Comparative Study on the Durability of Pile, Beam and Slab Reinforced Concrete Structure in Marine Environment

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Abstract. The durability of coastal reinforcement suffers serious threaten by the aggressive chloride in marine environment. The repairment of structures under service or new construction design has become an important part with increasing the requirement of long service lives of infrastructure, while the applied repairment should be inconsistence with the corrosion condition of different concrete structure in the port. Herein, this paper comparatively discusses the various deterioration level of pile, beam and slab under the same marine environment, and provide the guiding principles for further repairment. The results show that the beam structure exhibits the worst performance among three typical reinforcement structures. The exposed rebars of beam structures are seriously corroded due to the chloride attack and result in low corrosion potential and serious concrete spalling. In contrast, the slab structure exhibit better durability with intact appearance, low chloride penetration and high corrosion potential.

Keywords. Harbor & marine structure, chlorides, concrete, corrosion, durability.

1. Introduction
Corrosion of steel reinforcement exposed to marine environment leads to a major durability sustainability and safety issue for the harbor & marine engineering around the world [1, 2]. While, for the harbor & marine structure, the appearance and function of concrete structures was seriously deteriorated by the synergistic of atmospheric corrosion, chloride penetration and load fatigue [3, 4]. Researches have pointed that the concrete structure of wharf exhibits rust formation, racking, spalling, delamination and degradation after serviced for only 5~10 years [5]. It is necessary to provider appropriate repairment to prevent the degrading of corrosion in order to guarantee its safety. The detailed degradation information of different concrete structure should be determined before apply the repairment. Generally, the concrete structures including pile, beam and slab are the main components of wharf, and these concrete structures are also vulnerable to the degrading effects of corrosion, especially in splash zone [6]. Therefore, a typical marine wharf structure which has serviced for 20 years in south china was chose as the research object to explore the current state of knowledge on corrosion of marine concrete structure.

2. Experiment
The detailed information of corrosion medium such as chloride, pH, sulfate around the wharf was given in table 1. As we see, the pH value of seawater was 7.7, the average chlorine content, soluble substance content and sulfate content were 13008.1 mg/L, 26075.5 mg/L and 1791.0 mg/L.

Table 1. The content result of corrosion medium.

| Tides      | Chloride (mg/L) | soluble substance (mg/L) | pH | sulfate (mg/L) |
|------------|----------------|--------------------------|----|---------------|
| High tide  | 13136.3        | 26366                    | 7.7| 1815.8        |
| Low tide   | 12879.8        | 25785                    | 7.7| 1766.2        |
| Average    | 13008.1        | 26075.5                  | 7.7| 1791.0        |

Surface appearance of the pile, beam and slab were inspected by visual and camera photography. The number, location, strike, length and width of cracks and concrete damage, peeling, deterioration, steel corrosion in different structure were recorded. The service quality of concrete structure was rated as A, B, C and D according to “Technical Specification for detection and assessment of harbour and marine Structures”. The concrete thickness was measured by the reinforced protective layer thickness tester, respectively. The corrosion potential of rebar in concrete was tested by potentiostat in a two electrode system. The chloride content of concrete was further analysed in laboratory by automatic titrator, before test the concrete was grinding every 10 mm until to rebar, and then soak the concrete powder sample by acid solution method. The microscope was applied to analysis the rebar section loss by calculated the section area of corroded rebar.

3. Results and Discussion

3.1. Surface Morphology

There are 21 piles, 65 beams and 56 slabs of the wharf were checked in this project. The piles are maintained intact, the deterioration ratio of pile is 52.38%, which is mainly manifested as cracks on the side of the pile, and some concrete at the corner of the pile cap have peel off (figure 1(a)). The corrosion rust was also observed on the surface of concrete (figure 1(b)), it suggests that the corrosion medium has penetrated the concrete protective layer and leads to corrosion of steel. As for the beams, the degradation rate of beams was reach to 100%. Figure 1(c) and 1(d) show that all the beams were seriously damaged, and the concrete protective layers of beams have falls off with large area concrete both observed on the bottom and side. The steel was exposed to corrosion condition and some of them had lost their continuity. Similar damage was also observed in the junction between pile and beam. The appearance deterioration ratio of the slabs is 3.57%, most of the slabs are in good condition unless two concrete peeling phenomenon were observed at the bottom of slab (figure 1(e) and 1(f)). The surface appearance was rated to four grades according to “Technical Specification for detection and assessment of harbor and marine Structures”. As shown in table 2, after serviced for 20 years in marine environment, most of the slab structures were maintained intact with grade A. In the other side, the beam structure exhibited the worst performance with a 95.38% in grade D. Therefore, the surface appearance can be ordered as follow: slab, pile and beam.
Figure 1. The surface morphologies of pile, beam and slab under marine environment for 20 years.

### Table 2. The appearance quality of pile, beam and slab.

| Type    | Quantity | Rating (amount/ratio) | A  | B  | C  | D  |
|---------|----------|-----------------------|----|----|----|----|
| Pile    | 21       | 10                    | 2  | 8  | 47.62% | 9.52% | 38.10% | 4.76% |
| Beam    | 65       | 0                     | 0  | 3  | 0.00% | 0.00% | 4.62% | 95.38% |
| Slab    | 56       | 54                    | 0  | 2  | 96.43% | 0.00% | 3.57% | 0.00% |

3.2. Concrete Cover
We chose six typical reinforced concrete structures to measure the loss of concrete cover in this project based on the previous observation. The testing result of concrete cover thickness was indicated in table 3. The designed thickness of the concrete protective layer of the pile, beam and slab were 60 mm, 60 mm and 50 mm, respectively. The test results show that the percent of quality of protective layer thickness on the pile and slab all exceeds 90%. The thickness of the protective layer of beams inspected did not exceed 80%, which was failed to meet the requirements of the specification, and the test results were evaluated as unqualified. The above results were consistent with the surface appearance observation of pile, beam and slab.
Table 3. The concrete cover thickness test results of pile, beam and slab.

| Type   | Design (mm) | Zone | Test number | Min (mm) | Max (mm) | Ratio   | Quality |
|--------|-------------|------|-------------|----------|----------|---------|---------|
|        |             |      | 1 2 3 4 5 6 |          |          |         |         |
| Pile-1 | 60          | 1    | 63 62 60 65 | 60       | 73       | 91.7%   | Yes     |
|        |             | 2    | 61 71 70 68 | 62       | 71       | 94.4%   | Yes     |
|        |             | 3    | 63 61 73 67 | 62       | 72       | 94.4%   | Yes     |
|        |             | 4    | 65 70 66 70 | 65       | 72       | 94.4%   | Yes     |
| Pile-2 | 60          | 1    | 61 64 61 63 | 60       | 71       | 94.4%   | Yes     |
|        |             | 2    | 64 62 60 72 | 60       | 71       | 94.4%   | Yes     |
|        |             | 3    | 63 62 67 68 | 60       | 68       | 94.4%   | Yes     |
|        |             | 4    | 64 73 73 60 | 61       | 71       | 94.4%   | Yes     |
| Beam-1 | 60          | 1    | 66 60 57 63 | 51       | 69       | 66.7%   | No      |
|        |             | 2    | 64 63 58 66 | 60       | 62       | 66.7%   | No      |
|        |             | 3    | 64 62 66 54 | 50       | 55       | 66.7%   | No      |
|        |             | 4    | 59 67 54 69 | 57       | 51       | 66.7%   | No      |
| Beam-2 | 60          | 1    | 66 67 56 57 | 55       | 57       | 77.8%   | No      |
|        |             | 2    | 67 67 57 62 | 55       | 71       | 77.8%   | No      |
|        |             | 3    | 67 57 61 67 | 55       | 68       | 77.8%   | No      |
|        |             | 4    | 55 62 70 63 | 56       | 66       | 77.8%   | No      |
| Slab-1 | 50          | 1    | 55 57 58 55 | 53       | 58       | 100%    | Yes     |
|        |             | 2    | 55 53 58 58 | 53       | 58       | 100%    | Yes     |
|        |             | 3    | 58 56 58 56 | 54       | 54       | 100%    | Yes     |
| Slab-2 | 50          | 1    | 56 54 57 55 | 53       | 57       | 100%    | Yes     |
|        |             | 2    | 56 56 53 55 | 53       | 56       | 100%    | Yes     |
|        |             | 3    | 56 54 57 55 | 53       | 57       | 100%    | Yes     |

3.3. Chloride Penetration
Chloride content in concrete is the key role to induce corrosion of steel. Herein, the typical pile, beam and slab were extracted to test the permeation and diffusion of chloride ions in concrete after 20 years. According to the detection results of protective layer thickness, the number of grinding layers of pile, beam and slab structure was determined as 7, 7 and 5, respectively. The test results are shown in figure 2. The chloride content of all structures was degreased with increasing the penetrate thickness. The beam structure has the highest surface chloride content reach to 6.4%, it mainly due to the intermittent tide. On the contrary, the chloride content of slab structure was only half of beam structure. The chloride content of pile and beam structures around the steel have excess the critical chloride
concentration (0.45%), and that of slab structure was also prone to corrosion. It can be deduced that the whole concrete structure of wharf has been polluted by chloride after 20 years.

Figure 2. The chloride diffuse content with cover thickness in pile, beam and slab structure.

3.4. Corrosion of Steel Bar: Potential and Loss

The corrosion potential of three types concrete structure were tested by the half-cell potential method, and the test results were shown in figure 3. There are 60 points were tested for each structure. With respect to the pile structures, about 90% of the tested corrosion potential was negative to -350 mV (refer to Cu/CuSO₄), indicating that the steel of pile structure has corroded [7]. The corrosion condition of beam structure was more dangerous than that of pile structure. As we can see, all the corrosion potential of the tested points in beam structure was range from -350 mV to -420 mV. However, the slab structure exhibited a bit better performance than pile and beam. The corrosion potential value focuses on nearly -350 mV or even positive. Based on the site appearance inspection and the observation of steel, it is found that some steel reinforcement has indeed begun to corrode, all the concrete structure were at high risk to corrosion.

Figure 3. The open circuit potential distribution of rebar in (a) pile, (b) beam and (c) slab, respectively

According to the hydraulic structure detection and evaluation technology of port engineering, if the section loss rate of the reinforcement is within the range of 10% to 60%, the mechanical properties of
the reinforcement are seriously reduced. As indicated in figure 4, the section area loss ratio of steel in slab structure is within 5% to 10%. Observation results of pile reinforcement section area loss rate was more than 10%. Especially, the section loss rate of rebar in beam has exceeded 80%, suggesting that the mechanical properties of steel has been serious declined.

**Figure 4.** The comparative section loss ratio of steel in pile, beam and slab structure.

### 4. Conclusion

Durability of pile, beam and slab reinforced concrete structure in marine environment is comparatively addressed in this paper. The concrete structure observed in this wharf has suffered serious corrosion after serviced for 20 years. Especially, the beam structure exhibited the worst performance both in surface appearance, concrete cover, chloride penetration and steel corrosion among the three typical concrete structures. Therefore, it is necessary to develop an appropriate additional corrosion protection design of beam structure considering the consistency service life of the whole wharf.

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