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Deterioration of Steel-Concrete Composite Structures under Marine Conditions
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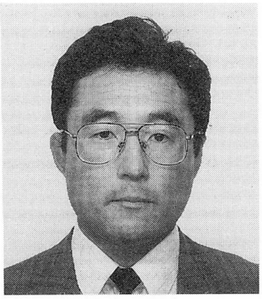
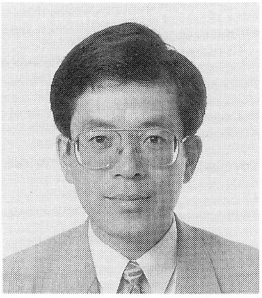
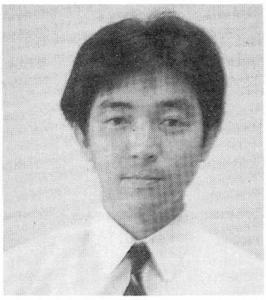

Tsutomu FUKUTE Hiroshi YOKOTA Hidenori HAMADA

SYNOPSIS

Steel-concrete composite members find wide application in structures because of their excellent mechanical characteristics. Under marine conditions, however, steel plates corrode and this may initiate cracks in the concrete. This paper presents the results of exposure tests of composite structures in a marine environment and various analysis results with the aim of clarifying the corrosion characteristics of the steel plates. Corrosion of the steel plates is a principal cause of composite member deterioration and it is shown to be affected by ambient conditions, such as found in splash or tidal zones. Furthermore, it is shown that corrosion occurs in micro corrosion cells on the plate surface. On the basis of these test results, the corrosion rates of steel plates are also investigated.

Keywords : steel-concrete composite structure, marine environment, corrosion, durability,

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1. INTRODUCTION

Composite structures comprising steel plates and concrete, and particularly sandwich and open-sandwich structures, exhibit excellent mechanical characteristics [1]. Figure 1 shows examples of open sandwich and sandwich structures. Such designs have been often applied to bridges and buildings, and recently they have begun to be used in offshore structures. In offshore work, such structures have a number of advantages such as superior strength and toughness, lowweight, and watertightness. These advantages bring safer and more economical construction, yet here are two main drawbacks in applying these composite structures in the offshore environment. Firstly, design standards have not yet been fully established. One of the authors has been conducting structural tests to establish design methods and has proposed several design equations[1]. The second drawback is a serious lack of information about the durability of steel plates under marine conditions. Corrosion trends have been documented for various types of steel structure in marine regions, but composite structures can be expected to show different corrosion trends because the steel plates contact sea water on their outside surfaces and concrete on the inside. This drawback, deterioration under marine conditions, is highlighted in this paper. Three series of exposure tests were conducted to clarify the corrosion tendencies of steel plates. Through these exposure tests, fundamental characteristics of the deterioration of composite structures are investigated, and the corrosion of steel plates either directly or indirectly exposed to the marine environment is quantified. Corrosion rate for steel plates are also discussed.

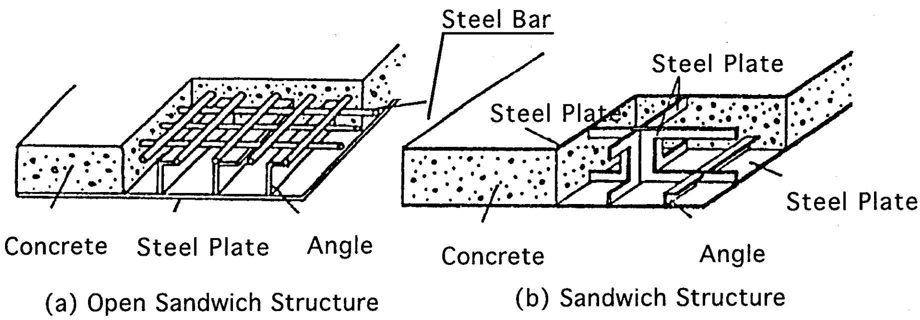


Fig.1 Example of Steel - concrete Composite Structures

2.FUNDAMENTAL DETERIORATION OF COMPOSITE STRUCTURES

2.1 Outline of Exposure Tests

The purpose of the exposure tests described in this section is to understand the fundamental characteristics of composite structure deterioration under marine conditions. The specimens used are designated "HR1", "HS1", HR2" and "HS2". "HR" designates an open sandwich structure and "HS" a sandwich structure. Figure 2 shows the shape and size of "HR1" and "HS1". The cross section of these specimens is 200 mm × 300 mm, and they are 2500 mm in length. The "HR2" and "HS2" have same cross section, but they are 1,000 mm long. In addition to these composite specimens, steel plates with angles having equal legs 40 by 40 by 3 mm are also tested as a reference. The steel plate used is SS 400 (Japan Industrial Standard), 10 mm in thickness. Steel plates and concrete are integrated using steel angles with equal legs 40 by 40 by 3 mm. These steel angles are attached to the steel plates at a spacing of 200 mm. In all specimens, D16 steel bars of SD295 are also embedded in order to check the corrosion characteristics of steel reinforcement in concrete. In this case, the steel bars and steel plates are not connected electrically. The cement used are ordinary portland cement and portland blast-furnace slag cement (B-type). The fine aggregate is crushed sand, and the coarse aggregate is crushed stone (maximum size : 20 mm). The water to cement ratio of the concrete is 65%. The

(unit : mm)

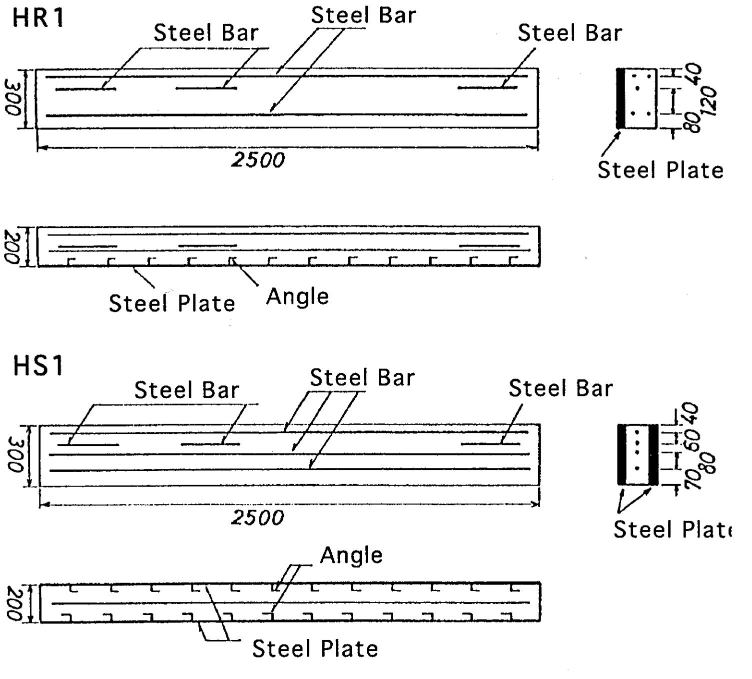


Fig.2 Shape and Size of Specimens

compressive strengths at 28 days are 27.9 N/mm^2 (ordinary portland cement) and 30.3 N/mm^2 (portland blast-furnace slag cement B-type). Test specimen for compressive strength are cylinders of size ϕ 10 ×20 cm. At one day old, the specimens are demoulded and air cured in a room at 20 ℃ and 50 % relative humidity for a month. After one month of air curing, the specimens are placed in exposure sites, a tidal pool, and a sea water splashing facility. The tidal pool simulates a "submerged zone". In this pool, specimens are submerged constantly in sea water. The sea water splashing facility simulates the "splash zone". In this facility, specimens are exposed to three hours of sea water splashing twice a day. After one year of exposure, the specimens are removed from the exposure sites and observed visually. After removing the steel plates from the concrete, the corrosion depth and corroded area of the steel plates is measured. Corrosion depth is calculated from the initial thickness and the residual thickness. The residual thickness is measured using an ultrasonic sounding thickness gauge.

2.2 Deterioration of Test Specimens

Photo 1 shows a specimen after one year of exposure in the splash zone. The whole surface of the steel plate exposed to splashing is corroded. On the sides of the concrete, several cracks running from the angles are observed. Figure 3 shows this crack condition schematically. The length of the cracks is about 20~50 mm, and they are about 0.2~0.3 mm wide. Photo 2 shows an example of the inner surface of a steel plate after one year of exposure in the splash zone. That is, the surface in contact with the concrete during the exposure period. The central area of the inner surface is not corroded, but the edge shows same evidence of corrosion. Figure 4 schematically shows the condition of steel plate inner surfaces of "HR2" and "HS2" after one year of exposure in the submerged zone and splash zone.

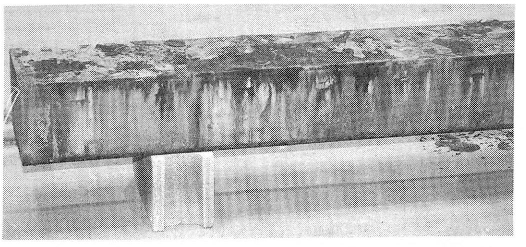


Photo 1 Example of Specimen after one year of Exposure in Splash Zone

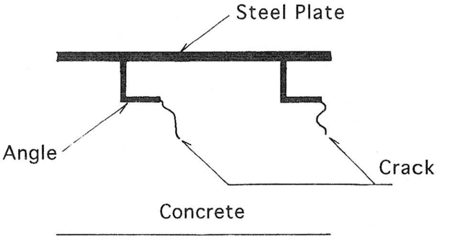


Fig.3 Crack Condition in Concrete

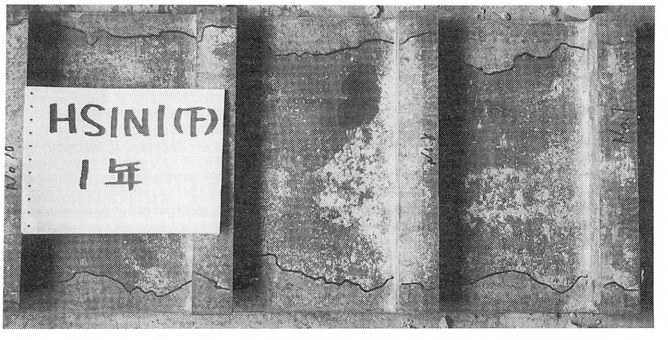


Photo 2 Example of Inner Surface of Steel Plate after One Year of Exposure in Splash Zone

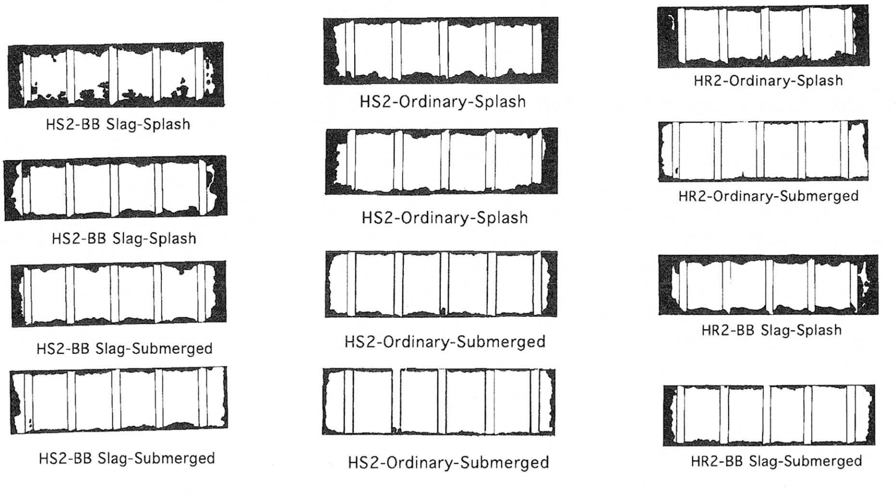


Fig.4 Corrosion on Inner Surface after Exposure

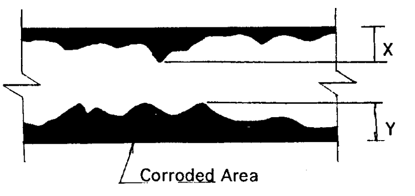
In this figure, black represents the corroded area. As a parameter of corrosion magnitude on the inner surface, we define the "maximum corroded distance". Figure 5 shows a definition of maximum corroded distance.

On the steel bars embedded in the specimens, no corrosion is found after one year of exposure.

2.3 Indexes of Steel Plate Corrosion Magnitude

Table 1 shows the maximum corrosion distance of the inner surface, the corroded area of the inner surface, and the corroded depth of the steel plate. Each datum for corroded depth represents an average of forty five data points. Figure 6 shows the relationship between maximum corroded distance and corroded area, and the relationship between corroded area and corroded depth. Coefficients of correlation are 0.75 and 0.80 respectively. It can be said that there is same correlation. Based on this correlation, corroded depth is used in this paper as an index indicating the steel plate corrosion magnitude.

Model of Inner Surface



X>Y : maximum corrosion distance is X
Y>X : maximum corrosion distance is Y

Fig.5 Definition of Maximum Corrosion Distance

2.4 Factors Influencing Corrosion of the Steel Plate

Table 1 Corrosion Magnitude of Steel Plate after Exposure

Type of Specimen	Cement	Exposure Condition	Maximum Corroded Distance (cm)	Corroded Area of Inner Surface (%)	Corroded Depth of Steel Plate (mm)
HR1	Ordinary	Splash	6.6	30.0	0.44
	BB	Splash	11.4	33.1	0.42
HS1	Ordinary	Splash	6.6	26.8	0.72
		Splash	6.3	25.1	0.56
	BB	Splash	10.4	32.4	0.77
		Splash	18.2	30.4	0.56
HR2	Ordinary	Splash	6.3	30.4	0.62
		Submerged	5.1	11.4	0.15
	BB	Splash	5.7	33.9	0.70
		Submerged	3.1	16.0	0.31
HS2	Ordinary	Splash	4.6	24.9	0.51
		Splash	6.8	29.7	0.56
		Submerged	2.6	14.3	0.40
		Submerged	2.9	9.9	0.08
	BB	Splash	8.6	30.0	0.72
		Splash	9.7	36.3	0.50
		Submerged	6.0	22.0	0.45
		Submerged	3.4	16.5	0.22
Steel Only		Splash			0.62
		Splash			0.81

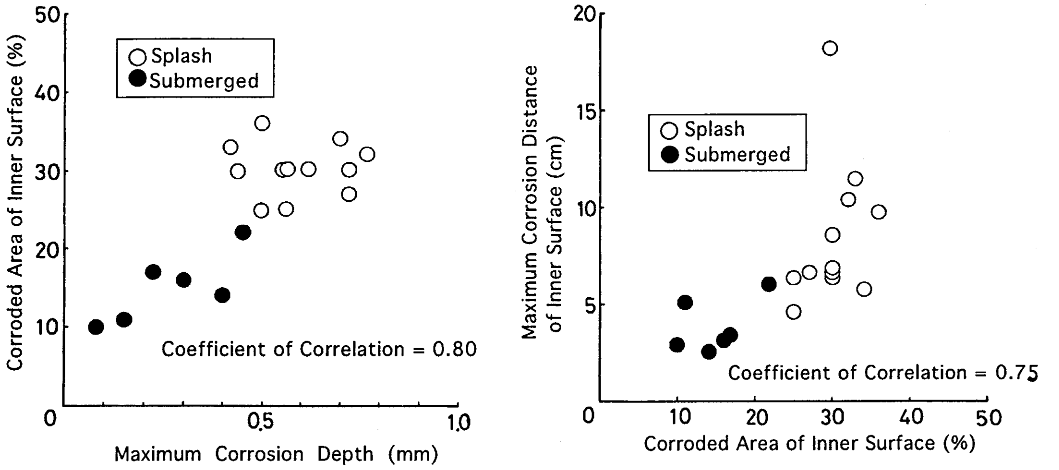


Fig.6 Relationship between Corrosion Indexes

Table 2 presents the effect of several factors on the steel plate corrosion magnitude. If a factor causes a difference of more than 0.3 mm in average corroded depth, it is judged to have an effect. On the other hand, if a factor causes a difference of less than 0.1 mm in average corroded depth, it is judged not to have an effect. From Table 2, it is clear that the factor with most dependence is the exposure conditions (splash zone or submerged zone). Other factors, such as size of the specimen, type of cement, and type of specimen, are independent. In other words, corrosion depends on environmental factors rather than factors inherent in the specimen.

Table 2 Effect of Various Factors

Factor	Corrosion Depth -- Average -- (mm)	Considered to Have an Effect
Size of specimen	large small (0.58 v.s. 0.60)	no
Exposure condition	splash submerged (0.60 v.s. 0.27)	yes
Cement	ordinary BB (0.45 v.s. 0.52)	no
Type of structure	sandwich open sandwich (0.50 v.s. 0.44)	no

2.5 Deterioration of Concrete

As mentioned earlier, all specimens exhibit cracks running from the steel angles. However, no other deterioration is found.

3. CORROSION CHARACTERISTICS OF STEEL PLATES

3.1 Features of Steel Plates in Composite Structures

The exposure tests described in section 2 make clear that main deterioration of a steel-concrete composite structure under marine conditions is corrosion of the steel plates. The purpose of the exposure tests described in this section is to investigate the corrosion characteristics of the steel plates in composite structures. The primary feature of the steel plates in a composite structure is that one surface (the outer surface) of the steel plate is exposed directly to the sea-water environment while the other surface (the inner surface) is in contact with concrete. From this structural feature, we deduce that a macro corrosion cell is very easily set up between the outer surface (anode) and the inner surface (cathode) in composite structures. In this section, a detailed investigation of this macro cell is described.

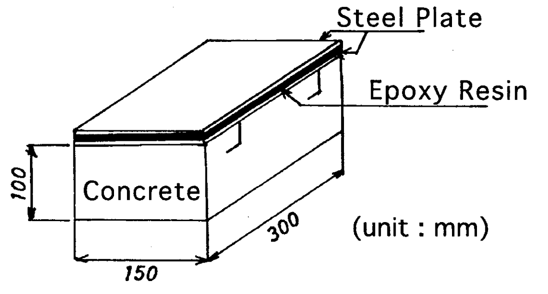


Fig.7 Shape and Size of Specimen

3.2 Outline of Exposure Test

Figure 7 shows the shape and size of the specimens used. The specimens were fabricated as follows. Firstly, two steel plates (SS 400 type; 3.2 mm in thickness) are joined using epoxy resin. Then this steel plate sandwich is affixed to the concrete using two steel angles with equal legs 40 mm by 40 mm by 3 mm. The two steel plates model the outer surface and inner surface, respectively. In other words, the outer plate is exposed to sea water directly (i.e. it is in a corrosive environment), and the inner plate is in contact with the concrete (thus in a non-corrosive environment). In order to measure the current flows between the steel plates, wires are connected to each plate.

Ordinary portland cement is used. The fine aggregate is river sand and the coarse aggregate is river gravel and crushed stone with a maximum size of 25 mm. The water to cement ratio is 55%. The

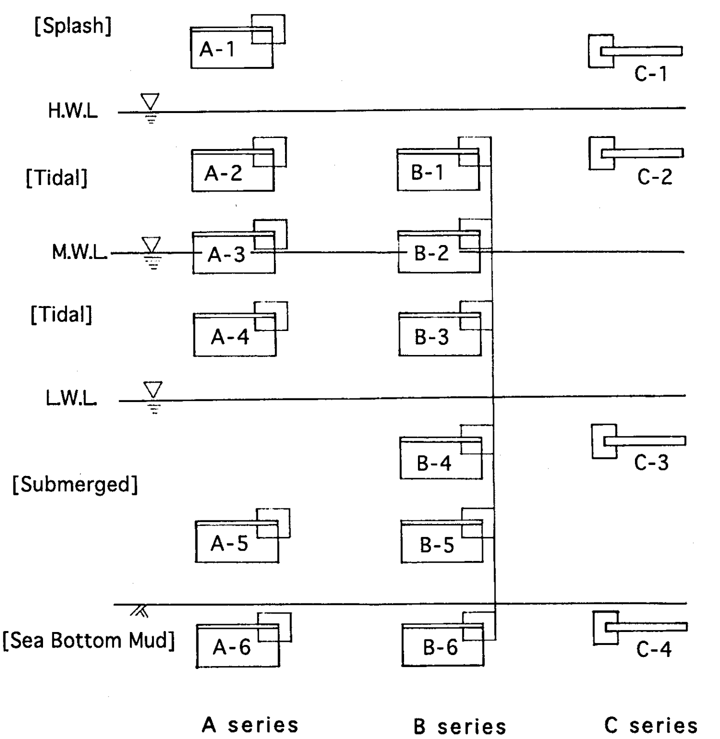


Fig.8 Exposure Conditions for the Three Series

compressive strength at 28 days is 27.9 N/mm^2. At one day, specimens are demoulded and air cured in a room at 20 ℃ and 50% relative humidity for a month. After one month of air curing, the specimens are placed in exposure sites consisting of a tidal pool and a sea water splashing facility. Details of these facilities are given in section 2. These exposure tests consisted of three exposure series, A, B and C. A and B are for composite structures and C is for a set of steel plates only. Figure 8 gives a schematic explanation of these series.

In series A, six specimens are used. In each specimen, the two steel plates are electrically connected, but there is no electrical connection between the six specimens. As shown in figure 8, specimen A-1 is placed in the splash zone, specimens A-2, A-3, and A-4 are placed in the tidal zone, specimen A-5 is in the submerged zone, and the specimen A-6 is placed in the sea bottom mud. In series B, there are six specimens. In each specimen, the two steel plates are electrically connected, and the six specimens are also electrically connected. Therefore in series B all the steel plates are electrically connected to each other. The C series consists of four sets of steel plates. The two steel plates in each set are electrically connected, but there is no electrical connection between the four sets of steel plates.

Over a one-year exposure period, current flows from each steel plate are measured constantly. After one year, all specimens are taken from the exposure sites and observed visually. After removing the steel plates from the concrete, the residual plate thickness is measured using a micrometer. The corrosion depth is calculated from the initial thickness and the residual thickness.

3.3 Corrosion Current during Exposure Period

Figure 9 shows the relationship between the direction of current flow between the two steel plates and the macro cell condition of the steel plates. As shown in (a), a current flow from the inner steel plate to the outer steel plate indicates that the outer steel plate is the anode and the inner steel plate is the cathode. On the other hand, as shown in (b), a current flow from the outer steel plate to the inner steel plate indicates that the inner steel plate is the anode and the outer steel plate is the cathode.

Figure 10 shows the current flow of the "A series" depending on tidal action. In specimen A-1 in the splash zone, no change in current direction occurs. A constant current flow of 0.2 mA (0.22 μ A/cm2 in current density) from the outer plate to the inner plate is detected. In specimens A-2 and A-3 in the tidal zone, a change in the direction of current flow takes place as the tides change. During tidal flow, the current is from the inner plate to the outer plate. However, when the ebb begins, the direction of the current reverses. Then, a constant current flow of 0.1 mA (0.11 μ A/cm2 in current density) from the outer plate to the inner plate is detected. In all specimens in the A series, the constant current is never higher than 0.2 mA.

Figure 11 shows the current flows for the B series depending on tidal action. There is no current flow

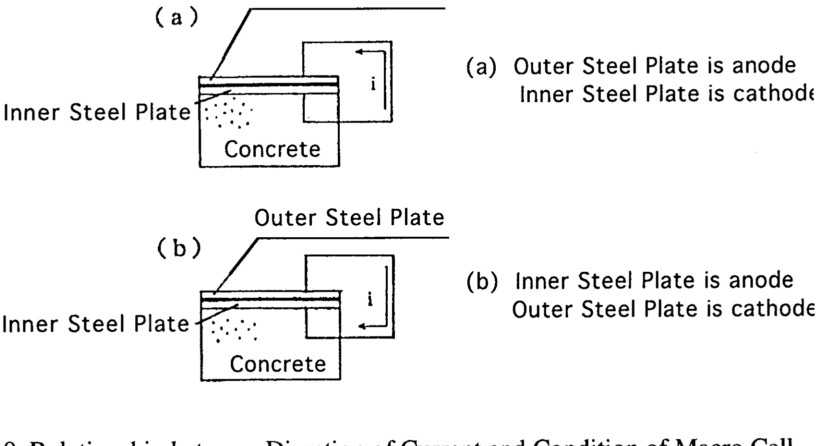


Fig.9 Relationship between Direction of Current and Condition of Macro Cell

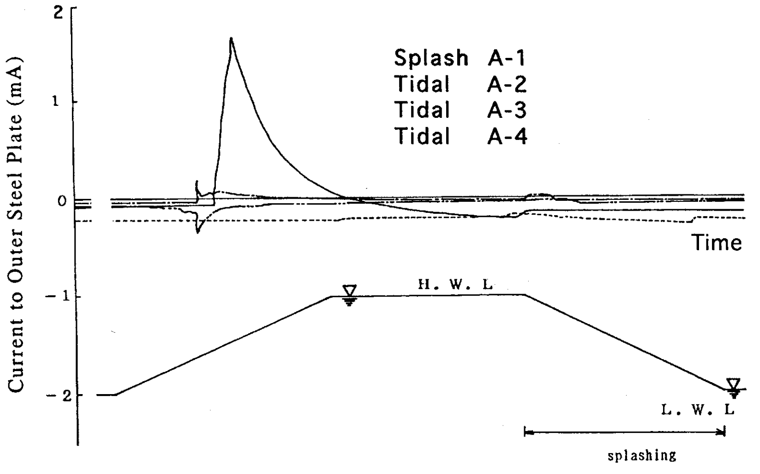


Fig.10 Current Flow during Tidal Action (A series)

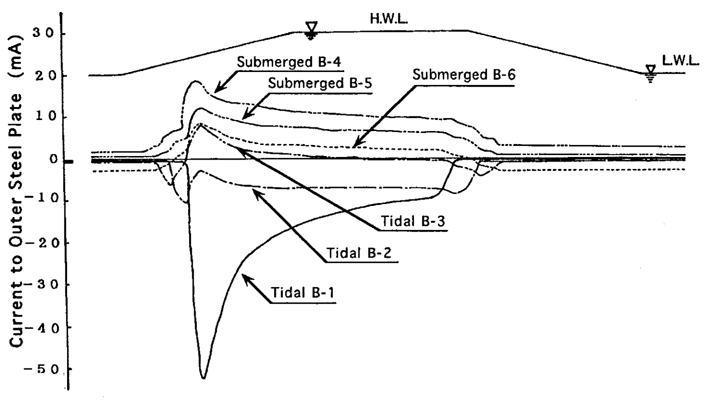


Fig.11 Current Flow during Tidal Action (B series)

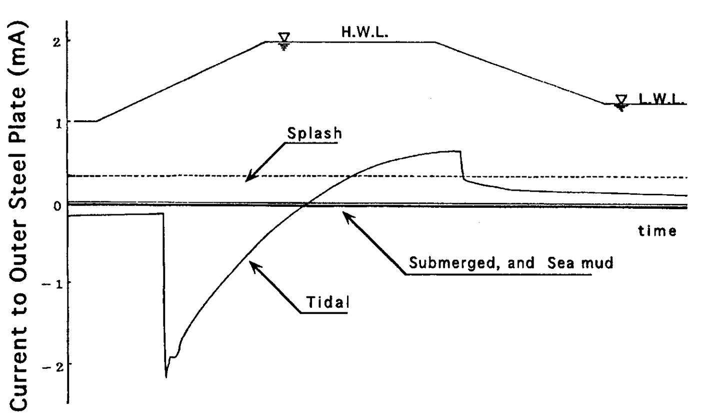


Fig.13 Current Flow during Tidal Action (C series)

from the inner plates in any case. Figure 11 shows the current flows for the outer plates. During tidal action, a macro corrosion cell is set up between the six specimens. Figure 12 shows the direction of current flow in this macro corrosion cell. Specimens B-1 and B-2 in the tidal zone act as the cathode, and the other specimens B-3, B-4, B-5, and B-6 form the anode. The value of the current flow is about 10 mA (the maximum is about 50 mA in B-1). Compared with the results of the A series shown in figure 10, the current flows in the B series are much larger.
Figure 13 shows current flow in the C series depending on tidal action. In the tidal zone, a change in direction of current flow occurs. This change is similar to that seen in the A series in figure 10.

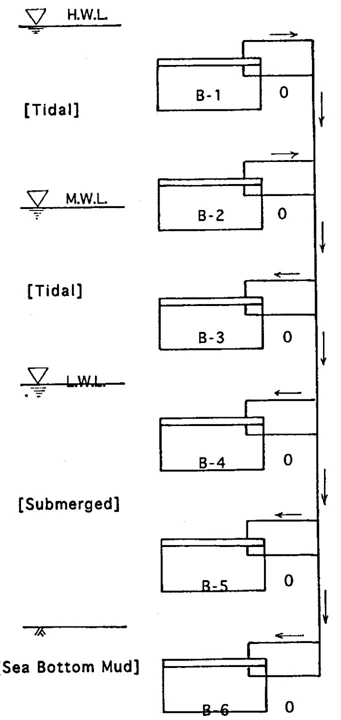


Fig.12 Direction of Current Flow during Tidal Action (B series)

3.4 Corrosion Depth of Steel Plate

Figure 14 shows the corrosion depth of steel plates in the A, B and C series. Each datum for one plate is an average of about forty data points obtained from all over the surface. The corrosion characteristics of the A and B series are quite different. In the A series, the corrosion depth changes according to the exposure conditions. The corrosion depths of the outer steel plates A-1 and A-2 are about 0.6 mm, while for A-5 and A-6 it is about 0.2 mm. On the other hand, in the B series, the corrosion depth of the outer steel plates is almost the same for all specimens. The corrosion depth is about 0.2 ~ 0.3 mm for the outer plates and about 0.1 mm for the inner plates. This is thought to be the influence of the macro corrosion cell generated between the six specimens of the B series during tidal action. In the C series, the corrosion characteristics and corrosion depth are almost the same as for the A series.

3.5 Discussion of the Corrosion Cell

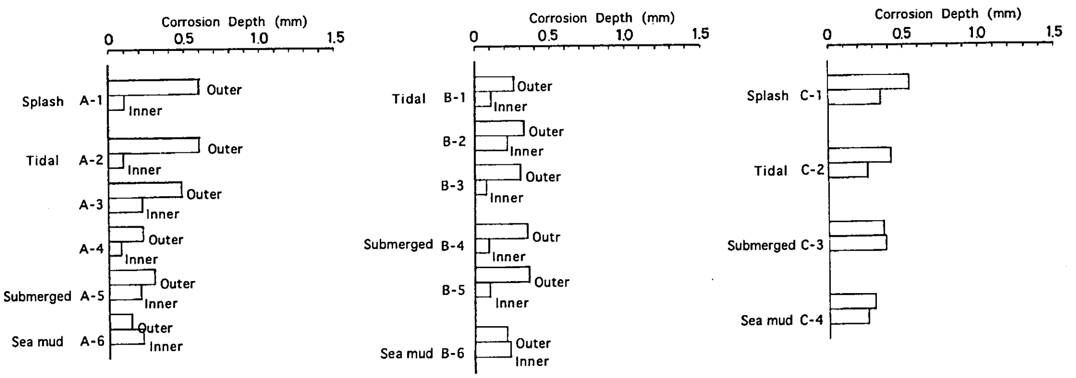


Fig.14 Corrosion Depth of Steel Plates

In this section, the macro cell set up between the inner and outer surface of the steel plate in the composite structure is discussed. In figure 10, which shows the current flow in the A series during tidal action, there is a current flow from the outer steel plate to the inner steel plate. This direction of current flow means that inner steel plate is the anode. This allows us to deduce that the slight corrosion found on the inner plate is caused by this macro corrosion cell between the inner and outer steel plates. If a constant corrosion current of 0.2 mA (0.22 μ A/cm^2 current density) continues for one year, the uniform depth of corrosion over the exposed surface will be 0.005 mm. In calculating this figure, the following constants are adapted;
(1) electrochemical equivalent of iron = 0.289 mg / Coulomb
(2) density of steel = 7.85 g/cm^3.
However, figure 14 shows that the actual corrosion depth in the A series ranges from 0.2 mm to 0.6 mm. Thus, the influence of this macro corrosion cell between the inner and outer plates on the total amount of corrosion is very small. We infer that corrosion of the outer steel plates in the A series results from many micro corrosion cells on the outer steel surface directly exposed to sea water.
In all specimens of the B series, the macro corrosion cell between the inner and outer plates of each specimen is almost negligible. However, the macro cell set up between the six specimens during tidal action is not negligible. If a constant corrosion current of 20 mA (22.2 μ A/cm^2 current density) continues for one year, the uniform depth of corrosion over the exposed surface will be 0.5 mm. The same two constants as described earlier in this section are used here. Thus, in contrast with the A series, the macro corrosion cell between the six specimens of the B series has a great influence on the total corrosion.

4.CORROSION MAGNITUDE OF STEEL PLATES WITHIN CONCRETE

4.1 Purpose of Exposure Tests

In the exposure tests described in section 2 and section 3, the steel plates form a covering layer over the concrete. In other words, the steel plates are exposed to sea water directly. However, in some kinds of structure it happens that the steel plates are within the concrete. In the case of such structures, the steel plates are not exposed to sea water directly, so it might be supposed that corrosion would be much less than for steel plates in direct contact. The purpose of the exposure test described in this section is to investigate the corrosion magnitude of such plates within the concrete.

4.2 Outline of Exposure Test

Figure 15 shows shape and size of the specimens used. Each specimen comprises three elements, a hollow body and two covers. The body consists of tubular steel and a tube of concrete, with the steel within the concrete. The covers and body are joined with epoxy resin adhesive. Each specimen is 350×350×400 mm, and the thickness of the body concrete is 55 mm. The steel SS400 type, 10mm in thickness is used. The angles used to hold the concrete to the steel are 30 mm by 30 mm by 3 mm. The mix, composition, and strength of the concrete are same as for the concrete used in the exposure test described in the section 3. Specimens are demoulded at one day and then receive one month of air curing. After air curing, the specimens are filled with sea water and sea sand, and they are placed in the sea water splashing facility. Figure 16 shows the exposure conditions : the steel plates are in contact with the sea water and sea sand inside them, but there is no direct contact with the splashed sea water outside. Thus, the supply of chloride ions and oxygen to the steel plate

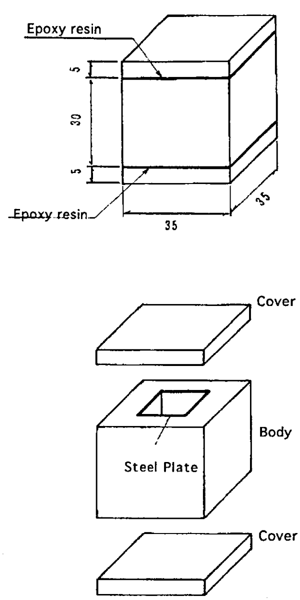


Fig.15 Shape and Size of Specimen

from outside is blocked by the concrete. After 2 years of exposure, the specimens are removed from the exposure site and observed visually. After visual observations, the specimens are crushed and steel plates are removed from the concrete. An ultrasonic thickness gauge is used to measure the residual thickness of the plates, and the average corrosion depth calculated.

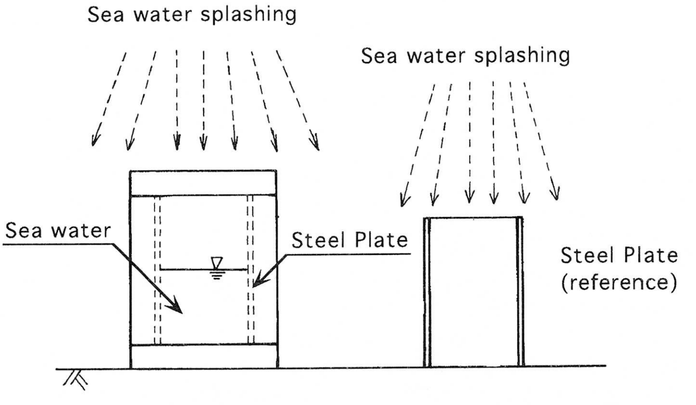


Fig.16 Exposure Conditions

4.3 Condition of Specimens after Exposure

After two years of exposure, no cracking of the concrete and no separation of cover and body is found. Photo 3 shows an example of a steel plate after exposure. The surface in contact with the concrete has no corrosion, but the opposite surface which has been in contact with sea water and sea sand has slight corrosion.

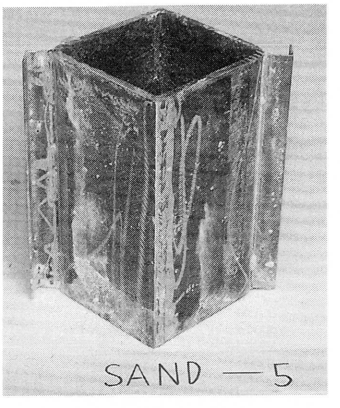


Photo 3 Example of Steel Plate after Two Years of Exposure

4.4 Corrosion Depth of Steel Plate

Table 3 presents the average corrosion depth after two years of exposure and the corrosion rate (corrosion depth per year) obtained from this exposure test. The corrosion depth of the steel plates is much less than that obtained in the exposure tests described in section 2 (Table 1) and section 3 (Figure 14). The reason for this difference in corrosion depth is thought to be the oxygen supply to the steel plates.

Table 3 Corrosion Depth and Corrosion Rate

Condition	Corrosion Depth (mm)	Corrosion Rate (mm/year)
Sea water and Sea sand	0.083	0.042
Sea water	0.062	0.031
Air	0.061	0.031
Average	0.069	0.034

In these exposure tests, the oxygen supply to the steel plate from outside is blocked by the concrete. The reduced oxygen supply leads to the reduction in corrosion depth. Table 3 indicates that the interior conditions (mixture of sea water and sea sand, sea water only, and air) have little effect on the corrosion depth.

5. CORROSION RATE OF STEEL PLATES IN COMPOSITE STRUCTURES

Average values of steel corrosion rate in steel structures are proposed for different locations after long-term field survey, and these are used in the design stage. The values are presented in Table 4 [3]. They represent corrosion on one face only and concentrated corrosion is not taken into account. The corrosion rates for composite structures obtained in the exposure tests described in this paper are summarized in Table 5. Although the rate for the splash zone in Table 5 is twice as large as that proposed in Table 4, the experimental results in Table 5 can be considered almost the same as the ones proposed in Table 4 since our exposure tests were conducted for only a rather short period of just two years. Also, the test environment (in the sea water splashing facility) is considerably more severe than a realistic environment (splash zone). As confirmed in Section 3.5, corrosion due to the macro cell set up between the inner plate and the outer plate is rather small. That is, even if the macro cell is taken into consideration, the steel plates in composite structures exhibit almost the same corrosion trends as ordinary steel structures. Little corrosion occurred on the plate face in contact with the concrete because there is little oxygen supply. This is similar to the situation on the inner surface of steel pipe piles. On the other hand, plates directly in contact with sea water can suffer extensive corrosion and they may need corrosion protection work such as cathodic protection [2]. Corrosion prevention methods have to be properly selected in consideration of precedents with similar structures.

Table 4 Standard Corrosion Rates of Steel Port and Harbour Structures

Environmental Condition	Corosion Rate (mm/year)
(1) ~ H.W.L.	0.3
(2) H.W.L. ~ (L.W.L. - 1.0m)	0.1 ~ 0.3
(3) Submerged zone	0.1 ~ 0.2
(4) Sea mud zone	0.03

Table 5 Average Corrosion Rate of Steel Plate in Composite Structures obtained from These Experiments

Exposure Condition	Corrosion rate (mm/year)
Splash zone (Sea water splashing facility)	0.60
Submerged zone (Tidal pool)	0.27
Sea water contact (with little oxygen supply)	0.03
Sea water and sea sand contact (with little oxygen supply)	0.04

6. CONCLUSIONS

On the basis of the results presented here, the following conclusions are drawn regarding the deterioration of composite structures:

1) Deterioration of composite structures is mainly caused by corrosion of the steel plates. Corrosion can initiate cracks in concrete. To construct more durable composite structures, it is necessary to use corrosion prevention measures to protect the steel plates.
2) A small macro cell arises in the steel plate from the potential difference between the two plate surfaces (inner surface and outer surface).
3) A concrete covering which blocks the steel plate from the sea water is confirmed to be one effective way to reduce corrosion.
4) The corrosion rate of steel plates in composite structure is almost the same as that of ordinary marine steel structures. That is, the proposed design values of corrosion rate for steel structures are applicable to composite structures.

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