Experimental Study on Flexural Behavior of Seawater Sea-Sand Concrete Beams Reinforced with Superelastic Shape Memory Alloy Bars

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Abstract: In order to research the flexural behavior of shape memory alloy (SMA)-reinforced seawater sea-sand concrete (SWSSC) beams and improve their self-healing ability, three SMA SWSSC beams and one anti-corrosive steel bar SWSSC beam were designed. The influence of the reinforcement ratio, strength grade of SWSSC and type of reinforcement on the flexural performance of the beam were considered. The failure process, maximum crack width, mid-span deflection, displacement ductility and stiffness degradation of beams were studied by cyclic loading tests. The test results showed that the number of cracks in SMA-reinforced beams were significantly smaller than that in anti-corrosive-reinforced beams, and the crack width and mid-span deflection recovery effect were better after unloading. However, the effect of increasing the SMA reinforcement ratio on crack recovery was not obvious. The increase in SMA reinforcement ratio and the strength grade of SWSSC can significantly improve the bearing capacity of the beam and the stiffness, but the stiffness degradation rate decreased. Moreover, the ductility of concrete beams with SMA bars was significantly increased.

Keywords: seawater sea-sand concrete; shape memory alloy; flexural performance; superelastic; crack recovery

1. Introduction

As the global population grows and modern infrastructure expands, the demand for concrete, the most widely used material in modern construction, is also increasing. Data show that global concrete production was about 25 billion tons in 2016. In China, ready-mixed concrete consumes about 1.38 billion tons of river sand and 275 million tons of fresh water each year [1]. River sand resources are becoming increasingly scarce due to the long-term exploitation of these raw materials, causing serious ecological problems, and long-distance transport consumes a lot of energy. With the development of China’s marine strategy, the efficient development and utilization of marine resources have begun to receive attention. The importance of seawater sea-sand for development and building in coastal and marine regions is highlighted in the marine plan.

In seawater sea-sand concrete (SWSSC), durability is one of the current challenges. Fiber-reinforced plastic (FRP) bars have been demonstrated in studies to have high corrosion resistance and durability [2,3], and can be substituted for steel bars in concrete members [4]. The engineering research and implementation of FRP bars in SWSSC structures have become a hot research topic. The most widely used FRP bars are carbon FRP (CFRP) bars, glass FRP (GFRP) bars and basalt FRP (BFRP) bars [5]. The bond behavior between FRP bars and concrete is very important for the anchorage and durability of concrete [6]. Dong et al. [7] created 24 pull-out specimens in order to study the bonding properties with sea-sand concrete. The bond strength can be changed by sandblasting the FRP bars [8] and changing the diameter and bond length of the steel bars [9]. Bazli et al. [10] showed the bonding qualities of various FRP bars, the orientation of FRP bars, and the diameters of FRP bars with SWSSC, and developed an analytical model. Al-Rousan et al. [11]
investigated the influence of bond strength deterioration on the seismic performance of FRP-reinforced beams using numerical modeling.

At present, FRP bars are widely used in SWSSC components. Hua et al. [12], Dong et al. [13], and Li et al. [14] used FRP bars in SWSSC beams to study the flexural capacity and durability. Zhang et al. [15] used FRP bars to reinforce SWSSC shear walls. In addition to FRP bars, Li et al. [16, 17] used FRP tubes to restrain SWSSC columns. Yang et al. [18, 19] examined the axial compression behavior of CFRP partly enclosed SWSSC cylinders. Axial compression experiments were performed by Li et al. [20] on 42 circular and square columns made of CFRP sheet restricted seawater sea-sand recycled aggregate concrete. Zeng et al. [21, 22] carried out axial compression tests on polyethylene terephthalate fiber-reinforced FRP tube confined concrete columns and square columns. Lou et al. [23] and Dolati et al. [24] used FRP bars instead of steel bars for prestressed concrete.

In recent years, the rapid development of SMA has provided new ideas for the design of SWSSC structures. SMA has excellent corrosion resistance, low maintenance cost and is suitable for harsh environments. By using accelerated corrosion experiments, Zhao et al. [25] and Pareek et al. [26] studied the corrosion resistance of SMA wires and bars. In a highly alkaline environment, Abo et al. [27] examined the corrosion of SMA, carbon steel and coupled carbon steel-SMA. The findings demonstrated that SMA specimens had significantly greater corrosion resistance and durability than carbon steel specimens.

In addition, the unique shape memory effect and superelasticity of SMA can realize the self-centering effect of the structure. Shi et al. [28] proposed a self-centering buckling restrained brace, which added an SMA cable to the buckling support to achieve self-centering. In the research of Qian et al. [29], SMA and engineered cementitious composites (ECC) were used to reinforce concrete beams. Under monotonic cyclic loading, the specimens showed good self-centering effects, ductility, and deformation properties. At the same time, Qian et al. [30] used SMA and ECC to reinforce the beam–column joints and carried out low-cycle load experiments and numerical simulations. SMA can significantly improve the self-centering ability of the joint, and ECC improved its ductility. Hong et al. [31] used Fe-SMA to repair cracks in prestressed concrete bending. Azadpour et al. [32] investigated the crack repair capability of SMA wires beams under cyclic loading. Hong et al. [33] applied superelastic SMA wires to concrete columns. The results showed that the superelastic SMA wires can improve the axial loading capacity and deformation performance of the column. Muntasir et al. [34, 35] used SMA bars in bridge piers and proposed a performance-based damage development state and seismic design method. Ge et al. [36] found that SMA bars can improve bridge serviceability after earthquakes. Wang et al. [37] used SMA bars in shear walls and Abraik et al. [38] established a numerical model. It showed smaller residual deformation and better energy dissipation capacity than shear walls using steel bars.

In addition, many scholars have researched SMA composites. Yousef et al. [39] used SMA and GFRP to reinforce concrete frames. Zafar et al. [40] proposed an SMA–FRP composite material for the seismic reinforcing of concrete structures. SMA-FRP composite reinforcement enhanced the ductility [41], fatigue and tensile properties [42] and energy dissipation capacity [43] of concrete structures. The SMA fibers in the ECC were added by Yang et al. [44] to enhance the ability of concrete structures to dissipate energy and perform self-centering. The semi-dog bone specimens were made for a cyclic pull-out test which found that knotted SMA fibers were better able to bond. Chen et al. [45–47] added SMA fibers to ECC to make a composite material. With the increase in SMA content, the self-healing ability increased, but the self-healing ability did not change after 0.7%. Additionally, they observed the excellent crack repair effect provided by composite materials in beam–column joints.

Previous studies have shown that the use of FRP bars can be used to solve the problem of steel corrosion. However, the ductility of FRP bars is low, resulting in poor energy dissipation capacity of the structure. SMA has good corrosion resistance and superelasticity, and the use of SMA bars provides the structure with good self-centering ability and energy dissipation capacity, and improves the ductility of the structure. In order to save resources,
we should expand the development and utilization of marine resources. This test used SWSSC instead of ordinary concrete to alleviate the shortage of resources, and SMA bars instead of FRP bars and anti-corrosive steel bars. In this test, four SWSSC beams were set up, and the effects of the reinforcement ratio, strength grade of SWSSC and types of reinforcement on the flexural performance of beams were considered. The failure process, maximum crack width, mid-span deflection, displacement ductility and stiffness degradation were studied by means of cyclic loading tests.

2. Experimental Program

2.1. Specimen Design

Three SMA bar-reinforced SWSSC beams and one anti-corrosive steel bar-reinforced SWSSC beam were designed and fabricated. The four beams for this test were cast from the same batch of concrete. The cross-sectional dimensions of the beam were 100 mm × 100 mm, its length was 1100 mm, its predicted span was 1000 mm, and its concrete protective layer thickness was 15 mm. SMA bars with diameters of 8 mm and 10 mm and HRB400 anti-corrosive steel bars with diameters of 8 mm were used to reinforce SWSSC beams. Anti-corrosive steel bars were made by coating the surface of steel bars with a metal rust inhibitor. Erection bars and stirrups were made of HRB400 steel bars with a diameter of 6 mm. Beam size and the reinforcement structure are shown in Figure 1. The effects of the reinforcement rate of the SMA bar, the strength grade of SWSSC and the type of reinforcement on the flexural performance of beams were studied (Table 1). In the table, B is beam, S is the anti-corrosive steel bar and SMA is the SMA bar. The diameters are 8 and 10 mm. C35 and C50 refer to the strength grades of SWSSC. The mechanical properties of the anti-corrosive steel bar and the SMA bars are shown in Table 2.

![Figure 1. Specimen size and reinforcement structure.](image)

**Table 1.** Basic parameters of specimens of anti-corrosive steel bar and SMA bar.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Concrete Grades</th>
<th>Types of Tensile Bar</th>
<th>Diameter of Tensile Bar</th>
<th>Ratio of Reinforcement</th>
</tr>
</thead>
<tbody>
<tr>
<td>B-S8-C35</td>
<td>C35</td>
<td>Anti-corrosive steel bar</td>
<td>8 mm</td>
<td>1.508%</td>
</tr>
<tr>
<td>B-SMA8-C35</td>
<td>C35</td>
<td>SMA bar</td>
<td>8 mm</td>
<td>1.508%</td>
</tr>
<tr>
<td>B-SMA10-C35</td>
<td>C35</td>
<td>SMA bar</td>
<td>10 mm</td>
<td>2.356%</td>
</tr>
<tr>
<td>B-SMA10-C50</td>
<td>C50</td>
<td>SMA bar</td>
<td>10 mm</td>
<td>2.356%</td>
</tr>
</tbody>
</table>

**Table 2.** Mechanical properties of the anti-corrosive steel bar and SMA bars.

<table>
<thead>
<tr>
<th>Types of Tensile Bar</th>
<th>Diameter (mm)</th>
<th>Yield Strength (MPa)</th>
<th>Ultimate Strength (MPa)</th>
<th>Elastic Modulus (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Erection bar</td>
<td>6</td>
<td>414.08</td>
<td>562.73</td>
<td>1.92 × 10^5</td>
</tr>
<tr>
<td>Anti-corrosive steel bar</td>
<td>8</td>
<td>441.89</td>
<td>581.19</td>
<td>2.07 × 10^5</td>
</tr>
<tr>
<td>SMA bar</td>
<td>8</td>
<td>374.5</td>
<td>4.17 × 10^4</td>
<td></td>
</tr>
<tr>
<td>SMA bar</td>
<td>10</td>
<td>410.7</td>
<td>5.03 × 10^4</td>
<td></td>
</tr>
</tbody>
</table>
2.2. Test Material

2.2.1. SMA Bars Materials

The material composition is shown in Table 3. In order to improve the superelasticity of SMA, the rod needed to be heat-treated first. The high-temperature furnace’s temperature was increased to 400 degrees centigrade for 30 min. After the temperature in the furnace was stable, the material was placed in the furnace and held at the target temperature for 15 min, after which the material was taken out for water cooling. The CMT universal material testing machine performed the uniaxial tensile test on SMA bars, as illustrated in Figure 2. The strain amplitude was 1%, 2%, 3%, 4%, 5% and 6%, respectively (Figure 3). When the strain amplitude reached 6%, the residual strains of SMA bars with diameters of 8 mm and 10 mm were 1.06% and 1.12%, respectively.

![CMT universal testing machine](image)

Figure 2. CMT universal testing machine.

![Stress-strain relationship curves of SMA bars](image)

Figure 3. Stress-strain relationship curves of SMA bars: (a) 8 mm; (b) 10 mm.

Table 3. SMA material composition content.

<table>
<thead>
<tr>
<th>Composition</th>
<th>Ni</th>
<th>Ti</th>
<th>O</th>
<th>C</th>
<th>N</th>
<th>H</th>
<th>Co</th>
<th>Cu</th>
<th>Cr</th>
<th>Fe</th>
<th>Nb</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ratio (Wt%)</td>
<td>55.90</td>
<td>remainder</td>
<td>0.039</td>
<td>0.032</td>
<td>0.001</td>
<td>0.001</td>
<td>0.005</td>
<td>0.005</td>
<td>0.005</td>
<td>0.012</td>
<td>0.005</td>
</tr>
</tbody>
</table>
2.2.2. Seawater Sea-Sand Concrete Material

The mix proportions of SWSSC are shown in Table 4. Natural sea-sand from Lianyungang City of China was selected and continuously graded. The cement was 42.5R-grade ordinary Portland cement. The crushed stone was made of continuously graded basalt crushed stone with a particle size of 5–10 mm. The seawater was obtained by artificial configuration, and the ratio of concentrated salt of artificial seawater to fresh water was 1:30. The 150 mm × 150 mm × 150 mm standard test block was made for the compressive strength test. Table 5 displays the outcomes of the compressive strength test. The table shows that the average compressive strength of C35 is 38.91 MPa and that of C50 is 51.42 MPa, which meets the standard strength requirements.

Table 4. Mix proportion of SWSSC.

<table>
<thead>
<tr>
<th>Concrete Grade</th>
<th>Cement (kg/m³)</th>
<th>Seawater (kg/m³)</th>
<th>Sea-Sand (kg/m³)</th>
<th>Gravel (kg/m³)</th>
<th>Water Reducer (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C35</td>
<td>372</td>
<td>175</td>
<td>797</td>
<td>1056</td>
<td>0.744</td>
</tr>
<tr>
<td>C50</td>
<td>515</td>
<td>175</td>
<td>667</td>
<td>1043</td>
<td>1.03</td>
</tr>
</tbody>
</table>

Table 5. Compressive strength test results of SWSSC.

<table>
<thead>
<tr>
<th>Concrete Grades</th>
<th>Group 1 (MPa)</th>
<th>Group 2 (MPa)</th>
<th>Average Value (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C35 (MPa)</td>
<td>38.47</td>
<td>39.35</td>
<td>38.91</td>
</tr>
<tr>
<td>C50 (MPa)</td>
<td>53.00</td>
<td>49.84</td>
<td>51.42</td>
</tr>
</tbody>
</table>

2.3. Loading Device and Loading System

The effective span of the beam is 1000 mm, the support is 50 mm from the end of the beam, and the pure bending section is 400 mm. Due to the smooth surface of the SMA bar and the poor bonding performance between the SWSSC, we designed and manufactured a fixture as shown in Figure 4. During the test, the SMA bars were tightened with the fixture to avoid slippage. The four-point bending test was adopted, and the HLFLJ-500 was selected for loading (Figure 5).

According to the “Concrete Structure Test Method Standard” (GB50152-2012) in China, displacement control and one-way cyclic graded loading were used in test loading. The specimens were first pre-loaded to test whether the equipment was working properly. The pre-loading was separated into two loads, and the final load could not be greater than 70% of the projected cracking load. The loading took the yield displacement value of the stressed bar as the grade difference, and the integer times were loaded step by step. The load was held at the peak point of each load level for 5 min to record the crack development. The specific loading system is shown in Figure 6.

Figure 4. Fixture installation drawing.
3. Test Phenomena and Failure Modes

3.1. B-S8-C35

In the first stage of cycle loading, the beam cracked when the load was increased to 4.095 kN. The mid-span of the beam developed three tiny fractures, each measuring around 15 mm in length. The component entered the yield state and the corresponding yield load was 34.675 kN when the displacement was loaded to 7.5 mm. At this time, the maximum crack width was 0.4 mm and the number of cracks increased to 12. As the displacement increased, the cracks continued to extend upward and the number of cracks was unchanged. When loaded to 15 mm, the beam reached its ultimate bearing capacity of 39.596 kN. The maximum crack width was observed to be 1.8 mm (Figure 7a), and the crack width after unloading was 1.2 mm (Figure 7b). The crack recovery rate was 33.3%. The top concrete peeled off and the beam was destroyed when the displacement was loaded
to 27.5 mm. Figure 7c is the final failure mode of B-S8-C35, and a total of 12 cracks were observed in the B-S8-C35.

3.2. B-SMA8-C35

When the load was increased to 3.817 kN, a vertical crack of 0.06 mm in width and 25 mm in length appeared in the span. When the displacement was increased to 2.5 mm, the crack width was 0.1 mm, and the crack closed after unloading. When the displacement was loaded to 10 mm, the component entered the yield state and the corresponding yield load was 21.567 kN. At this time, the maximum crack width reached 1.7 mm and the crack width was 0.5 mm after unloading. The maximum crack width was observed to be 3.2 mm in the ninth cycle, as shown in Figure 8a. The crack width was 1.1 mm after unloading, as shown in Figure 8b. This indicates that the component has good crack repair ability. When the displacement was loaded to 25 mm, the beam reached its ultimate bearing capacity of 30.204 kN. As the load increased, the bearing capacity began to decline and the compression zone concrete began to crack. The top of the beam compression zone concrete was crushed when loaded to 40 mm. Figure 8c is the final failure mode of B-SMA8-C35, and a total of six vertical cracks were observed in B-SMA8-C35.
3.2. B-SMA8-C35

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Figure 8. Test phenomena and failure mode of B-SMA8-C35: (a) loading; (b) unloading; (c) failure mode.

3.3. B-SMA10-C35

When the load was increased to 3.823 kN, the first small vertical crack appeared in the beam and the crack height was about 20 mm. After the first cycle, the number of cracks increased to five. The maximum crack width was 0.05 mm and all closed after unloading. Seven cracks appeared in the beam when the displacement was loaded to 5 mm, and the maximum crack width increased to 0.2 mm. When the load was loaded to 10 mm, the SMA bars yielded and the corresponding yield load was 26.269 kN. At this time, the maximum crack width increased to 1.1 mm and the crack width after unloading was 0.32 mm. The highest crack width in the seventh cycle was 2.1 mm (Figure 9a). As indicated in Figure 9b, the crack after unloading was 0.7 mm wide. The crack recovery rate was 66.67%. When the displacement continued to be loaded to 22.5 mm, the beam reached its ultimate load of 35.524 kN and then the bearing capacity decreased. As the displacement continued to increase, the crack width increased and an oblique bifurcation crack extending to the support appeared at the main crack. When the displacement was loaded to 37.5 mm, the top concrete was crushed. Figure 9c is the final failure mode of B-SMA10-C35, and a total of seven vertical cracks were observed in B-SMA10-C35.
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![Figure 9: Test phenomena and failure mode of B-SMA10-C35](image)

3.4. B-SMA10-C50

When the load was increased to 4.487 kN, the first vertical crack with 23 mm length appeared in the middle span of the specimen. When loaded to 2.5 mm, the crack width was 0.03 mm and the crack was closed after unloading. The number of cracks increased to seven when loaded to 5 mm. At this time, the maximum crack width was 0.15 mm and the crack width was 0.02 mm after unloading. When displacement continued to increase to 10 mm, the SMA bars entered the yield state and the corresponding yield load was 30.112 kN. At this time, the cracks continued to extend upward and the width increased to 0.9 mm. After unloading, the crack width was 0.25 mm and the recovery effect was better. The maximum crack width in the eighth cycle was measured to be 2.5 mm, as shown in Figure 10a. The width after unloading was 0.9 mm and the crack recovery rate was 64%, as shown in Figure 10b. When loaded to 22.5 mm, the crack began to extend to the loading point and the beam reached the ultimate bearing capacity of 43.260 kN. At this time, the crack width continued to increase, and the top concrete surface bulged. When the displacement was loaded to 37.5 mm, the load bearing capacity of the component dropped below 85% of the limit load and the component was destroyed. Figure 10c is the final failure mode of B-SMA10-C50, and a total of eight cracks were observed in the B-SMA10-C50.
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Figure 10. Test phenomena and failure mode of B-SMA10-C50: (a) loading; (b) unloading; (c) failure mode.

4. Test Results

4.1. Load–Displacement Curve

We recorded mid-span deflection and the load value at the loading and plotted the load–displacement curve, as shown in Figure 11.

It can be found that the B-SMA8-C35 experienced greater deformation before failure under the same reinforcement ratio by comparing Figure 11a,b. The residual displacement and rigidity degeneration rate under the same loading displacement were significantly smaller than those of B-S8-C35. This shows that SMA bars can improve the ductility of the specimen.

Figure 11b,c showed that the B-SMA10-C35 load–displacement curve was fuller. This shows that raising the reinforcement ratio could improve the energy dissipation capacity of the specimen. At the same time, it can be seen that the peak load of B-SMA10-C35 was greater than that of B-SMA8-C35. This demonstrates that raising the reinforcement ratio of the specimen can also enhance the bearing capability.
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Figure 11c,d show that the bearing capacity of the beam rose by 21.77% as the strength grade of SWSSC increased from C35 to C50. This demonstrates that raising the strength grade of SWSSC can greatly increase the specimen’s ability to withstand flexural loads. Since the bending capacity of the normal section of the beam was proportional to the strength of the concrete, the higher the strength, the smaller the height of the compression zone, and the greater the bearing capacity.

4.2. Skeleton Curve

The skeleton curve comprehensively reflects the mechanical performance of specimens at various loading stages. Figure 12 depicts the mid-span skeleton curves of each beam in this test, and the load values are shown in Table 6.

During the elastic stage, the skeleton curve of beams increased linearly. Because the elastic modulus of the anti-corrosive steel bar was much larger than that of the SMA bar, the slope of the skeleton curve of the anti-corrosive steel bar was larger.

At the initial loading, the skeleton curves of the three SMA bar-reinforced beams were basically coincident. The slope of the skeleton curves of beams with a high reinforcement ratio of SMA bars and a high strength grade of SWSSC was steeper. It was discovered that boosting the reinforcement ratio and concrete strength grade can greatly enhance beam bearing capacity.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Cracking Load/kN</th>
<th>Yield Load/kN</th>
<th>Peak Load/kN</th>
</tr>
</thead>
<tbody>
<tr>
<td>B-S8-C35</td>
<td>4.10</td>
<td>34.68</td>
<td>39.60</td>
</tr>
<tr>
<td>B-SMA8-C35</td>
<td>3.82</td>
<td>21.57</td>
<td>30.20</td>
</tr>
<tr>
<td>B-SMA10-C35</td>
<td>3.83</td>
<td>26.27</td>
<td>35.52</td>
</tr>
<tr>
<td>B-SMA10-C50</td>
<td>4.49</td>
<td>30.11</td>
<td>43.26</td>
</tr>
</tbody>
</table>

Figure 11. Load mid-span displacement curve: (a) B-S8-C35; (b) B-SMA8-C35; (c) B-SMA10-C35; (d) B-SMA10-C50.
Table 6. Characteristic points of specimens.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Cracking Load/kN</th>
<th>Yield Load/kN</th>
<th>Peak Load/kN</th>
</tr>
</thead>
<tbody>
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<td>B-SMA10-C35</td>
<td>3.83</td>
<td>26.27</td>
<td>35.52</td>
</tr>
<tr>
<td>B-SMA10-C50</td>
<td>4.49</td>
<td>30.11</td>
<td>43.26</td>
</tr>
</tbody>
</table>

5. Analysis and Discussion

5.1. Maximum Crack Width

The change in crack width after peak load and unloading reflected the crack self-healing ability of the specimen.

Figure 13 shows that the crack width of the beam developed slowly during the elastic stage. At this time, the crack width was small, and the crack was basically closed after unloading. After entering the yield stage, the crack width of each beam increased significantly, and the residual crack width was obvious after unloading.

The crack width of the three SMA bar-reinforced specimens before yielding was larger than that of the anti-corrosive steel bar-reinforced specimens. Due to the low elastic modulus of the SMA bar-reinforced beams, the bond between SMA bars and SWSSC was weak. After unloading, the crack widths of SMA bars were significantly reduced and the cracks closed very well. This reflects the good superelasticity of SMA bars, which can improve the crack self-healing ability of the beam.

Comparing the specimens in Figure 13b,c, the crack width of B-SMA10-C35 was smaller during loading when increasing the diameter and reinforcement rate of SMA, indicating that increasing the reinforcement rate inhibited the development of crack width. After unloading, the crack width of both were close, and increasing the reinforcement rate did not further improve the recovery effect.

Comparing Figure 13c,d, the effect of increasing the strength of concrete on the crack width was not obvious.

Figure 12. Skeleton curve.

The stiffness of B-S8-C35 decreased rapidly once the maximum load was reached, and the load carrying capacity was quickly lost. The bearing capacity of SMA bars decreased slowly and can withstand greater deformation. It showed that SMA can significantly improve the ductility of the specimen.
5.3. Ductility Analysis

Ductility is defined as the deformation capacity of the structure when the load is no longer applied. The displacement ductility factor is represented by the displacement ductility factor, which is the ratio of ultimate displacement to yield displacement of the specimen. The larger the ductility factor, the better the deformation and ductility of the specimen.

The analysis shows that the mid-span deflection of the four specimens increased linearly with the increase in the number of cycles. After unloading, the deflection was restored. It can be seen that the number of cycles and the degree of recovery of SMA bar-reinforced beams were greater than those reinforced with anti-corrosive steel bars. The superelasticity of SMA can enhance the ductility and recovery ability of the beam.

Comparing Figure 13c,d, the effect of increasing the strength of concrete on the crack deformation and ductility of the specimen was analyzed (Figure 14).

5.2. Mid-Span Deflection

The mid-span deflection corresponding to each stage of cyclic loading to the peak and after unloading were analyzed (Figure 14).

Figure 14. Maximum crack width change: (a) B-S8-C35; (b) B-SMA8-C35; (c) B-SMA10-C35; (d) B-SMA10-C50.
The analysis shows that the mid-span deflection of the four specimens increased linearly with the increase in the number of cycles. After unloading, the deflection was restored. It can be seen that the number of cycles and the degree of recovery of SMA bar-reinforced beams were greater than those reinforced with anti-corrosive steel bars. It showed that the superelasticity of SMA can enhance the ductility and recovery ability of the beam. Under the same reinforcement ratio, before the damage of B-S8-C35, the difference in peak mid-span deflection between anti-corrosive steel bar- and SMA bar-reinforced beams was very small, but the elastic modulus of steel bars was much stronger than that of SMA bars. It was proved that the use of SMA bars can improve the deflection of the component after unloading. However, increasing the reinforcement ratio and concrete strength grade has no noticeable effect on the deflection of the beam after unloading.

5.3. Ductility Analysis

Ductility refers to the deformation capacity of the structure when there is no noticeable drop in bearing capacity after the yield point is achieved. In this test, the deformation ability of each specimen is represented by the displacement ductility coefficient \( \mu \), which is the ratio of ultimate displacement to yield displacement of the specimen, as shown in Equation (1). The larger the ductility coefficient, the better the deformation capacity of the specimen.

\[
\mu = \frac{\Delta_u}{\Delta_y}
\]

where \( \Delta_u \) indicates the displacement corresponding to the specimen yielding under cyclic loading, and \( \Delta_y \) indicates the displacement corresponding to the specimen when the bearing ability drops to 85% of the peak load.

The displacement ductility factors of specimens are shown in Table 7. Through analysis, we know that under the same reinforcement ratio, the yield displacement, ultimate displacement and ductility coefficient of SMA bar-reinforced beams were greater than those reinforced with anti-corrosive steel bars. They increased by 33.48%, 44.57% and 8.4%, respectively. This shows that using SMA bars can significantly increase the deformation and ductility of specimens.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>( P_y / \text{kN} )</th>
<th>( \Delta_y / \text{mm} )</th>
<th>( P_u / \text{kN} )</th>
<th>( \Delta_u / \text{mm} )</th>
<th>( \mu )</th>
</tr>
</thead>
<tbody>
<tr>
<td>B-S8-C35</td>
<td>34.68</td>
<td>8.40</td>
<td>31.38</td>
<td>30.13</td>
<td>3.59</td>
</tr>
<tr>
<td>B-SMA8-C35</td>
<td>21.57</td>
<td>11.21</td>
<td>24.45</td>
<td>43.55</td>
<td>3.88</td>
</tr>
<tr>
<td>B-SMA10-C35</td>
<td>26.27</td>
<td>10.43</td>
<td>29.40</td>
<td>41.40</td>
<td>3.97</td>
</tr>
<tr>
<td>B-SMA10-C50</td>
<td>30.11</td>
<td>10.91</td>
<td>37.08</td>
<td>42.46</td>
<td>3.89</td>
</tr>
</tbody>
</table>

Increasing the reinforcement rate and the diameter could increase the bearing capacity of the specimen, but the increase in displacement ductility coefficient was not obvious. The ultimate bearing capacity and stiffness of the beams increased but the ductility decreased slightly when the strength grade of SWSSC was increased.

5.4. Rigidity Degeneration

Rigidity degradation refers to the phenomenon where the specimen stiffness decreases continuously with the increase in load or displacement due to the elastic-plastic nature of the specimen after cracking and accumulated damage under cyclic reciprocal loading. This test used the cut-line stiffness \( K_i \) as the basis for evaluating the stiffness degradation of the specimen, and the specific calculation formula is shown in Equation (2):

\[
K_i = \frac{\sum_{j=1}^{nk} P_{ij}}{\sum_{j=1}^{nk} \Delta_{ij}}
\]
where $K_i$ represents the secant stiffness of the specimen at the $i$th cycle, $p_{ij}$ and $\Delta_{ij}$ indicate the peak load and peak displacement of the specimen at the $i$th cycle, respectively. Figure 15 is the degradation curve of the secant stiffness.

![Stiffness degradation curve](image)

**Figure 15.** Stiffness degradation curve.

The initial stiffness of the SMA-reinforced beams was less than anti-corrosive steel bars, which was due to smaller modulus of SMA bars. The stiffness degradation rate of anti-corrosive SMA bars was less than that of steel bars, indicating that the use of SMA bars can effectively slow down the stiffness degradation rate of the specimen.

Increasing the reinforcement ratio and strength grade of SWSSC, the stiffness of the specimen increased and the stiffness degradation rate decreased. This shows that increasing the reinforcement ratio and concrete strength of the specimen can limit the damage development of the specimen and delay the stiffness degradation of the specimen.

6. Conclusions

In this paper, three SMA bar-reinforced SWSSC beams and one anti-corrosive steel bar-reinforced SWSSC beam were subjected to cyclic loading tests. The failure process, crack self-healing ability, ductility and stiffness degradation of the specimens under the same loading system were investigated. The following conclusions can be drawn:

1. Under the same reinforcement rate, cracks can be effectively closed with SMA bars compared with anti-corrosive steel bars. It was proved that SMA bars can improve the crack repair ability of the structure.
2. The displacements and stiffness degradation rate of the beams reinforced with SMA bars were smaller than those reinforced with anti-corrosion steel bars. This indicates that SMA bars can increase the ductility and deflection of beam.
3. With the reinforcement rate of SMA bars increased, the flexural stiffness of beams strengthened with SMA bars increased and the crack width decreased.
4. When increasing the SMA diameter and the reinforcement rate, the loading stage suppresses the development of crack width. After unloading, the crack width of B-SMA8-35 and B-SMA10-35 was close, and increasing the reinforcement ratio did not further improve the recovery effect.

SMA bars were used to replace FRP bars as stress bars for SWSSC structures. Due to the superelasticity of SMA, it had a good self-healing effect on the cracks generated by the structure after loading and avoided further harm caused by the surrounding environment to the structure. At the same time, the ductility, energy dissipation capacity and seismic performance of structures were improved. For concrete structures, whether they have excellent durability often has a greater impact on their safety. Therefore, further research is needed.
to study the durability of SMA bar-reinforced SWSSC beams in specific environments to ensure their safety.

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References
7. Dong, Z.; Wu, G.; Xu, Y. Bond and Flexural Behavior of Sea Sand Concrete Members Reinforced with Hybrid Steel-Composite Bars Presubjected to Wet-Dry Cycles. J. Compos. Constr. 2017, 21, 04016095. [CrossRef]
16. Li, Y.; Zhao, X.; Singh Raman, R.K. Behaviour of seawater and sea sand concrete filled FRP square hollow sections. Thin Wall Struct. 2020, 148, 106596. [CrossRef]
17. Li, Y.; Zhao, X. Hybrid double tube sections utilising seawater and sea sand concrete, FRP and stainless steel. Thin Wall Struct. 2020, 149, 106643. [CrossRef]


27. Alarab, L.A.; Ross, B.E.; Pouraee, A. Corrosion Assessment of Coupled Steel Reinforcement with Ni-Ti-Based Shape Memory Alloy in Simulated-Concrete Pore Solution. J. Mater. Civil Eng. 2016, 28. [CrossRef]


29. Qian, H.; Zhang, Q.; Zhang, X.; Deng, E.; Gao, J. Experimental Investigation on Bending Behavior of Existing RC Beam Retrified with SMA-ECC Composites Bar. Materials 2021, 14, 15. [CrossRef]

30. Qian, H.; Li, Z.; Pei, J.; Kang, L.; Li, H. Seismic performance of self-centering beam-column joints reinforced with superelastic shape memory alloy bars and engineering cementitious composites materials. Compos. Struct. 2022, 294, 115782. [CrossRef]

31. Hong, K.; Yeon, Y.; Ji, S.; Lee, S. Flexural Behavior of RC Beams Using Fe-Based Shape Memory Alloy Rebars as Tensile Reinforcement. Buildings 2022, 12, 190. [CrossRef]


33. Kong, C.; Qian, H.; Song, G. Uniaxial Compressive Behavior of Concrete Columns Confined with Superelastic Shape Memory Alloy Wires. Materials 2020, 13, 1227. [CrossRef] [PubMed]


35. Billah, A.H.M.M.; Alam, M.S. Performance-Based Seismic Design of Shape Memory Alloy Reinforced Concrete Bridge Piers. II: Methodology and Design Example. J. Struct. Eng. 2016, 142. [CrossRef]


41. Wierschem, N.; Andrawes, B. Superelastic SMA–FRP composite reinforcement for concrete structures. Smart Mater. Struct. 2010, 19, 25011. [CrossRef]


44. Yang, Z.; Du, Y.; Liang, Y.; Ke, X. Mechanical Behavior of Shape Memory Alloy Fibers Embedded in Engineered Cementitious Composite Matrix under Cyclic Pulloff Loads. Materials 2022, 15, 4531. [CrossRef]

