
547 15, respectively, and DF exhibits a declining trend with the increase of λ .

548 (4) The FE models can well simulate the static performance and uncover the effect of parameters
549 on key coefficients related to the capacity of circular SSC-FST members. Additionally, the predicted
550 capacities of circular SSC-FST members using the simplified formulae fit well with the simulated
551 and tested results.

552 It is worth noting that, due to the limitations of equipment capacity and research funding, the
553 dimension, material and parameter range of the specimens chosen in this study only represent typical
554 cases of the circular SSC-FST members, rather than all cases in real projects. More tests (e.g.,
555 considering the inclusion of different slag aggregates) should be conducted to further validate the FE
556 model and ultimately provide a solid data basis for proposing more accurate design methods.

557 **CRedit authorship contribution statement**

558 **You-Fu Yang:** Conceptualization, Methodology, Supervision, Writing – review & editing. **Yu-Qin**
559 **Zhang:** Data curation, Investigation, Software, Writing – original draft. **Feng Fu:** Conceptualization,
560 Methodology, Writing – review & editing.

561 **Declaration of Competing Interest**

562 The authors declare that they have no known competing financial interests or personal relationships
563 that could have appeared to influence the work reported in this paper.

564 **Data availability**

565 Data will be made available on request.

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569 **References**

- 570 [1] J. Baalamurugan, V. Ganesh Kumar, S. Chandrasekaran, S. Balasundar, B. Venkatraman, R. Padmapriya, V.K.
571 Bupesh Raja, Recycling of steel slag aggregates for the development of high density concrete: Alternative &
572 environment-friendly radiation shielding composite, Compos. Part B: Eng. 216 (2021) 108885, <https://doi.org/10.1016/j.compositesb.2021.108885>.
573

- [2] A.C.P. Martins, J.M. Franco de Carvalho, M.N. Duarte, L.G. Pedroti, J.C.L. Ribeiro, R.A.F. Peixoto, Use of steel slag and LAS-based modifying admixture in obtaining highly eco-efficient precast concrete products, *J. Build. Eng.* 66 (2023) 105884, <https://doi.org/10.1016/j.jobe.2023.105884>.
- [3] Q. Song, M.Z. Guo, L. Wang, T.C. Ling, Use of steel slag as sustainable construction materials: A review of accelerated carbonation treatment, *Resour. Conserv. Recycl.* 173 (2021) 105740, <https://doi.org/10.1016/j.resconrec.2021.105740>.
- [4] Q. Dong, G. Wang, X. Chen, J. Tan, X. Gu, Recycling of steel slag aggregate in Portland cement concrete: an overview, *J. Clean. Prod.* 282 (2021) 124447, <https://doi.org/10.1016/j.jclepro.2020.124447>.
- [5] A.M. Rashad, Behavior of steel slag aggregate in mortar and concrete-A comprehensive overview, *J. Build. Eng.* 53 (2022) 104536, <https://doi.org/10.1016/j.jobe.2022.104536>.
- [6] F. Aliyah, I. Kambali, A.F. Setiawan, Y.M. Radzi, A.A. Rahman, Utilization of steel slag from industrial waste for ionizing radiation shielding concrete: A systematic review, *Construct. Build. Mater.* 382 (2023) 131360, <https://doi.org/10.1016/j.conbuildmat.2023.131360>.
- [7] Q. Van Ho, T.P. Huynh, A comprehensive investigation on the impacts of steel slag aggregate on characteristics of high-performance concrete incorporating industrial by-products, *J. Build. Eng.* 80 (2023) 107982, <https://doi.org/10.1016/j.jobe.2023.107982>.
- [8] N. Santillán, S. Speranza, J.M. Torrents, I. Segura, Evaluation of conductive concrete made with steel slag aggregates, *Construct. Build. Mater.* 360 (2022) 129515, <https://doi.org/10.1016/j.conbuildmat.2022.129515>.
- [9] X. Yu, Z. Tao, T.Y. Song, Effect of different types of aggregates on the performance of concrete-filled steel tubular stub columns, *Mater. Struct.* 49(9) (2016) 3591-3605, <https://doi.org/10.1617/s11527-015-0742-z>.
- [10] L.H. Han, Y.F. Yang, H. Yang, W. Li, Life-cycle based analytical theory of concrete-filled steel tubular structures and its applications, *Chin. Sci. Bull.* 65(28-29) (2020) 3173-3184, <https://doi.org/10.1360/TB-2020-0618>.
- [11] F. Yu, Y. Cao, Y. Fang, Y. Zhang, K. Niu, Mechanical behavior of self-stressing steel slag aggregate concrete filled steel tubular short columns with different loading modes, *Structures* 26 (2020) 947-957, <https://doi.org/10.1016/j.istruc.2020.05.015>.
- [12] M.H. Lai, Y.H. Lin, Y.Y. Jin, Q. Fei, Z.C. Wang, J.C.M. Ho, Uni-axial behaviour of steel slag concrete-filled-steel-tube columns with external confinement, *Thin-Walled Struct.* 185 (2023) 110562, <https://doi.org/10.1016/j.tws.2023.110562>.
- [13] R.M. Abende, D. Salman, R. Al Louzi, Experimental and numerical investigations of interfacial bond in self-compacting concrete-filled steel tubes made with waste steel slag aggregates, *Dev. Built. Environ.* 11 (2022) 100080, <https://doi.org/10.1016/j.dibe.2022.100080>.
- [14] F. Yu, Y. Fang, K. Niu, Y. Zhang, T. Chen, Experimental study on bond-slip constitutive relation of SSSCFST columns, *Struct. Concr.* 22(4) (2021) 2338-2357, <https://doi.org/10.1002/suco.201900546>.
- [15] Y. Fang, F. Yu, Y. Zhang, L. Xu, X. Wang, Mechanical behavior and bearing capacity calculation of self-stressing steel slag aggregate reinforced concrete filled circular steel tube columns, *Acta Materiae Compositae Sinica* 37(5) (2020) 1211-1220, <https://doi.org/10.13801/j.cnki.fhclxb.20190916.001>. (in Chinese)
- [16] Y.F. Yang, F. Fu, Y.Q. Zhang, Static performance of steel slag concrete filled steel square hollow section members, *J. Constr. Steel Res.* 205 (2023) 107896, <https://doi.org/10.1016/j.jcsr.2023.107896>.
- [17] S.Q. Zhou, Y.F. Yang, F. Fu, Performance of SSC filled circular steel tube short columns under axial compression, *Structures*, 57 (2023) 105147, <https://doi.org/10.1016/j.istruc.2023.105147>.
- [18] L. Lu, T. Liang, T. Zhang, Q. Ren, Q. Wang, S. Wang, Axial compressive behaviors of circular steel slag concrete-filled steel tube slender columns. *Struct. Concr.* 24(6) (2023) 6953-6972, <https://doi.org/10.1002/suco.202300238>.
- [19] C. Luo, F. Wang, H. Chen, A. Qi, Y. Chen, Study on the hysteretic behavior of recycled aggregate concrete-filled steel tube columns containing ferronickel slag, *J. Build. Eng.* 46 (2022) 103695, <https://doi.org/10.1016/j.jobe.2021.103695>.

621 [20] S. Bu, F. Yu, T. Chen, Y. Fang, Y. Qin, Experimental study on seismic behavior of circular steel tube confined
622 reinforced self-stressing steel slag concrete columns, *Struct. Concr.* 24(1) (2023) 1102-1117,
623 <https://doi.org/10.1002/suco.202200036>.

624 [21] P.K. Gupta, R.K. Patra, Behaviour of concrete-filled steel tube having granulated blast furnace slag as fine
625 aggregate in normal strength concrete after exposure to elevated temperature, *Adv. Struct. Eng.* 26(15) (2023)
626 2814-2829, <https://doi.org/10.1177/13694332231205057>.

627 [22] S. Saxena, A.R. Tembhurkar, Impact of use of steel slag as coarse aggregate and wastewater on fresh and
628 hardened properties of concrete, *Construct. Build. Mater.* 165 (2018) 126-137, [https://doi.org/10.1016/](https://doi.org/10.1016/j.conbuildmat.2018.01.030)
629 [j.conbuildmat.2018.01.030](https://doi.org/10.1016/j.conbuildmat.2018.01.030).

630 [23] N.H. Roslan, M. Ismail, N.H.A. Khalid, B. Muhammad, Properties of concrete containing electric arc furnace
631 steel slag and steel sludge, *J. Build. Eng.* 28 (2020) 101060, <https://doi.org/10.1016/j.jobbe.2019.101060>.

632 [24] Y.F. An, L.H. Han, X.L. Zhao, Behaviour and design calculations on very slender thin-walled CFST columns,
633 *Thin-Walled Struct.* 53 (2012) 161-175, <https://doi.org/10.1016/j.tws.2012.01.011>.

634 [25] Z. Liu, Y. Lu, S. Li, J. Liao, Axial behavior of slender steel tube filled with steel-fiber-reinforced recycled
635 aggregate concrete, *J. Constr. Steel Res.* 162 (2019) 105748, <https://doi.org/10.1016/j.jcsr.2019.105748>.

636 [26] L.H. Han, H. Lu, G.H. Yao, F.Y. Liao, Further study on the flexural behaviour of concrete-filled steel tubes, *J.*
637 *Constr. Steel Res.* 62(6) (2006) 554-565, <https://doi.org/10.1016/j.jcsr.2005.09.002>.

638 [27] C. Pellegrino, P. Cavignis, F. Faleschini, K. Brunelli, Properties of concretes with black/ oxidizing electric arc
639 furnace slag aggregate, *Cem and Concr Compos* 37 (2013) 232-240, [http://dx.doi.org/10.1016/](http://dx.doi.org/10.1016/j.cemconcomp.2012.09.001)
640 [j.cemconcomp.2012.09.001](http://dx.doi.org/10.1016/j.cemconcomp.2012.09.001).

641 [28] Simulia, ABAQUS 6.14 analysis user's manual, Dassault Systemes Simulia Corp., Providence, RI, USA, 2014.

642 [29] Y.F. Yang, F. Fu, X.M. Bie, X.H. Dai, Axial compressive behaviour of CFDST stub columns with large void
643 ratio, *J. Constr. Steel Res.* 186 (2021) 106892, <https://doi.org/10.1016/j.jcsr.2021.106892>.

644 [30] Fédération Internationale du Béton, Fib model code for concrete structures 2010, 2013.

645 [31] American Concrete Institute, Building code requirements for structural concrete (ACI 318-19) and commentary,
646 2019.

647 [32] European Committee for Standardization, Eurocode 2: Design of concrete structures-Part 1-1: General rules
648 and rules for buildings, 2004.

649 [33] V. Birtel, P. Mark, Parameterised finite element modelling of RC beam shear failure, in: Proceedings of the
650 19th Annual International ABAQUS Users' Conference, 2006.

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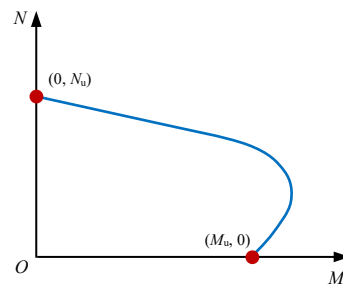
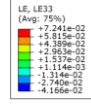
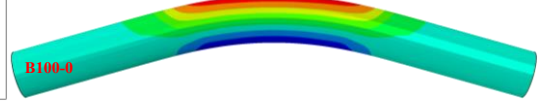
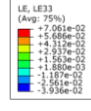
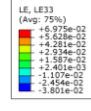
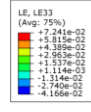
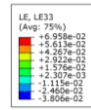
Figures:

Fig. 1. Schematic diagram of $N - M$ correlation curve of circular SSC-FST members.



(1) Tested results

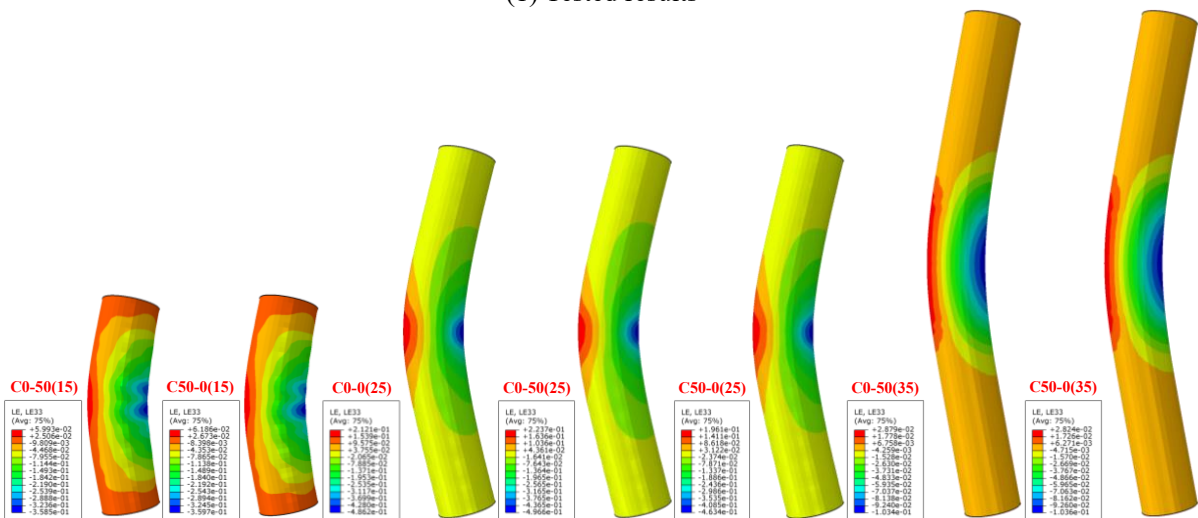


(2) Simulated results (logarithmic strain)

(a) Beams



(1) Tested results



(2) Simulated results (logarithmic strain)

(b) Columns

Fig. 4. Failure modes of concrete core in the specimens.

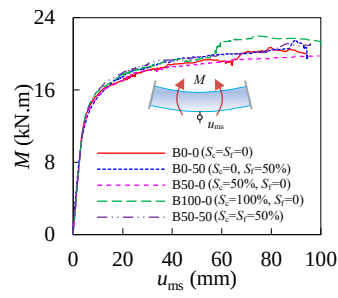
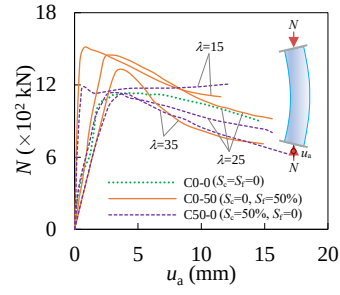
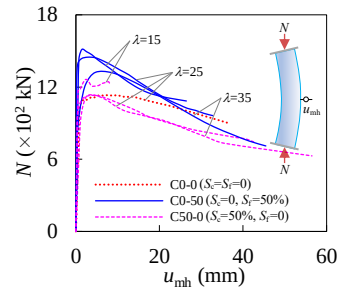


Fig. 5. Moment (M) vs. mid-span displacement (u_{ms}) diagrams of beam specimens.



(a) N - u_a curves



(b) N - u_{mh} curves

Fig. 6. Load (N) vs. displacement (u_a and u_{mh}) curves of column specimens.

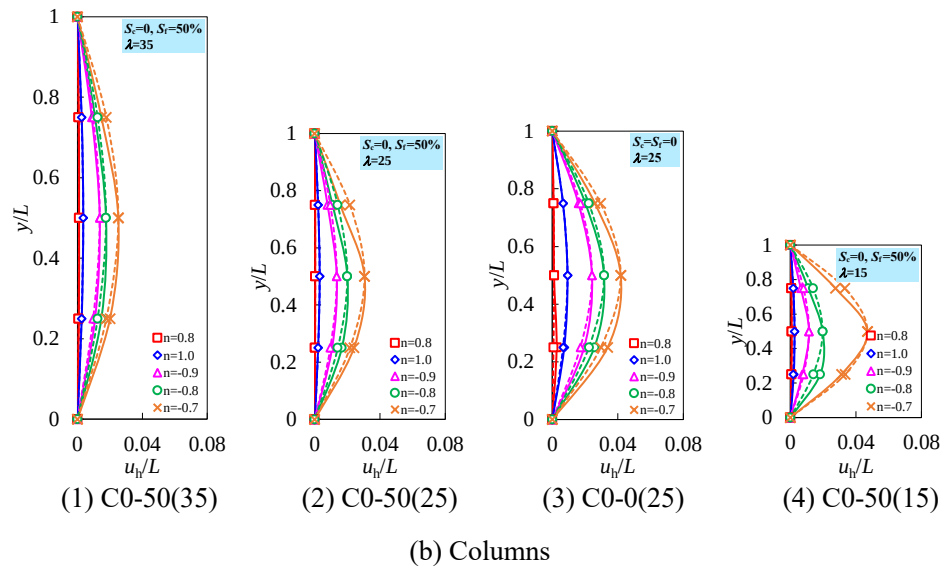
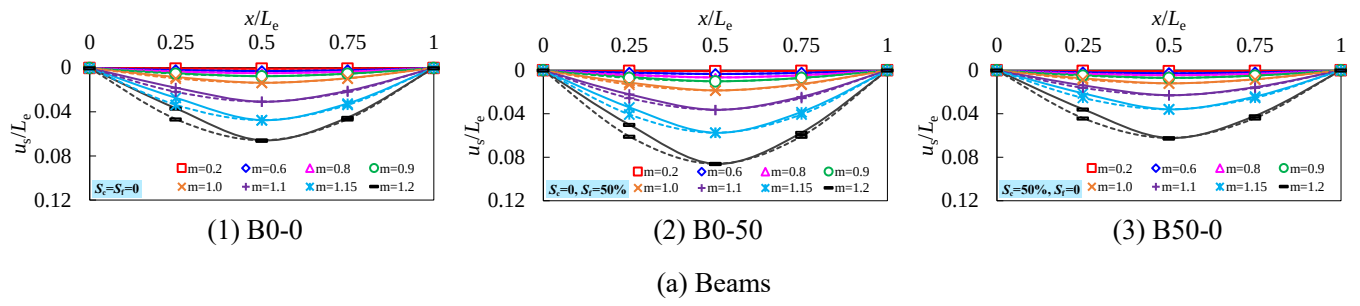


Fig. 7. Distribution of displacements along the length of typical specimens.

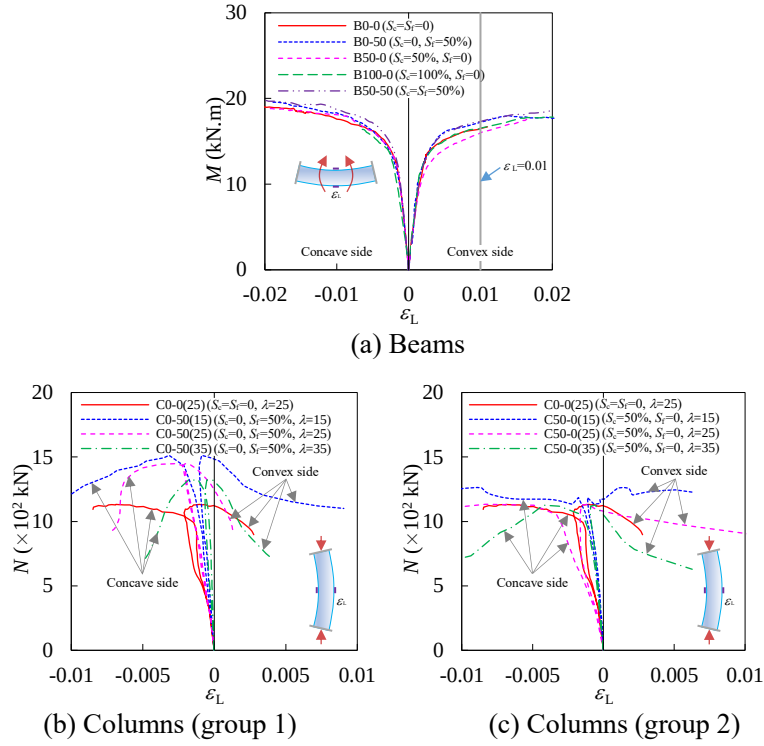
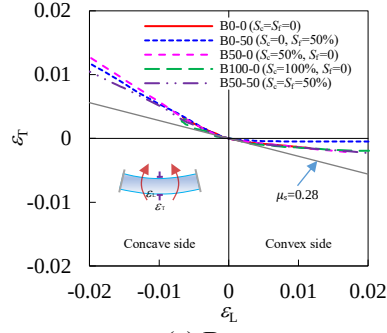
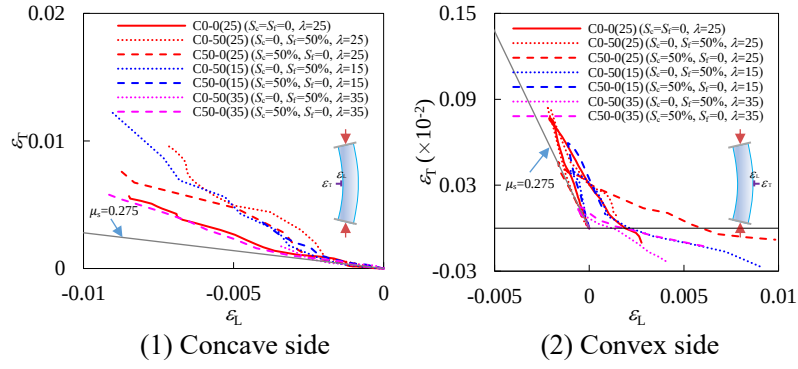


Fig. 8. Typical moment/load (M/N) vs. longitudinal strain (ϵ_L) curves of the specimens.

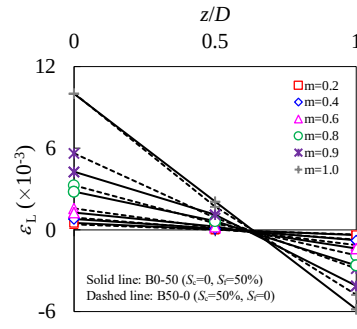


(a) Beams

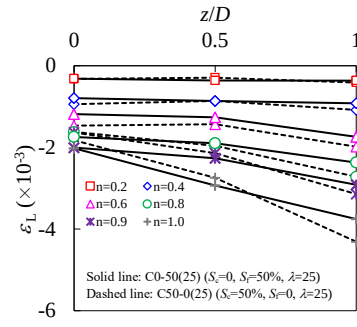


(b) Columns

Fig. 9. Longitudinal strain (ϵ_L) vs. transverse strain (ϵ_T) relationships at the recorded positions.

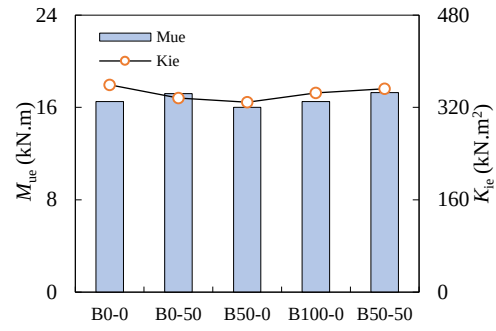


(a) Beams

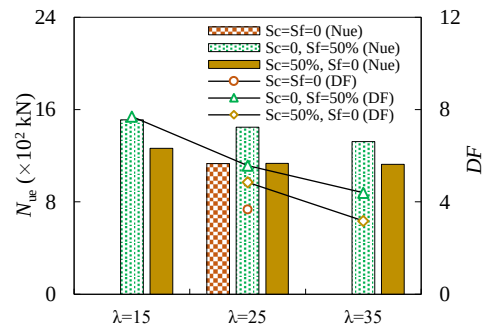


(b) Columns

Fig. 10. Distribution of longitudinal strain (ε_L) along the diameter of half-length section.



(a) Beams



(b) Columns

Fig. 11. Variation of mechanical index of the specimens.

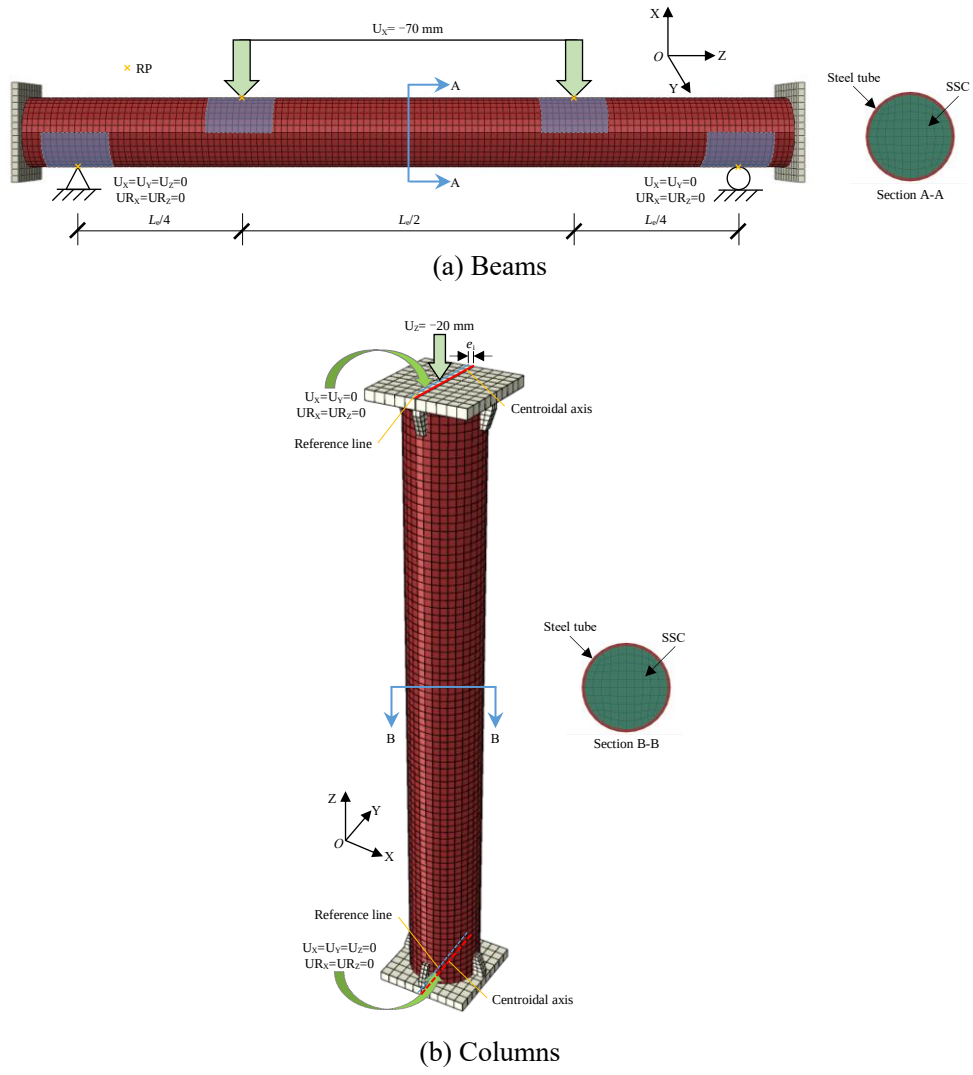
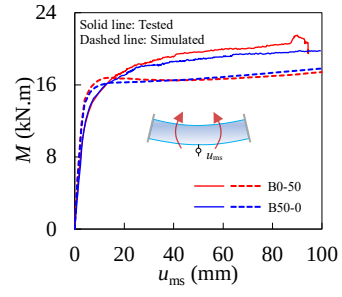
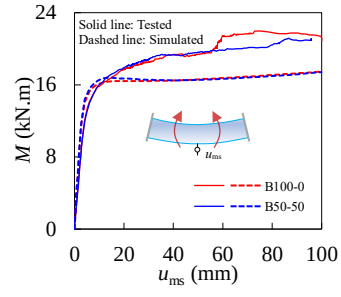


Fig. 12. Meshing and boundary conditions of the FE models.

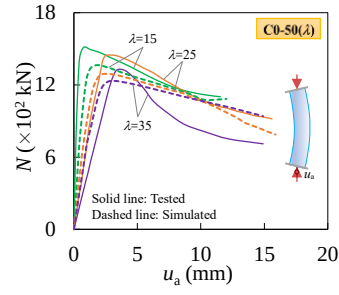


(a) Group 1

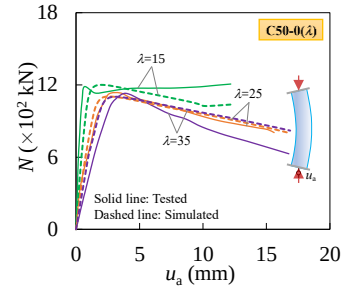


(b) Group 2

Fig. 13. Comparison of $M - u_{ms}$ curves of circular SSC-FST beam specimens in this study.

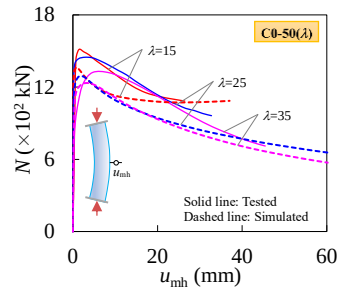


(1) Group 1 in this study

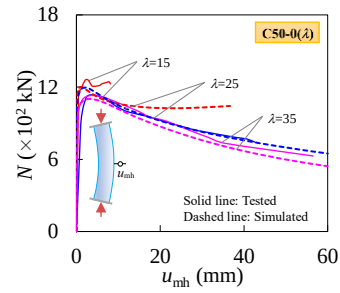


(2) Group 2 in this study

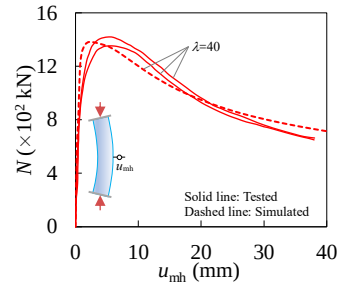
(a) $N - u_a$ curves



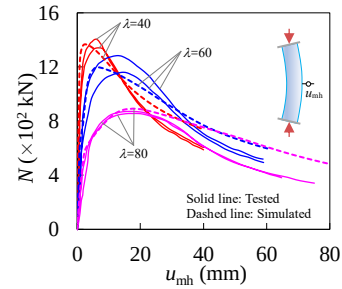
(1) Group 1 in this study



(2) Group 2 in this study



(3) Specimens ($S_c=50\%$) in [18]



(4) Specimens ($S_c=100\%$) in [18]

(c) $N - u_{mh}$ curves

Fig. 14. Contrast between simulated and tested $N - u_a(u_{mh})$ curves of columns.

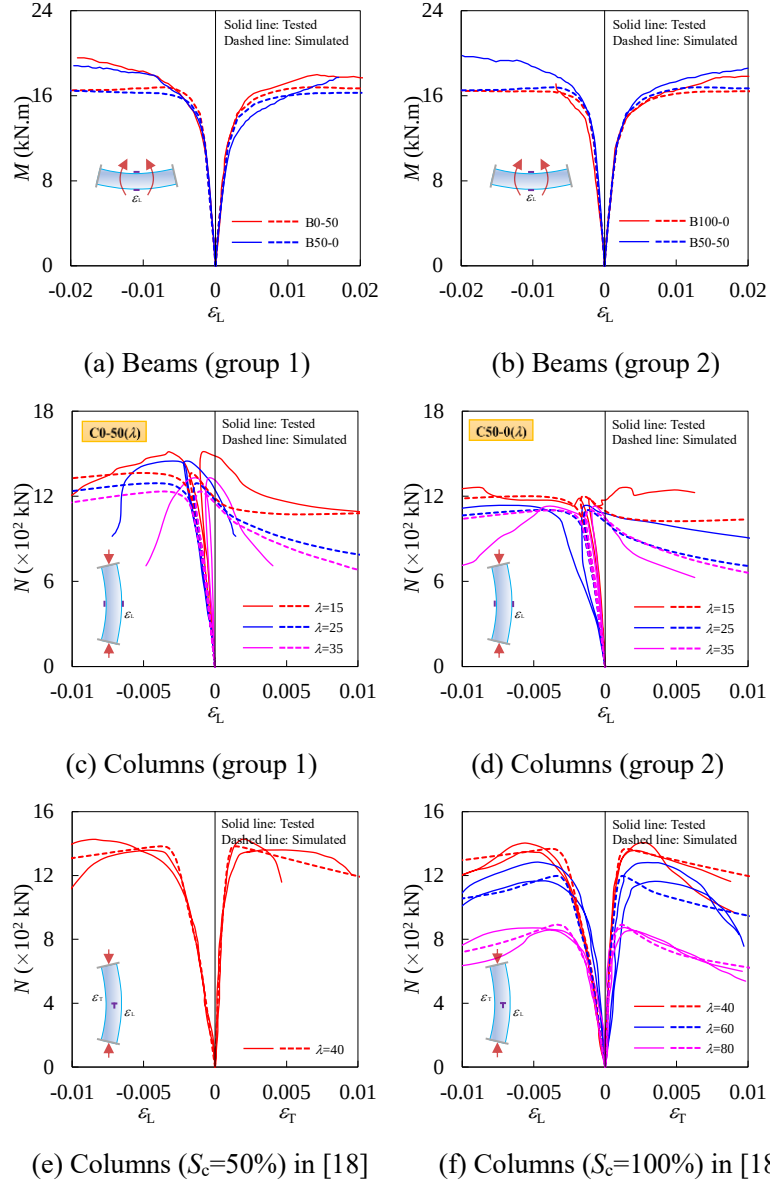
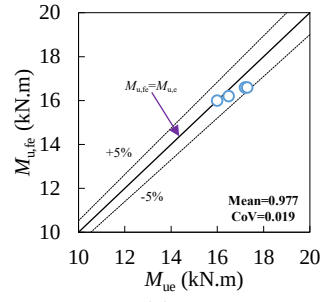
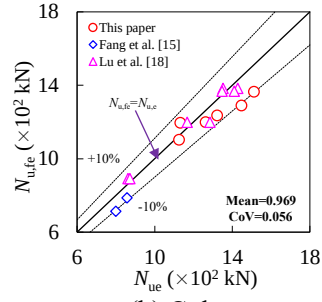


Fig. 15. Comparison of $M - \varepsilon_L$ and $N - \varepsilon_{L(T)}$ curves between simulated and tested results.



(a) Beams



(b) Columns

Fig. 16. Contrast between simulated and measured capacities of circular SSC-FST specimens.

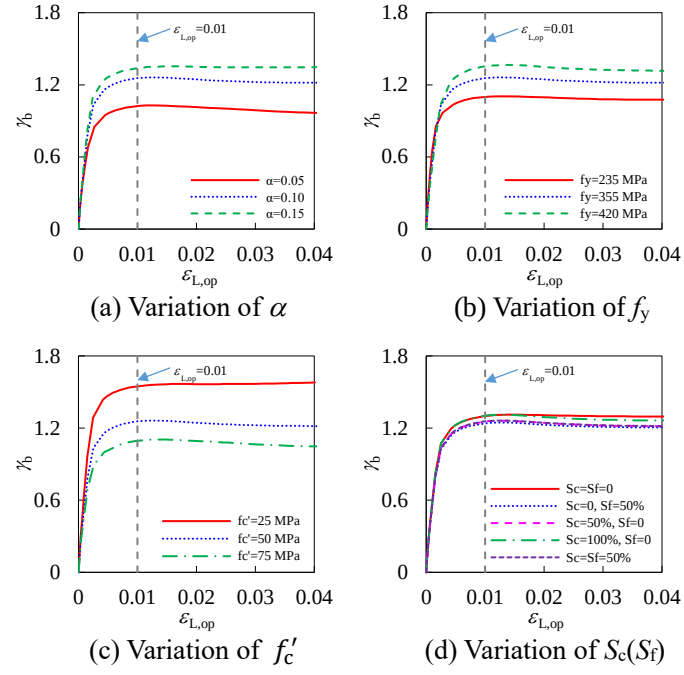


Fig. 17. Effect of parameters on $\gamma_b - \epsilon_{L,op}$ relationship.

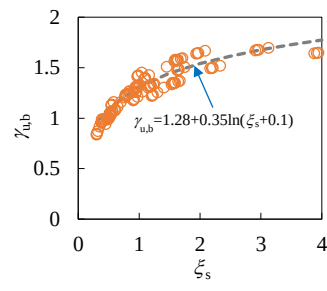


Fig. 18. Influence of ξ_s on $\gamma_{u,b}$.

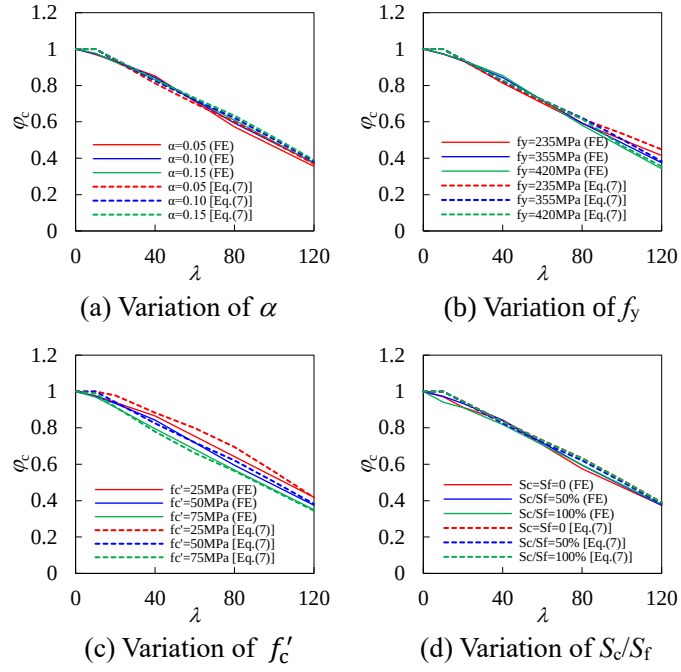


Fig. 19. Impact of parameters on $\phi_c - \lambda$ curves of circular SSC-FST columns.

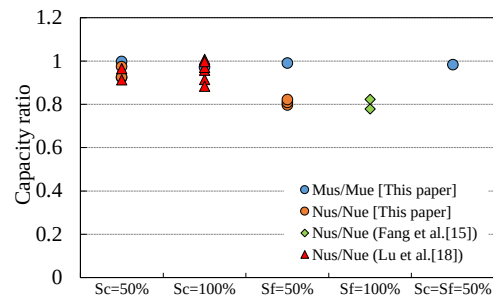


Fig. 20. Variation in ratios of simplified capacity to measured one.

Tables:**Table 1.** Specimen details.

Type	No.	Label	D (mm)	t (mm)	L (mm)	S_c (%)	S_f (%)	λ	f_y (MPa)	f_{cu} (MPa)
Beam	1	B0-0	114	3.4	1200	0	0	-	300.0	51.2
	2	B0-50	114	3.4	1200	0	50	-	300.0	76.8
	3	B50-0	114	3.4	1200	50	0	-	300.0	61.1
	4	B100-0	114	3.4	1200	100	0	-	300.0	61.9
	5	B50-50	114	3.4	1200	50	50	-	300.0	76.8
Column	1	C0-0(25)	150	3.2	938	0	0	25	324.7	49.8
	2	C0-50(25)	150	3.2	938	0	50	25	324.7	53.2
	3	C50-0(25)	150	3.2	938	50	0	25	324.7	48.5
	4	C0-50(15)	150	3.2	563	0	50	15	324.7	53.2
	5	C50-0(15)	150	3.2	563	50	0	15	324.7	48.5
	6	C0-50(35)	150	3.2	1313	0	50	35	324.7	53.2
	7	C50-0(35)	150	3.2	1313	0	50	35	324.7	48.5

Table 2. Properties of steel.

t (mm)	f_y (MPa)	f_u (MPa)	E_s (N/mm ²)	μ_s	δ (%)
3.4	300.0	370.3	1.85×10^5	0.280	13.54
3.2	324.7	429.9	2.04×10^5	0.275	14.60

Table 3. Mixture proportion and properties of concrete.

Group	S_c (%)	S_f (%)	Mixture proportion (kg/m ³)								Properties			
			Cement	Fly ash	Coarse aggregate		Fine aggregate		Tap water	Water reducer	Slump (mm)	Spread (mm)	$f_{cu,28}$ (MPa)	E_c (GPa)
					NCA	Coarse SSA	NFA	Fine SSA						
G-B	0	0	398	170	770	0	795	0	204	2.35	270	645	46.3	32.3
	0	50	398	170	770	0	398	398	204	2.35	260	710	64.3	34.3
	50	0	398	170	385	385	795	0	204	2.35	280	660	57.7	33.2
	100	0	398	170	0	770	795	0	204	2.35	265	675	53.3	32.5
	50	50	398	170	385	385	398	398	204	2.35	265	690	69.7	32.7
G-C	0	0	398	170	770	0	795	0	200	10	260	625	40.7	32.4
	0	50	398	170	770	0	398	398	200	10	270	590	47.0	33.1
	50	0	398	170	385	385	398	398	200	10	260	635	39.5	28.1

Note: G-B=concrete in the beam specimens, and G-C=concrete in the column specimens.

Table 4. The obtained mechanical indexes of the specimens.

Type	No.	Label	S_c (%)	S_f (%)	λ	M_{ue} (kN.m)	$\frac{M_{ue,ssc}}{M_{ue,nc}}$	K_{ie} (kN.m ²)	$\frac{K_{ie,ssc}}{K_{ie,nc}}$	N_{ue} (kN)	$\frac{N_{ue,ssc}}{N_{ue,nc}}$	DF	$\frac{DF_{ssc}}{DF_{nc}}$
Beam	1	B0-0	0	0	–	16.5	–	359.2	–	–	–	–	–
	2	B0-50	0	50	–	17.2	1.042	336.3	0.936	–	–	–	–
	3	B50-0	50	0	–	16.0	0.970	329.1	0.916	–	–	–	–
	4	B100-0	100	0	–	16.5	1.000	345.4	0.962	–	–	–	–
	5	B50-50	50	50	–	17.3	1.048	352.4	0.981	–	–	–	–
Column	1	C0-0(25)	0	0	25	–	–	–	–	1132.2	–	3.67	–
	2	C0-50(25)	0	50	25	–	–	–	–	1448.0	1.279	5.57	1.518
	3	C50-0(25)	50	0	25	–	–	–	–	1132.9	1.001	4.85	1.322
	4	C0-50(15)	0	50	15	–	–	–	–	1512.7	–	7.70	–
	5	C50-0(15)	50	0	15	–	–	–	–	1263.4	–	N/A	–
	6	C0-50(35)	0	50	35	–	–	–	–	1321.9	–	4.40	–
	7	C50-0(35)	0	50	35	–	–	–	–	1126.2	–	3.18	–

Note: The mechanical indexes with subscripts 'ssc' and 'nc' stand for those of SSC-FST and the reference CFST specimens, respectively.

Table 5. Plastic parameters in CDP model

θ	ϵ	σ_{b0}/σ_{c0}	$q_{(TM)}/q_{(CM)}$	p_v
30	0.1	1.16	2/3	5.0×10^{-6}

Note: θ is the dilation angle, ϵ is the flow potential eccentricity, σ_{b0} and σ_{c0} are the initial equibiaxial compressive yield stress and the initial uniaxial compressive yield stress, respectively, $q_{(TM)}$ and $q_{(CM)}$ are the second stress invariant on the tensile meridian and that on the compressive meridian, respectively, and p_v is the viscosity coefficient.

Table 6. The details of the parameters in the additional FE models.

D (mm)	t (mm)	α	f_y (MPa)	f'_c (MPa)	$S_c(S_f)$ (%)	λ
400	9.3	0.10	355	50	0(0)	40
	4.8	0.05	235, 355, and 420	25, 50, and 75	50(0), 0(50), or 50(50)	10, 20, 40, 80, and 120
	9.3	0.10				
	13.5	0.15				
	4.8	0.05	235, 355, and 420	25, 50, and 75	100(0), 0(100), or 100(100)	
	9.3	0.10				
	13.5	0.15				

Note: The effective span of the beams is fixed at $5D$.