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## Application of Composite Members to Marine Structures in Japan

Utilisation d'éléments mixtes dans les structures marines  
au Japon

Anwendung der Verbundbauweise für Meeresbauten in Japan

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### SUMMARY

Composite structures combining steel and concrete have been applied to port and harbour facilities in Japan since the early 1980s. Composite structures have such superior merits as high strength, high rigidity, watertightness, light weight, and rapid construction in marine areas. This paper presents the outline of some facilities made of composite structures and their design. The facilities described herein are a floating type breakwater, a gravity type seawall, and an undersea tunnel.

### RÉSUMÉ

Depuis le début des années 1980, les éléments mixtes acier-béton ont été introduits au Japon dans les installations portuaires. Les éléments composites possèdent, dans un environnement marin, des caractéristiques remarquables telles que résistance élevée, haute rigidité, étanchéité à l'eau, faible poids et mise en place rapide. Cet article présente les méthodes de conception et les grandes lignes de quelques-unes des installations portuaires réalisées avec des éléments mixtes. Les installations décrites sont un môle flottant, une digue et un tunnel sous-marin.

### ZUSAMMENFASSUNG

Seit Anfang der 80-er Jahre sind Verbundelemente aus Stahl und Beton für Hafen- und Meeresbauten in Japan verwendet worden. Verbundelemente haben in Meeresbereichen große Vorteile wie z.B. große Steifheit, Wasserdichtheit, geringes Gewicht und kurze Bauzeit. Dieser Beitrag gibt einen Überblick über einige aus Verbundelementen hergestellte Bauwerke und ihre Entwurfsmethoden. Bei den hier behandelten Bauwerken handelt es sich um einen schwimmenden Wellenbrecher, eine Küstenschutzmauer vom Schwerkrafttyp und einen Untermeerestunnel.



1. INTRODUCTION

Structural members composed of steel and concrete have been widely used in land facilities for many years. Those members exhibit merits of both materials. In marine facilities, structural members composed of steel plates and concrete began to be introduced around the early 1980s in Japan. Some port and harbour facilities have been constructed with those composite members since then. This paper presents the mechanical characteristics of composite structures in marine circumstances and the outline of structures and design methods of actual marine facilities, a floating type breakwater, a gravity type seawall, and an undersea tunnel.

2. STRUCTURAL CHARACTERISTICS

Composite structures of steel plates and (reinforced) concrete are schematically depicted in Figure 1. Two types of structure have considerable potential in marine areas, that is, an open-sandwich structure and a sandwich structure. The open-sandwich structure has both a plated and a concrete surfaces, and the sandwich structure has two plated surfaces. In both types of structures, steel plates carry tensile forces and reinforcing bars, steel plates and concrete carry compressive forces. This load-carrying mechanism is the same as that of an ordinary reinforced concrete structure.

To make sure this mechanism, steel and concrete should be joined tightly by a appropriate method. Natural bond forces between steel and concrete may be expected, but they are rather small. Shear connectors are generally applied to carry shear and pull-off stresses between them. Headed studs are most popular as the shear connector. Besides studs, many kinds of shear connector have been examined, and channels, angles, T-shapes, etc. will be introduced in port and harbour facilities. These make it possible to stiffen the steel plate and to result in reducing form and false work.

Basic mechanical characteristics of a composite structure will be roughly mentioned.

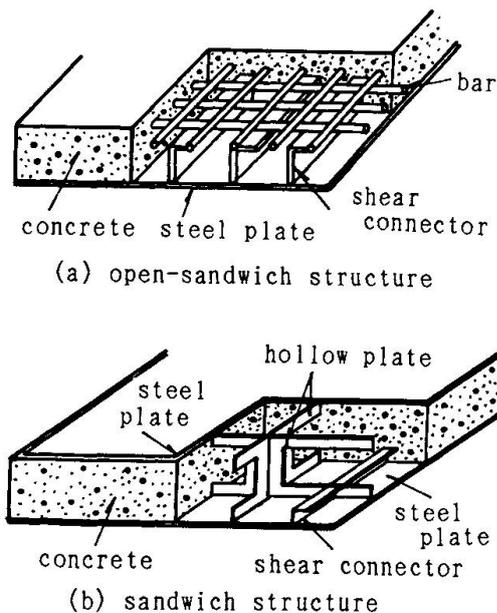


Figure 1 Composite structures

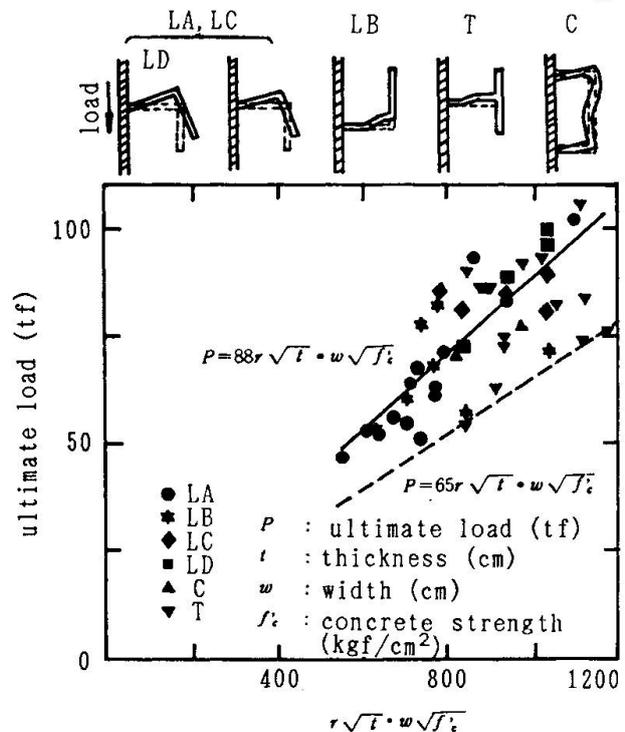


Figure 2 Load-carrying capacity of shear connectors

2.1 Shear connectors

Shear connectors will be designed due to induced shear forces between the two materials. The mode of failure and load-carrying capacity of shape steel shear connectors which have been obtained by push-off tests [1] are shown in Figure 2. Shape and direction of the shear connector and the strength of concrete had great effects on them.

2.2 Flexure and shear strength

The composite structure subjected to flexure may be designed as if it were an ordinary reinforced concrete. That is, the steel plate can be considered to be a reinforcing bar with the same cross sectional area. Loading tests on composite beams [2] showed that cracks concentrate at the tip of shear connectors and their widths become large, as depicted in Figure 3.

Excessive cracks can degrade the durability and the watertightness of the member in marine areas. Furthermore, these cracks may cause shear failure. Stirrups can be applied to the composite structure and they have to be welded the steel plate. Besides stirrups, long J-shaped reinforcement should prevent shear failure. The design for the shear reinforcement can be made on the assumption that the shear resisting mechanism is principally the tied-arch action [2] as shown in Figure 4. On that occasion, adequate shear reinforcement should be supplied and effective depth and shear span length should be modified due to the presence of the shear connectors.

2.3 Buckling

Buckling has to be examined when the steel plate exists on the compression side. If buckling will not occur, a composite structure behaves with excellent

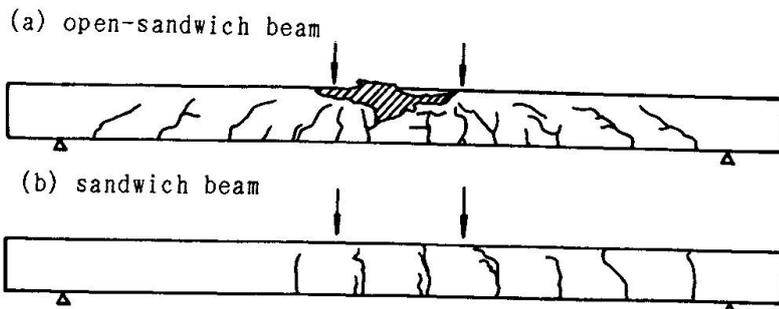


Figure 3 Crack formation

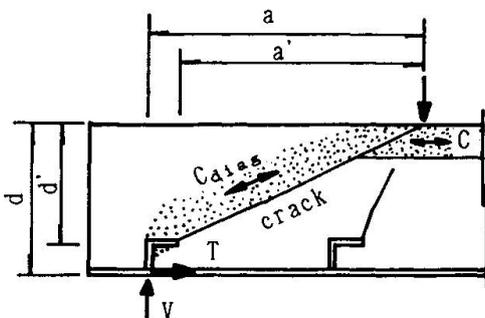


Figure 4 Shear resisting mechanism

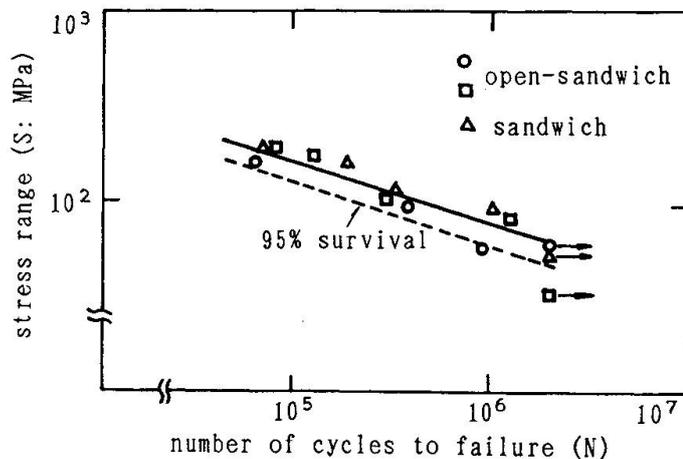


Figure 5 S-N relationship of steel plates



ductility. The interval of the shear connector relates to buckling strength of the compressive steel plate. This may be examined by Euler's formula.

#### 2.4 Fatigue endurance

In the composite structure, many reinforcing bars and shear connectors which are welded to the steel plate may cause fatigue failure. On the basis of the experimental results undertaken by the authors [3], fatigue strength of the composite structure is considerably smaller than that of an ordinary reinforced concrete. Under repeated loads, the tensile steel plate may be broken by its fatigue. An empirical S-N relationship of the steel plate in the composite structure subjected to flexure is shown in Figure 5. Using this relationship and sea waves near Japan, the Miner-sum is calculated to be 0.28, and this indicates that the possibility of fatigue failure could be small.

#### 2.5 Connections

L and T connections of the composite structure have been tested [4]. The yield of the tensile steel plate causes to collapse the open-sandwich structure and the buckling of the hollow diaphragm and the crushing of concrete occur in the sandwich structure. The structural details at these connections are being examined.

### 3. ADVANTAGES IN MARINE AREAS

The composite structure is expected to have the following splendid performance in marine areas, while its structural mechanism and characteristics are trying to make clear:

#### - Excellent mechanical behaviours

This structure has high strength and rigidity. Thus, thin section may achieve its required behaviours. This makes it possible to construct a complicated facility and to have many varieties of its size and shape. Furthermore, light weight is advantageous for the structures constructed on soft sea mud.

#### - Watertightness

The outer steel plate prevents sea water from leaking when cracks form. This contributes to a floating structure and an undersea tunnel element.

#### - Rapid construction

Bar installment, form work, and false work may be very much reduced. Skilled workers on such works are not essential to fabricate a structure. Furthermore, each structural element can be fabricated in a factory, that is, a prefabricated structure. This can cut down the construction period on the site, often on the sea.

#### - Total costs

Although material cost is not always low because of high price of steel, total cost can be reduced due to rapid construction, small energy consumption on fabricating, and so on.

A structure which has high potential and performance and is made with reasonable cost is required for future marine development. Two alternatives in composite port and harbour structures are the open-sandwich and the sandwich ones. For the open-sandwich structure, concrete is directly exposed to sea water and the steel plate is not. That is, durability of the structure may not be serious when concrete cover thickness to embedded steel bars and the maximum crack width are paid attention in design as well as for an ordinary reinforced concrete. On the other hand, for the sandwich structure, the steel plate is suffered from sea wave attack. In particular, special attention has to be paid prior to application in

severe circumstances such as in the splash zone. Heavy protection such as cathodic protection is essential. In the circumstances that always submerged in sea water, little oxygen is supplied and less possibility of corrosion.

#### 4. EXAMPLES OF APPLICATION

##### 4.1 Floating breakwater

A floating type breakwater is intended to prevent port and harbour areas from wave invasion by floating bodies which are moored to the sea bed by chains. This type of breakwater is adopted in large depth of water and mild wave condition. Floating type breakwaters have often been constructed in small ports and harbours, particularly fishing ports. The floating breakwater presented herein is constructed at Hiroshima, south-west of Japan, which is against tidal waves as shown in Figure 6. This breakwater consists of six pontoons, which are fabricated by prestressed concrete and the composite structure with steel and concrete. Each pontoon is 60 through 70 m long, 10 m wide, and 3 m high. Prestressing forces also enable to attain watertightness and light weight. Longitudinal prestressing stress is 4.7 MPa. Main forces acting the pontoon are wave forces and water pressures. Ultimate, serviceability, and fatigue limit states are examined using the design wave of 30 years return period. Neoprene rubber coating is applied to the surface of the pontoons for certain watertightness.

##### 4.2 Gravity seawall

A gravity type seawall to which the open sandwich structure is applied will be

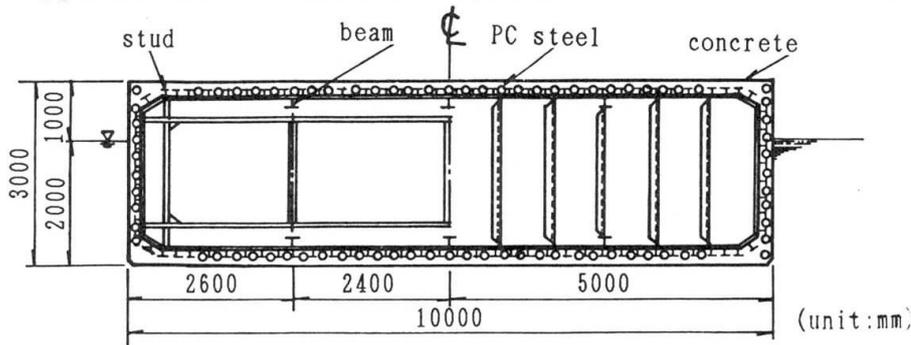


Figure 6 Cross section of the floating body

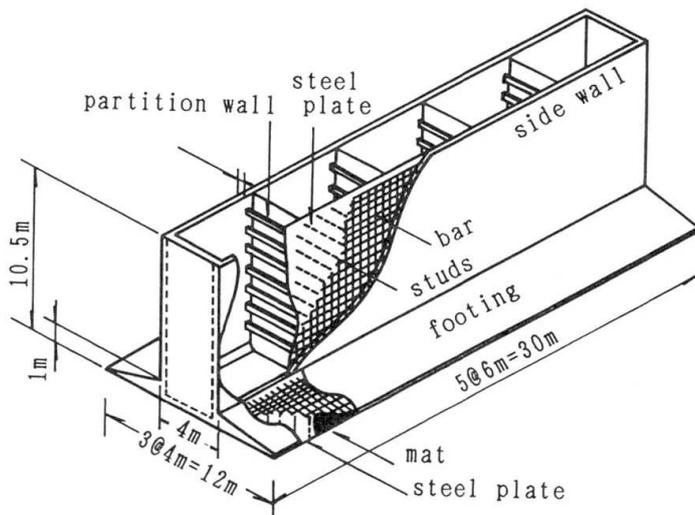


Figure 7 Details of the caisson

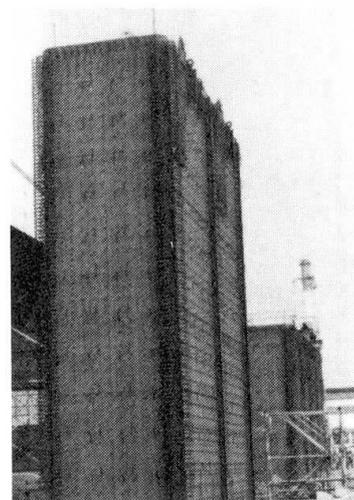


Figure 8 Steel plates and studs

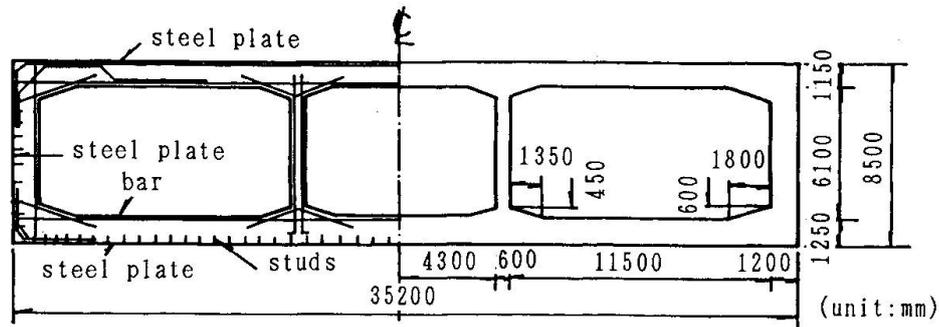


Figure 9 Cross section of the tunnel element

introduced. This seawall is located in front of reclaimed lands at Yokohama, near Tokyo. The schematic view of the breakwater caisson and its sizes are shown in Figure 7. The fundamental size of the caisson is 20 m long, 6 m wide, and 14.9 m high. The bottom slab, 40 cm thick, is made of the open-sandwich structure. The steel plate, 6 mm thick, is used at the bottom surface and composed to surrounding concrete by headed studs. The partition wall is made of a steel plate itself of 8 mm thick with stiffeners. The composite bottom plate makes it possible to enlarge the length of footings, which results in light weight of the whole structure. This caisson is designed according to the present specification which has been applied to an ordinary reinforced concrete seawall. The load-carrying capacities of the footing, L and T connections between walls and the slab have been examined by static loading tests at a laboratory. The caisson at the fabrication in a dock is shown in Figure 8.

#### 4.3 Undersea tunnel

An undersea tunnel will be constructed to link lands separated by a river or a channel in port and harbour areas. They are usually constructed by reinforced concrete and/or steel shells. In Osaka port, the construction of an undersea tunnel is now in progress. This tunnel, 2700 m long, is made by ten composite elements. The walls and slabs are made of open-sandwich structure as shown in Figure 9. In ordinary methods of construction them, outer steel plates are used only for watertightness, that is, they have no structural elements. When outer steel plates are used both for watertightness and structural elements, they have enough strength, and leads to light weight and economical. Here, these steel plates directly touches the sea water action, and should be degraded by corrosion. Thus, cathodic protection and other effective countermeasures may be applied to reduce the danger of corrosion and subsequent failure.

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