Mechanical properties of discrete BFRP needles
reinforced seawater sea-sand concrete-filled
GFRP tubular stub columns

Zhiqiang Dong a,b; Gang Wu a,b,*; Xiao-Ling Zhao c; Hong Zhu a,b; Yang Wei d; Zeyu Yan a,b

Abstract: This paper proposes a new type of tubular column, which is composed of glass
fiber-reinforced polymer (GFRP) tube and discrete basalt fiber-reinforced polymer (BFRP)
needles reinforced seawater sea-sand concrete (SWSSC). The discrete BFRP needles, with an
aspect ratio of 10.0, were cut from BFRP bar production scrap and mixed into fresh concrete
to replace 20% of the coarse aggregates by volume. The axial compression properties and
lateral bending properties of the tubular columns were tested. The test variables included the
wall thickness of the GFRP tubes (i.e., 3 mm and 4 mm), the type of coarse aggregates (i.e.,
gravel or coral), and the incorporation of BFRP needles or not. Additionally, unconfined bare
columns were tested for comparison. The test results showed that the inclusion of BFRP
needles had moderate adverse effects on the peak compressive strength of bare columns: the
peak axial stress reduced slightly by 2.5% for gravel concrete and 7.2% for coral concrete,
respectively. Besides, for the four types of concrete in this paper, the 3- and 4-mm GFRP
tube-confinement increased the peak axial compressive strengths by 23–52% and 65–83%,
respectively. In addition, the adoption of GFRP tubes was able to improve the bending
performance of columns significantly, especially for energy consumption.

a Key Laboratory of Concrete and Prestressed Concrete Structures of Ministry of Education, Southeast University, Nanjing, 210096, China.
b National and Local Joint Engineering Research Center for Intelligent Construction and Maintenance, Nanjing, 210096, China.
c Dept. of Civil and Environmental Engineering, UNSW, Sydney, NSW 2052, Australia. E-mail: xiaolin.zhao@unsw.edu.au
d College of Civil Engineering, Nanjing Forestry University, No.159 Longpan Road, Nanjing, 210037, China.
* Corresponding author.
E-mail address: g.wu@seu.edu.cn (Gang Wu)
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1. Introduction

When construction is performed on islands that are far from the mainland, the lack of building raw materials is a critical factor that affects the construction efficiency and costs. The freshwater, fine aggregates (river sand or manufactured sand), and coarse aggregates (gravel) required for concrete preparation must be transported from faraway mainland, which is costly and inefficient. However, if the local seawater, sea-sand or even coral aggregates [1-6] are directly used, the corrosion rate of the embedded traditional steel bars will be significantly accelerated due to the excessive chlorine ions, which will seriously shorten the service life of concrete structures. Therefore, it is of great significance to develop new durable and economical marine structures.

Fiber-reinforced polymer (FRP) has well-known properties, such as high strength-weight ratio, corrosion-resistance, and fatigue resistance[7, 8]. For the last three decades, FRP has been increasingly widely used in many industries (e.g., construction, wind power, the chemical, aerospace, and automotive industries) and inevitably produces increasing FRP wastes. In general, FRP wastes can be divided into two categories according to their formation sources: industrial wastes and general wastes. Industrial wastes come from the molding process, which are mainly pure and clean scraps produced during molding. General wastes come from the using process, which mainly refer to discarded products that have reached their service life and lost their functions, products accidentally damaged during
transportation, construction or use, and products eliminated due to upgrades. Since most FRP products adopt a thermosetting polymer (e.g., epoxy, vinyl ester, unsaturated polyester, and phenolic resin) as the matrix resin, the stable three-dimensional cross-linked network structure formed after solidification makes them difficult to remold and recycle. Therefore, considering the large quantity of FRP wastes generated by various industries, it is imperative to develop low-cost and green recycling technologies.

At present, landfill and incineration are the mainstream treatment methods for FRP wastes. However, they have obvious shortcomings such as occupying land resources and polluting the environment. Compared to landfill and incineration, recycling is a more worthwhile approach to dispose FRP wastes [9]. Traditional recycling methods fall into three categories: mechanical recycling [10], thermal recycling [11], and chemical recycling [12]. Recently, scholars have proposed a new waste recycling method in the field of mechanical recycling: cutting and crushing FRP wastes (mainly wind turbine blades and FRP rebars) into stone-like aggregates (aspect ratio of 1.0) or needle-like aggregates (aspect ratio of 10.0) and filling them into concrete as a coarse aggregate replacement to achieve green and low-energy consumption recycling [9, 13-18]. Test results indicated that the inclusion of FRP needles did not reduce the workability or stability of concrete. The splitting tensile strength of concrete was increased, while the compressive strength was slightly reduced.

In addition, due to its excellent resistance to chloride ions, FRP has promising application prospects in chloride-rich marine environments. In recent years, many scholars have begun to advance the application of new high-endurance structures for the marine environment by combining FRP and seawater sea-sand concrete (SWSSC), including the FRP
tube-SWSSC column [19-23], FRP-bar-reinforced SWSSC beam [24-26], and FRP-bar-reinforced SWSSC shear wall [27]. In addition, to further utilize local materials, crushed corals were adopted by Wang et al. 2017 [28] as concrete aggregates, and the mechanical properties of FRP columns filled with seawater coral aggregate concrete were studied. The study indicated that the combination of FRP tube and in situ seawater coral aggregate concrete had good application prospect in the marine environment.

As mentioned, considering the growing number of discarded FRP materials, FRP can be a good choice to combine with SWSSC to apply in a chloride-rich marine environment (especially the discarded wind turbine blades that were once in service in coastal areas [13, 17]). Hence, the authors have cut the discarded basalt fiber-reinforced polymer (BFRP) bar production scraps into needle-like aggregates with an aspect ratio of 10.0 and filled them into SWSSC as coarse aggregates. The compressive, tensile, and flexural properties of the prepared concrete were systematically studied [29]. The test results show that the splitting tensile strengths and flexural performances have been significantly improved, while the compressive strength has only been slightly reduced (it can be effectively strengthened by the FRP tube confinement). Undoubtedly, it is greener and less power-consuming to recycle FRP wastes in the form of large pieces of aggregates than the traditional form of powdered filler manufactured by mechanical grinding. Currently, only a small number of related studies involved the combination of ordinary concrete and large pieces of FRP wastes [14-16, 18], while little attention has been paid to the combination of SWSSC and FRP wastes.

Based on the above research background, this paper proposes a new type of composite tubular column for the marine environment. It is composed of a GFRP tube and SWSSC
containing discrete needle-like BFRP wastes (two types of coarse aggregates were used: ordinary gravel and coral). This new hybrid column can be locally constructed, and the FRP wastes can be effectively recycled. Compression and four-point bending tests were conducted to investigate the effect of the FRP tube thickness (3 mm and 4 mm), type of aggregates (ordinary gravel and coral), and inclusion of BFRP needles. In addition, the ultimate load capacities of GFRP tube confined columns were theoretically calculated. The research in this paper aims to provide a reference for the green and efficient recycling of FRP wastes and the rapid and efficient construction of new corrosion-resistant structures in harsh marine environments.

2. Raw materials

2.1 Glass fiber-reinforced polymer (GFRP) tubes

The adopted glass fiber-reinforced polymer (GFRP) tubes were fabricated by the filament winding process with constant fiber orientation. Based on the manufacturer data, the fibers were at an angle of $\pm 63^\circ$ to the longitudinal axis, and the resin matrix was unsaturated polyester resin. The specific gravity of GFRP tubes was 1.9, and the fiber volume ratio was 65%. Two sizes of GFRP tubes were adopted in this paper: they had a uniform inner diameter of 150 mm and a nominal wall thickness of 3.0 mm and 4.0 mm. The measured wall thickness was 2.5 mm and 3.4 mm. The nominal wall thickness was used to calculate material performances.

Because the fibers were at an angle to the longitudinal axis, the GFRP tube could provide strength and stiffness in both hoop and longitudinal directions. As shown in Fig. 1a, the tensile properties of the GFRP tubes in the longitudinal direction were tested with a tensile
coupon following ASTM D3039/D3039M-14 [30]. The tests were performed on a universal
testing machine with a 100-kN capacity, and the adopted loading speed was 2.0 mm/min. To
test Poisson’s ratio, 4 strain gauges were attached to the middle part of each coupon: on the
convex and concave sides and in the longitudinal and transverse directions. The modulus of
elasticity was measured by an attached extensometer. Because the test coupon was curved,
two sets of customized aluminum gripping pieces were used to ensure that the coupon ends
were tightly gripped by the gripping head of the test machine (as shown in Fig. 1a).

As shown in Fig. 1b, the tensile properties of the GFRP tubes in the hoop direction were
tested in accordance with ASTM D2290-12 [31] using the “disk-split” method. It consists of
two U-shaped headers and two semicircular steel cylinders with identical curvature to the
tested GFRP rings. Three GFRP rings with a width of 13 mm were prepared for each tube size.
The adopted loading speed was 2.5 mm/min, and the capacity of the universal testing machine
was 600 kN. To monitor the strain to calculate the elastic modulus of GFRP tubes, three strain
gauges were attached on the test rings: one was centered at the gaps, and two were located at
±25 mm away from the gap.

The measured results are shown in Fig. 2 and Table 1. The stress-strain relationship of
the GFRP tube was linear in the hoop direction and obviously nonlinear in the longitudinal
direction, which was mainly caused by the failure of the resin matrix. Due to the fiber
orientation, the strength in the hoop direction was much higher than that in the longitudinal
direction, the hoop strength was between 191.0 and 227.1 MPa, and the tensile strength in the
longitudinal direction was between 16.2 and 27.6 MPa. In addition, the elastic modulus in the
hoop direction was slightly higher than that in the longitudinal direction.
Fig. 1 Mechanical property tests for GFRP tubes: (a) Tensile strength test (Unit: mm); (b) Hoop strength test (Unit: mm)

Fig. 2 Tested typical stress-strain curves of GFRP tubes

Table 1 Material properties of GFRP tubes

<table>
<thead>
<tr>
<th>Tube Size (Diameter×nominal thickness)</th>
<th>Hoop direction</th>
<th>Longitudinal direction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$f_{uh}$ (MPa)</td>
<td>$E_h$ (GPa)</td>
</tr>
<tr>
<td>150 mm×3 mm</td>
<td>191.0±6.7</td>
<td>17.0±1.6</td>
</tr>
<tr>
<td>150 mm×4 mm</td>
<td>227.1±10.7</td>
<td>24.4±0.8</td>
</tr>
</tbody>
</table>

Notes: $f_{uh}$ and $E_h$ are the ultimate tensile stress and elastic modulus in the hoop direction, respectively. $\varepsilon_{h,rup}$ is the ultimate tensile strain in the hoop direction. $f_{ul}$ and $\varepsilon_{ul}$ are the ultimate tensile stress and ultimate strain in the longitudinal direction, respectively. $E_l$ is the elastic modulus in the initial stage. Three specimens were tested for each group.
2.2 Basalt fiber-reinforced polymer (BFRP) needles

As shown in Fig. 3, the basalt fiber-reinforced polymer (BFRP) needles in this paper were identical as those in the authors’ previous published paper [29]. These needles were used to replace the coarse aggregate as many as possible with a volume replace ratio of 20%, which had been proved reasonable and feasible [29]. The adopted needles had a length of 100 mm, a nominal diameter of 10.0 mm (aspect ratio of 10.0), and a linear density of 130 g/m. The tensile strength was 1141 MPa, the elastic modulus was 47 GPa, and the resin matrix was vinyl ester with a resin volume ratio of 35%.

![Fig. 3 Prepared BFRP needles with an aspect ratio of 10.0](image)

2.3 Aggregates

As shown in Fig. 4a, the fine aggregate, i.e., natural sea-sand, was identical to that utilized in the authors’ previous published papers [24, 29, 32-34]. It was purchased from the coastal city of Zhangzhou, Fujian province, China. Fig. 5 shows the particle size distribution curve of the sea-sand according to the Chinese specification [35]; the calculated fineness modulus after the sieving test was 2.404, which shows that sea-sand belongs to the class of
medium sand. The content of chloride ions of the sea-sand was 0.08%. As shown in Fig. 4b and Fig. 4c, two types of coarse aggregates were used in the test: ordinary gravel locally produced in Nanjing and natural coral produced from the Taiwan Strait. Their particle size distribution curves are shown in Fig. 5. It can be seen that the particle size of the gravel aggregate was mainly continuously distributed continuously between 4.75 and 9.55 mm, and the particle size of the coral aggregate was continuously distributed between 4.75 and 19.0 mm. As can be seen in Fig. 4c, there were many dense pores on the surface of the natural coral aggregate.

**Fig. 4** Three types of aggregates adopted: (a) Sea-sand; (b) Gravel; (c) Coral
Fig. 5 Screening test results of the adopted aggregates

Table 2 Concrete mixture proportions

<table>
<thead>
<tr>
<th>Materials</th>
<th>SSGC</th>
<th>SSCC</th>
<th>BNSSGC</th>
<th>BNSSCC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Portland cement (Type: 42.5)</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>Seawater</td>
<td>0.35</td>
<td>0.55</td>
<td>0.35</td>
<td>0.55</td>
</tr>
<tr>
<td>Sea-sand</td>
<td>1.50</td>
<td>1.50</td>
<td>1.50</td>
<td>1.50</td>
</tr>
<tr>
<td>Gravel</td>
<td>2.50</td>
<td>-</td>
<td>2.00</td>
<td>-</td>
</tr>
<tr>
<td>Coral</td>
<td>-</td>
<td>2.50</td>
<td>-</td>
<td>2.00</td>
</tr>
<tr>
<td>Polycarboxylate superplasticizer</td>
<td>0.01</td>
<td>0.012</td>
<td>0.01</td>
<td>0.012</td>
</tr>
<tr>
<td>BFRP needles [Numbers]</td>
<td>-</td>
<td>-</td>
<td>[25]</td>
<td>[26]</td>
</tr>
</tbody>
</table>

2.4 Concrete mixture

Four types of concrete were prepared on site in the laboratory: seawater sea-sand gravel concrete (SSGC), seawater sea-sand coral concrete (SSCC), BFRP needles reinforced SSGC (BNSSGC) and BFRP needles reinforced SCC (BNSSCC). The detailed concrete mixture proportions are shown in Table 2. Among them, the Portland cement used was Chinese standard Type 42.5, the seawater was natural seawater from the Yellow Sea of China, and the water reducer was Q8011HPWR (Shaanxi Qinfen Building Materials Co., Ltd.), which is a polycarboxylate superplasticizer with a water reduction rate of 26%. The four types of
concrete were mixed in the laboratory in May 2019. According to the GB/T 50080-2016 [36], the measured slumps of the SSGC, SSCC, BNSSGC and BNSSCC were 4.0 cm, 2.2 cm, 5.0 cm and 0.5 cm, respectively. All specimens were cured in an ambient indoor air environment.

3. Experimental program

3.1 Specimen preparation

Figure 6 shows the cross-section information of the four types of GFRP tube-confined columns. In this paper, twenty-four cylinders were cast in total. Among them, twelve short columns with heights of 300 mm were prepared for the compressive test, and twelve long columns with heights of 600 mm were prepared for the four-point bending test. The specimens preparation process is shown in Fig. 7. First, one end of the GFRP tubes was sealed with a plastic cap (Fig. 7a); second, the four types of concrete were mixed on-site using an electric mixer. It should be noted that to prevent the difficulty of mixing, BFRP needles were not poured into all at once but were gradually added during the mixing process. Figure 7b shows the prepared concrete containing BFRP needles. Finally, the concrete was filled into the tubes and compacted with a slender vibration rod (Fig. 7c).

The detailed test matrix is shown in Table 3. With respect to the specimen number, “Control” represents a naked column without GFRP tube confinement, “GFRP” represents the GFRP tube confinement, numbers “3” and “4” represent the nominal wall thickness of the GFRP tube, and the last item represents the type of filled concrete.
Fig. 6 Cross-sections of the GFRP confined specimens (Unit: mm)

(a) (b) (c)

Fig. 7 Specimen preparation process: (a) Prepared tubes; (b) Concrete mixing; (c) Concrete pouring

Table 3 Experimental matrix

<table>
<thead>
<tr>
<th>Concrete</th>
<th>Specimen No.</th>
<th>$t_o$ (mm)</th>
<th>$\beta$ (%)</th>
<th>Aggregates</th>
</tr>
</thead>
<tbody>
<tr>
<td>SSGC</td>
<td>Control-SSGC</td>
<td>-</td>
<td>-</td>
<td>Gravel</td>
</tr>
<tr>
<td></td>
<td>GFRP-3-SSGC</td>
<td>3</td>
<td>-</td>
<td>Gravel</td>
</tr>
<tr>
<td></td>
<td>GFRP-4-SSGC</td>
<td>4</td>
<td>-</td>
<td>Gravel</td>
</tr>
<tr>
<td>BNSSGC</td>
<td>Control-BNSSGC</td>
<td>-</td>
<td>20</td>
<td>Gravel</td>
</tr>
<tr>
<td></td>
<td>GFRP-3-BNSSGC</td>
<td>3</td>
<td>20</td>
<td>Gravel</td>
</tr>
<tr>
<td></td>
<td>GFRP-4-BNSSGC</td>
<td>4</td>
<td>20</td>
<td>Gravel</td>
</tr>
<tr>
<td>SCC</td>
<td>Control-SSCC</td>
<td>-</td>
<td>-</td>
<td>Coral</td>
</tr>
<tr>
<td></td>
<td>GFRP-3-SSCC</td>
<td>3</td>
<td>-</td>
<td>Coral</td>
</tr>
<tr>
<td></td>
<td>GFRP-4-SSCC</td>
<td>4</td>
<td>-</td>
<td>Coral</td>
</tr>
<tr>
<td>BNSSCC</td>
<td>Control-BNSSCC</td>
<td>-</td>
<td>20</td>
<td>Coral</td>
</tr>
<tr>
<td></td>
<td>GFRP-3-BNSSCC</td>
<td>3</td>
<td>20</td>
<td>Coral</td>
</tr>
<tr>
<td></td>
<td>GFRP-4-BNSSCC</td>
<td>4</td>
<td>20</td>
<td>Coral</td>
</tr>
</tbody>
</table>

Notes: $t_o$ is the nominal wall thickness of the GFRP tube; $\beta$ is the volume replacement ratio of BFRP needles to coarse aggregates.

3.2 Axial compression test

As shown in Fig. 8, the axial compression performance of the short column was tested
on a universal compression-testing machine with a capacity of 3,000 kN. The loading speed was 0.25 mm/min [28]. To lower the effects of end-crushing, three layers of BFRP sheet with a width of 25 mm were wound at both ends. As shown in Fig. 8a, four linear variable differential transformers (LVDTs) were evenly arranged around the cylinder to test the overall deformation of the short column. Readers should note that a certain degree of end-crushing effects may be included in the overall deformation due to the adopted layout of LVDTs. Four circumferential strain gauges were uniformly attached in the middle of the short column to test the hoop strain of the GFRP tube, and four axial strain gauges were uniformly attached to test the axial compressive strain of the GFRP tube. The load was monitored by the compression testing machine; the LVDTs and strain gauges were connected to a data acquisition system. Fig. 8b shows the photograph during the loading process.

![Test setup for compression properties: (a) Test setup and instrumentation; (b) Photograph during testing](image)

### 3.3 Four-point bending test

As shown in Fig. 9, with reference to Hadi 2009 [37] and Hadi and Widiarsa 2012 [38],
four-point bending tests were conducted to evaluate the resistance of these proposed new
types of columns to accident lateral loads. The test was performed on a universal testing
machine with a capacity of 600 kN. The loading speed of the control specimens was 0.2
mm/min, and the loading speed of the GFRP tube-confined specimens was 1.0 mm/min. The
load vs. displacement curves were recorded by the testing machine. Figure 9a shows the
schematic diagram of the loading device, and Figure 9b shows the photograph during testing.

Fig. 9 Test setup for the flexural properties: (a) Test setup for the four-point bending test (Unit:
mm); (b) Photograph during testing

4. Test results

4.1 Axial compression test results

4.1.1 Experimental observation and failure modes

Figure 10 shows the photographs of the control specimens and representative 4-mm
GFRP tube-confined specimens in the final stage. By comparing the failure modes of the four
control specimens, as shown in Fig. 10a, we observed that those specimens with BFRP
needles (i.e., BNSSGC and BNSSCC) had wider cracks at the final failure stage than those without BFRP needles (i.e., SSGC and SSCC); the degree of concrete crushing of the former was more serious than the latter. However, due to the pulling action of the internal BFRP needles, the seriously cracked fragments did not fall down. In addition, the SSGC specimens with gravel aggregates had more vertical cracks than the SSCC specimens with coral aggregates. A possible reason is that the coral aggregate itself was less hard than the gravel aggregate. It is well known that the crushing of ordinary gravel aggregate concrete is mainly controlled by the inter-facial mortar layer between the gravel aggregates, and the aggregates themselves are generally not destroyed during the crushing. However, since the coral aggregate was porous, the coral aggregate would experience crushing, shearing and other damage during the destruction of concrete.

The representative failure modes of the four 4-mm GFRP tube-confined specimens in Fig. 10b show that there was no significant difference in failure morphologies. After reaching the ultimate hoop strain of the GFRP tubes, slight pitter-patter sounds were heard in the middle of the test specimens. As the loading continued, the middle part of the test specimens appeared obviously white, and the epidermis of the GFRP tube showed strip-like breaks along the circumferential direction. When the load application further continued, the pitter-patter sounds became louder and denser, and the whitened area increased. Finally, the whitened area was connected into a whole piece, and the GFRP tube was totally ruptured.
Fig. 10 Typical failure modes of compression tests: (a) Control group; (b) 4-mm GFRP tube confined group

4.1.2 Axial stress-axial and hoop strains behavior

The tested axial stress-axial and hoop strain curves of all specimens are shown in Fig. 11.

The axial strains can be obtained in two manners: the ratio of the axial end shortening measured by LVDTs to the specimen length (overall strain) and the average readings of axial strain gauges at mid-height (localized strain). The overall strain reflects the overall compression deformation of the column, and the localized strain reflects the local strain of the GFRP tube at mid-height. The axial strain values in Fig. 11a and Fig. 11b were the overall strain, and the axial strain values in Fig. 11c and Fig. 11d were the localized strain. At the initial stage of loading, the obtained overall strain by the LVDTs was basically consistent with the localized strain measured by the strain gauges. It should be noted that, for GFRP
tube-confined columns, in the calculation of their axial stresses, the adopted diameter was 150 mm + 2×tube wall thickness.

Figure 11a shows the tested axial stress-strain curves of specimens with gravel aggregates. For the unconfined control group, the Control-SSGC specimen showed a sharp drop after reaching the peak stress, while the Control-BNSSGC specimen with BFRP needles showed a gentle decrease after reaching the peak stress. This may be caused by two factors: (1) the elastic compression deformation of BFRP needles due to their low elastic modulus and (2) the pulling action of BFRP needles due to the relatively long length. A similar phenomenon was observed in the GFRP tube-confined specimens. For example, the curve of the GFRP-3-BNSSGC specimen had a long plateau after falling from the peak point. In addition, it can be seen from Fig. 11a that the ultimate stress and ultimate strain of GFRP tubular specimens were significantly increased compared to the control specimens and the improvement increased with the increase in wall thickness of the GFRP tubes. Fig. 11c shows the tested axial strain-hoop strain curves of specimens with gravel aggregates. Under the same axial strain, both specimens with SSGC had larger hoop strains than the specimens with BNSSGC, which implies that the SSGC had larger lateral expansion than the BNSSGC. This result was also believed to be caused by the compression deformation of BFRP needles and the pulling action of the long needles.

Figure 11b shows the tested axial stress-strain curves of the specimens with coral aggregates. Compared to the control specimens, the ultimate stress and ultimate strain of GFRP tube-confined specimens were also significantly improved. However, the magnitude of the increase was not as obvious as that of the specimens with gravel aggregates due to a lower
lateral expansion under the same axial strain. Moreover, with regard to the unconfined control
specimens, the descending branch of the Control-BNSSCC specimen was also relatively
gentler than that of the Control-SSCC specimen. A similar phenomenon was observed in the
GFRP tube-confined specimens. For example, the GFRP-3-SSCC specimen and
GFRP-3-BNSSCC specimen had similar peak stresses, but the descending branch of the latter
was more gentle than that of the former. Figure 11d shows the tested axial strain-hoop strain
curves of the specimens with coral aggregates. The specimens with SSCC had larger hoop
strains than those with BNSSCC under the same axial strain, which is consistent with the
results shown in Fig. 11c for concrete with gravel aggregates.

Parts of the key test results are listed in Table 4. Where, $k (\Delta_{\text{hoop}}/\Delta_{\text{axial}})$ is the
hoop-to-localized axial strain ratio based on the data of the attached strain gauges. The value
of $k$ decreases when the wall thickness of the GFRP tube increases. The obtained values of the
peak stress and the corresponding peak strain of the twelve compression specimens are shown
in Fig. 12. The following is a quantitative comparative analysis of the test results according to
the experimental variables.
Fig. 11 Tested axial stress-strain and the corresponding axial-hoop strain curves: (a) Axial stress-strain curves of the specimens with gravel aggregates; (b) Axial stress-strain curves of the specimens with coal aggregates; (c) Axial-hoop strain curves of the specimens with gravel aggregates; (d) Axial-hoop strain curves of the specimens with coral aggregates.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>$f_{co}$ ($\text{MPa}$)</th>
<th>$f_{cp}/f_{co}$</th>
<th>$\varepsilon_{co}$</th>
<th>$\varepsilon_{cp}$</th>
<th>$\varepsilon_{cp}/\varepsilon_{co}$</th>
<th>$k$</th>
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<tbody>
<tr>
<td>Control-SSGC</td>
<td>55.1</td>
<td>1.00</td>
<td>0.0037</td>
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<td>/</td>
<td></td>
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<tr>
<td>GFRP-3-SSGC</td>
<td>83.6</td>
<td>1.52</td>
<td>0.0170</td>
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<td>GFRP-4-SSGC</td>
<td>100.9</td>
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<td>Control-BNSSGC</td>
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<td>0.0045</td>
<td>1.00</td>
<td>/</td>
<td></td>
</tr>
<tr>
<td>GFRP-3-BNSSGC</td>
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<td>0.0185</td>
<td>4.11</td>
<td>0.878</td>
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<tr>
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<td>0.0232</td>
<td>5.16</td>
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<tr>
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<td>/</td>
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<td>GFRP-4-SSCC</td>
<td>68.6</td>
<td>1.65</td>
<td>0.0210</td>
<td>5.38</td>
<td>0.656</td>
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</tr>
<tr>
<td>Control-BNSSCC</td>
<td>38.7</td>
<td>1.00</td>
<td>0.0047</td>
<td>1.00</td>
<td>/</td>
<td></td>
</tr>
<tr>
<td>GFRP-3-BNSSCC</td>
<td>53.2</td>
<td>1.37</td>
<td>0.0217</td>
<td>4.62</td>
<td>/</td>
<td></td>
</tr>
<tr>
<td>GFRP-4-BNSSCC</td>
<td>66.0</td>
<td>1.71</td>
<td>0.0248</td>
<td>5.28</td>
<td>0.560</td>
<td></td>
</tr>
</tbody>
</table>

Notes: $f_{co}$ and $\varepsilon_{co}$ are the peak axial stress and corresponding axial strain of the control specimens; $f_{cp}$ and $\varepsilon_{cp}$ are the peak axial stress and corresponding axial strain of the GFRP tube-confined specimens; $k$ is the hoop-to-localized axial strain ratio; ‘/’ means not available due to data discreteness.
Fig. 12 Tested peak axial stress and corresponding axial strain: (a) Peak axial stress; (b) Peak axial strain

**Effects of BFRP needle inclusion**

Based on the concept of green recycling, needle-like BFRP scraps were incorporated into the SWSSC to partially replace the coarse aggregates. As shown in Table 4, the peak stress was 55.1 MPa for the Control-SSGC and 53.7 MPa for the Control-BNSSGC, which was a slight decrease of 2.5%. Similarly, the peak stress was 41.7 MPa for the Control-SSCC and 38.7 MPa for the Control-BNSSCC, which was a slight decrease of 7.2%. A possible reason for these moderate reductions is that the interlock performance with mortar of the cylindrical BFRP needles was not as good as that of the angular-shape aggregates (gravels or corals). As shown in Table 4 and Fig. 12b, the peak axial strain was 0.0037 for the Control-SSGC and 0.0045 for the Control-BNSSGC, which was a 17.8% improvement. The peak axial strain was 0.0039 for the Control-SSCC and 0.0047 for the Control-BNSSCC, which was a 17.0% improvement. Thus, partially replacing the coarse aggregate with BFRP needles can increase the compressive strain of the concrete.

**Effects of GFRP tube confinement**

Two types of GFRP tubes (nominal wall thickness of 3.0 mm and 4.0 mm) were used in
this paper. As shown in Fig. 12, the bearing capacities of the four types of concrete after being confined by GFRP tubes were improved. The degree of improvement increased with the increase in wall thickness of the GFRP tube. For the 3-mm GFRP tube, the improvement was 23–52%; for the 4-mm GFRP tube, the improvement was 65–83%. Among them, the SSGC had the highest efficiency of increase (52% and 83%), and the SSCC had the lowest efficiency of increase (23% and 65%). As shown in Fig. 12b, due to the confinement of the GFRP tube, the concrete was under a three-dimensional state of stress, and its peak axial strain was greatly improved. For the 3-mm GFRP tube, the improvement was 311-364%. For the 4-mm GFRP tube, the improvement was 410-476%. Similarly, the improvement delay with the increase in wall thickness of the GFRP tube.

4.2 Four-point bending test results

4.2.1 Experimental observation and failure modes

The typical failure modes of the bending tests are shown in Fig. 13. In Fig. 13a, the plain control concrete without BFRP needles (Control-SSGC) was suddenly broken into two halves without obvious middle-span displacements. However, in Fig. 13b, the control specimen with BFRP needles (Control-BNSSGC) was severely cracked but not broken into two halves due to the bridge effect of the inner randomly distributed BFRP needles across the cracked section.

Figures 13c and 13d show the typical bending failure modes of GFRP tube-confined specimens. In the initial stage of loading, the deflections of the specimens were small. With the increase of the load, the bottom side of the GFRP tube gradually reached its ultimate axial tensile strain. After that, the bottom area of the mid-span gradually became white, and pitter-patter sounds were heard. With the load continued, the whitened area gradually moved
upward, and the bottom tensile crack continued growing. Finally, a loud bang was heard, and the load suddenly decreased.

Fig. 13 Typical failure modes of the bending tests: (a) Control-SSGC; (b) Control-BNSSGC; (c) GFRP-4-SSCC; (d) GFRP-4-BNSSCC

4.2.2 Load-displacement behaviors

Fig. 14 Load vs. displacement curves: (a) Specimens with gravel aggregate concrete; (b)
Table 5 Bending test results

<table>
<thead>
<tr>
<th>Specimen</th>
<th>$F_{mc}$, $F_{mp}$ (kN)</th>
<th>$F_{mp}/F_{mc}$</th>
<th>$\delta_{mc}$, $\delta_{mp}$ (mm)</th>
<th>$\delta_{mp}/\delta_{mc}$</th>
<th>$E_{energy}$ (kN.mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control-SSGC</td>
<td>34.5</td>
<td>1.00</td>
<td>1.4</td>
<td>1.00</td>
<td>16.2</td>
</tr>
<tr>
<td>GFRP-3-SSGC</td>
<td>143.1</td>
<td>4.14</td>
<td>10.2</td>
<td>7.28</td>
<td>915.5</td>
</tr>
<tr>
<td>GFRP-4-SSGC</td>
<td>160.1</td>
<td>4.64</td>
<td>9.9</td>
<td>7.08</td>
<td>987.2</td>
</tr>
<tr>
<td>Control-BNSSGC</td>
<td>27.3</td>
<td>1.00</td>
<td>1.1</td>
<td>1.00</td>
<td>10.2</td>
</tr>
<tr>
<td>GFRP-3-BNSSGC</td>
<td>145.0</td>
<td>5.31</td>
<td>10.0</td>
<td>9.06</td>
<td>923.8</td>
</tr>
<tr>
<td>GFRP-4-BNSSGC</td>
<td>162.9</td>
<td>5.97</td>
<td>10.2</td>
<td>9.26</td>
<td>1039.5</td>
</tr>
<tr>
<td>Control-SSCC</td>
<td>21.4</td>
<td>1.00</td>
<td>1.3</td>
<td>1.00</td>
<td>9.6</td>
</tr>
<tr>
<td>GFRP-3-SSCC</td>
<td>/</td>
<td>/</td>
<td>/</td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td>GFRP-4-SSCC</td>
<td>158.7</td>
<td>7.43</td>
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<td>1124.0</td>
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<tr>
<td>Control-BNSSCC</td>
<td>18.8</td>
<td>1.00</td>
<td>1.1</td>
<td>1.00</td>
<td>5.8</td>
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<tr>
<td>GFRP-3-BNSSCC</td>
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<td>6.24</td>
<td>10.0</td>
<td>8.85</td>
<td>629.5</td>
</tr>
<tr>
<td>GFRP-4-BNSSCC</td>
<td>171.8</td>
<td>9.15</td>
<td>11.5</td>
<td>10.15</td>
<td>1276.6</td>
</tr>
</tbody>
</table>

Notes: $F_{mc}$ and $\delta_{mc}$ are the ultimate load and the corresponding displacement of the control specimens; $F_{mp}$ and $\delta_{mp}$ are the ultimate load and the corresponding displacement of the GFRP tube-confined specimens; $E_{energy}$ is the energy consumption under the curve until the ultimate load. "/" indicates not available.

The obtained load-displacement curves of the bending tests are shown in Fig. 14. The ultimate load, ultimate displacement, and energy consumption (area under the curve) of each specimen are listed in Table 5. During the test of specimen GFRP-3-SSCC, due to the insufficient bearing capacity of the initially designed loading frame, the test failed, and no valid data were obtained. Subsequent tests were conducted after the loading device was improved.

Comparing the curves of the Control-SSGC and Control-BNSSGC in Fig. 14a, we observe that because of the presence of BFRP needles across the crack, the latter had a more pronounced residual strength segment. Similar phenomena were observed for the Control-SSCC and Control-BNSSCC in Fig. 14b. However, the residual load strength of the Control-BNSSCC was relatively low. After further inspection of the cracked section, we found that most BFRP needles were happened to be parallel to the cracked section due to the
randomness of the BFRP needle distribution. In addition, Table 5 shows that the specimens with BFRP needles had lower ultimate bending capacities than those without BFRP needles, which was consistent with the results obtained by the authors in a previous published paper using rectangular blocks [29]. For example, the ultimate bending load value was 34.5 kN for the Control-SSGC specimen and 27.3 kN for the Control-BNSSGC specimen. The ultimate bending load value was 21.4 kN for the Control-SSCC specimen and 18.8 kN for the Control-BNSSCC specimen. The above phenomenon was also believed to be caused by the weaker interlock performance with mortar of the cylindrical BFRP needles than that of the angular-shape aggregates (gravels or corals).

As shown in Fig. 14, the load-displacement curves of the GFRP tube-confined specimens were nonlinear, and the flexural stiffness gradually decreased when the load increased; this was believed to be caused by the axial nonlinear tensile properties of the GFRP tube. As shown in Table 5, the ultimate load, ultimate displacement, and energy consumption of the GFRP tube-confined specimens were greatly improved compared to the unconfined control specimens. For example, the ultimate bending capacity and displacement of GFRP-4-SSGC were 4.64 times and 7.08 times those of the Control-SSGC, respectively, and the energy consumption was greatly increased from 16.2 kN.mm to 987.2 kN.mm. The GFRP tube confinement can effectively improve the bending performance of the column in this paper. Moreover, in terms of efficiency, the improvements were more significant for concrete with BFRP needles than plain concrete without BFRP needles. For example, the ultimate bending capacity of GFRP-4-SSCC was 7.43 times that of the Control-SSCC, while the ultimate bending capacity of GFRP-4-BNSSCC was 9.15 times that of the Control-BNSSCC. A
possible reason was that the existence of GFRP tubes limited the development of cracks and improved the interlock performance between BFRP needles and mortar.

5. Comparison with theoretical estimation for the ultimate compressive strength

Based on the existing FRP-confined concrete models in literature [39] [28], the theoretical ultimate compressive strengths of the GFRP-confined columns with the four types of concrete adopted in this paper were calculated and compared with the test results. It can be used as a reference for design. For the GFRP tubular columns filled with gravel aggregate concrete (i.e. SSGC and BNSSGC), the model proposed by Jiang and Teng 2007 [39] for FRP-confined ordinary gravel aggregate concrete was adopted. The ultimate compressive strength ($f_{cp}$) after confined with FRP tube was calculated by the following formulas:

$$\frac{f_{cp}}{f_{co}} = 1 + 3.5 \frac{f_t}{f_{co}}$$ (1)

$$f_t = 2t_0f_{uh}/d_T$$ (2)

Where $f_{co}$ is the peak axial stress of the unconfined control specimens (Table 4), $f_t$ is the confining pressure supplied by the GFRP tube, $f_{uh}$ is the ultimate tensile stress of the GFRP tube in the hoop direction (Table 1), $t_0$ and $d_T$ are the nominal wall thickness and inner diameter of the GFRP tube, respectively (Table 3).

However, it has been found that the coral aggregate concrete would experience a compacting process under the combination of compression and confinement. The resulting delay in the expansion of coral aggregate concrete cannot be captured by the existing model for FRP-confined ordinary gravel aggregate concrete [28]. Wang et al. 2017 [28] had proposed a calculation model for the ultimate compressive strength of FRP-confined coral aggregate concrete based on the modification to Zhou et al. 2016’s model [40], which was
initially established for FRP-confined lightweight aggregate (ceramsite aggregate) concrete.

In this paper, Wang et al. 2017’s model [28] was used to calculate the ultimate compressive strength of the GFRP tubular columns filled with coral aggregate concrete (i.e. SCCC and BNSSCC). The calculation formula was as follow:

$$f_{cp} = f_{co} \left( 1 + 2.11 \left( \lambda \frac{f_{cp}}{f_{co}} \right)^{0.65} \right)$$  \hspace{1cm} (3)

Where $\lambda$ is the ratio of tube crushing strength of the coral aggregate to that of the ceramsite aggregate, and its value is 0.375.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>$f_{cp}$ (MPa)</th>
<th>Test ($f_{cp}/f_{co}$)</th>
<th>Calculation ($f_{cp}/f_{co}$)</th>
<th>$\Delta$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GFRP-3-SSGC</td>
<td>83.6</td>
<td>1.52</td>
<td>1.49</td>
<td>-2.3</td>
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<tr>
<td>GFRP-4-SSGC</td>
<td>100.9</td>
<td>1.83</td>
<td>1.77</td>
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<tr>
<td>GFRP-3-BNSSGC</td>
<td>66.4</td>
<td>1.24</td>
<td>1.50</td>
<td>20.8</td>
</tr>
<tr>
<td>GFRP-4-BNSSGC</td>
<td>91.4</td>
<td>1.7</td>
<td>1.79</td>
<td>5.3</td>
</tr>
<tr>
<td>GFRP-3-SSCC</td>
<td>51.3</td>
<td>1.23</td>
<td>1.37</td>
<td>11.4</td>
</tr>
<tr>
<td>GFRP-4-SSCC</td>
<td>68.6</td>
<td>1.65</td>
<td>1.50</td>
<td>-9.1</td>
</tr>
<tr>
<td>GFRP-3-BNSSCC</td>
<td>53.2</td>
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<td>GFRP-4-BNSSCC</td>
<td>66.0</td>
<td>1.71</td>
<td>1.52</td>
<td>-10.9</td>
</tr>
</tbody>
</table>

Note: The symbol “$\Delta$” means the deviation.

The calculated results and tested results are shown in Table 6 and Fig. 15. It can be seen that for specimens with SSGC (i.e., GFRP-3-SSGC and GFRP-4-SSGC), the calculated results were slightly lower than the test results, but the deviations were small, which were only 2.3% and 3.3%. However, for specimens with BNSSGC (i.e., GFRP-3-BNSSGC and GFRP-4-BNSSGC), the calculated results were higher than the tested results, especially for the 3 mm GFRP tube-confined column. The deviation was as large as 20.8%. A possible reason was that the elastic compression of BFRP needles may delay the overall lateral expansion of the BNSSGC. For the two types of concrete with coral aggregates (i.e. SCCC...
and BNSSCC), the calculated results were slightly higher than the test results for specimens with 3 mm GFRP tube, while the conclusion was opposite for specimens with 4 mm GFRP tube. However, the prediction accuracy of Wang et al. 2017’s model [28] was acceptable with the deviation controlled at a maximum of 11.4%.

![Fig. 15 Comparison of test results and calculated results for the ultimate compressive strength](image)

### 6. Conclusions

In this paper, the compressive and bending properties of the proposed new type of GFRP tubular columns were preliminarily tested. The effects of the type of coarse aggregates, wall thickness of the GFRP tubes, and inclusion of BFRP needles were investigated. Based on the test results, the following main conclusions are drawn:

1. The inclusion of BFRP needles had negligible adverse effects on the peak compressive strength of naked columns: the peak axial strength was slightly reduced by 2.5% for gravel concrete and 7.2% for coral concrete. While the corresponding peak axial strain increased by 17.8% and 17.0%, respectively. The naked specimens containing BFRP needles had lower ultimate bending capacities than those without BFRP needles.

2. For the four types of concrete in this paper, the 3- and 4-mm GFRP
tube-confinement increased the peak axial compressive strengths by 23–52% and 65–83%,
respectively.

(3) The adoption of GFRP tubes was able to improve the bending performance of
columns significantly, especially for the energy consumption; e.g., the value increased from
16.2 kN.mm for the Control-SSGC specimen to 987.2 kN.mm of the GFRP-4-SSGC
specimen.

(4) Based on the calculation results of this paper, it was found that for the
GFRP-confined BNSSGC column, the prediction accuracy of the existing theoretical model
for ordinary gravel concrete was poor, and it was necessary to carry out correction research on
the basis of more data. For the GFRP-confined BNSSCC column, the existing modified
model for coral concrete seemed to be acceptable for the prediction of the ultimate
compressive strength.

Overall, the proposed BFRP needles reinforced SWSSC (both BNSSGC and BNSSCC)
have promising application prospects in practical engineering, and their performance can be
further improved with the GFRP tube confinement. In addition, although the BFRP needles
would not corrode in the presence of chloride ions, the concrete alkaline environment may
have certain adverse effects on their interface bond with concrete and mechanical properties,
which may have potential adverse effects on their long-term mechanical properties. Currently,
relevant durability tests are in progress.

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References


