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# Applications of Steel-Concrete Composite Constructions

## Applications de la construction mixte acier-béton

## Anwendungen der Verbundbauweise

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**SUMMARY**

The paper gives an outline of recent applications of steel-concrete composite constructions, mainly in bridges with illustrations in Japan. Besides conventional simply-supported composite girders, continuous composite girders are becoming widely used. The importance of the effect of shearing force acting on a shear connector welded to a tension flange on the fatigue strength of the tension flange is pointed out. A number of applications of composite constructions to slabs, columns, connections, shells, etc. are discussed. Finally, a mixed stucture is illustrated for one of the most promising composite constructions in a broad sense.

**RÉSUMÉ**

L'article présente quelques exemples de constructions mixtes acier-béton, et plus particulièrement de ponts au Japon. En plus de l'application conventionnelle de la poutre mixte sur appuis simples, la poutre continue mixte devient de plus en plus utilisée. L'auteur souligne l'importance de l'effort de cisaillement dans les connecteurs soudés à des semelles tendues sur la résistance à la fatigue de ces dernières. Les exemples présentés concernent l'emploi de la construction mixte pour des dalles, colonnes, assemblages, coques, etc. Une structure hybride montre enfin l'avenir prometteur des constructions mixtes.

**ZUSAMMENFASSUNG**

Der Aufsatz beschreibt in Kürze neuzeitliche Anwendungen der Verbundbauweise und bezieht sich dabei vorwiegend auf Brücken und Beispiele aus Japan. Neben einfachen Balken werden mehr und mehr auch durchlaufende Balken in Verbundbauweise ausgeführt. Auf den Einfluss von Schubdübeln im Bereich von Zugflanschen auf die Ermüdungsfestigkeit wird hingewiesen. Beispiele zeigen die Anwendung der Verbundbauweise auf Platten, Stützen, Verbindungen, Schalen usw. Schliesslich wird eine hybride Konstruktion beschrieben, welche die Entwicklungsmöglichkeiten der Verbundbauweise aufzeigt.

## 1. INTRODUCTION

The 9th Congress of IABSE had a session on theme of "Interaction of Different Structural Materials," in 1972. ASCE published a State-of-the-Art Report on "Composite Steel-Concrete Construction" in 1974. The both activities clearly showed that composite steel-concrete constructions are utilized extensively throughout the world, making rapid and remarkable progress. At the present paper, the author discusses the progress of composite structures related to highway construction, mainly in Japan.

## 2. SHEAR CONNECTORS

Various types of shear connectors have been introduced (Fig. 1) and utilized since early 1950, but at present headed studs are used almost exclusively as shear connectors in Japan. In 1977, the Japan Society of Steel Construction has established the Standard of Headed Studs [1]. In the 2nd half of 1960 to 1973, the fatigue strength of shear connectors was examined to take advantage, in bridge design, of the latest research on the ultimate strength of shear connectors. Recently, fatigue tests of plates with studs have been carried out by several investigators for the application of studs to negative moment portions (Fig. 2). Among them, Maeda and Kajikawa [2] confirmed that there was a substantial reduction of the tension flange fatigue strength in the presence of shear connectors (Fig. 3, Fig. 4, Fig. 5).

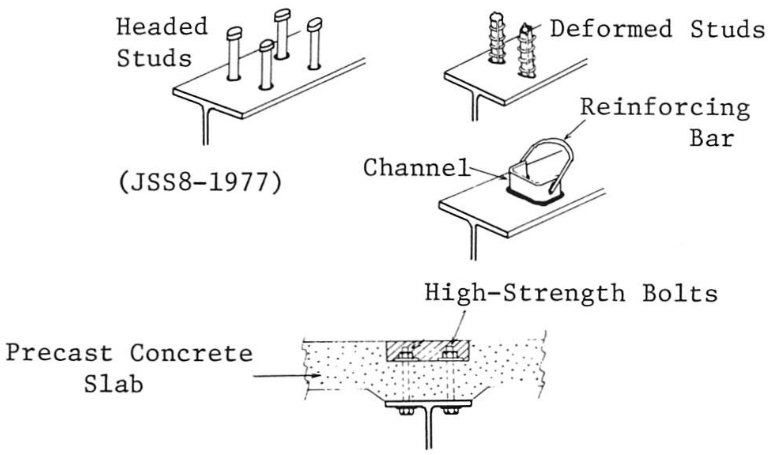



Fig. 1 Shear Connectors

## 3. COMPOSITE BEAMS AND GIRDERS

Since 1965, studies on the elastic-plastic behavior and load-carrying capacity of simple span composite beams and non-prestressed continuous composite beams, as well as on their fatigue strength, have been conducted, but elastic design methods for composite beams have been retained in the Japanese Specifications to this day. On the other hand, a number of important new findings based on the ultimate strength and fatigue strength of non-prestressed continuous composite beams, were codified in the 1973 Japanese Highway Bridge Specifications. Recently, various other new types of composite beams have been used in Japan.

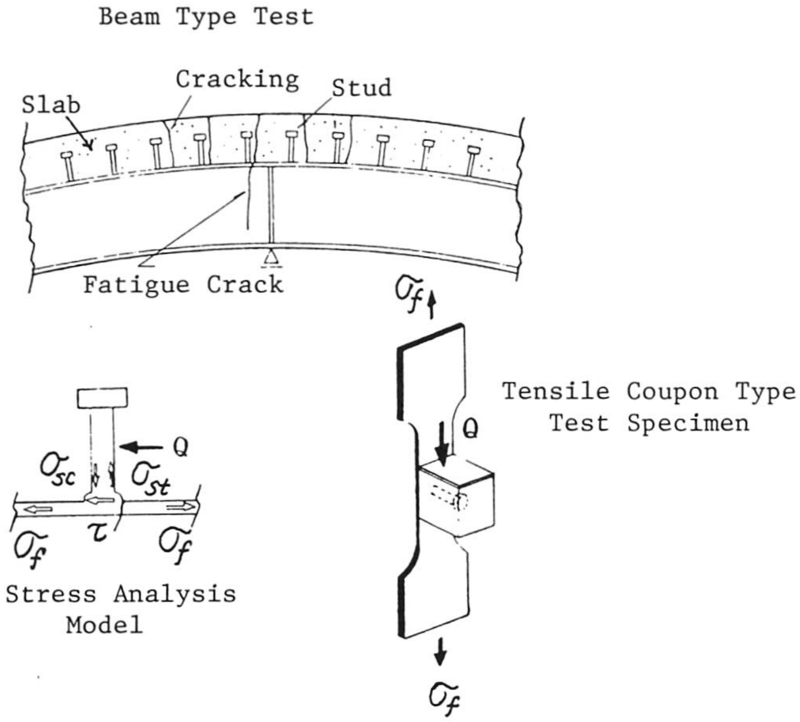



Fig.2 Fatigue Test of Flange Plate in Tension with Welded Studs

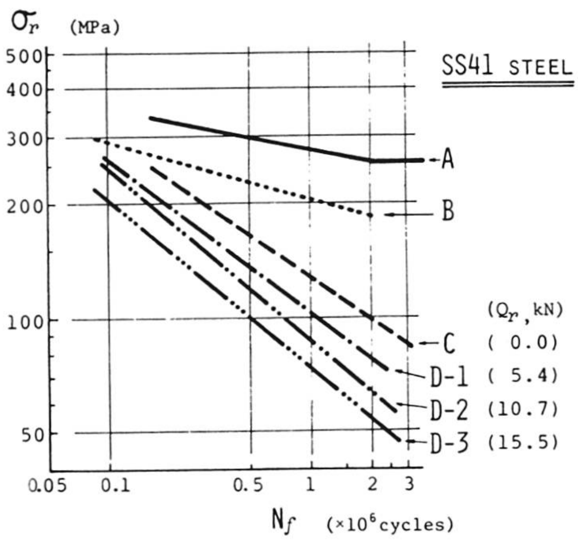



Fig. 3 S-N Diagrams of Tensile Fatigue Tests of SS41 Steel

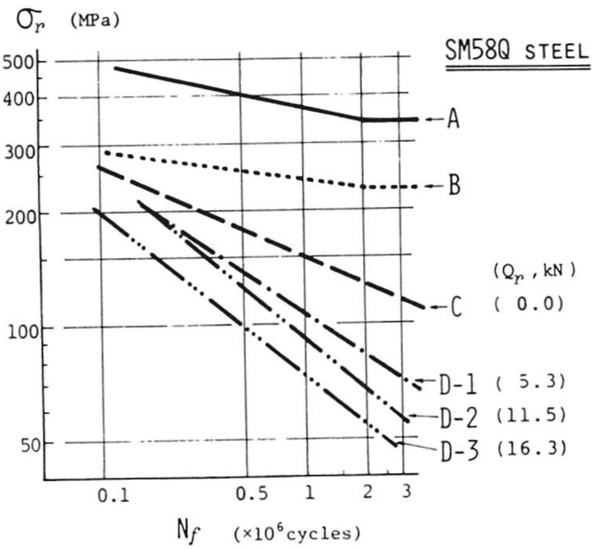



Fig. 4 S-N Diagrams of Tensile Fatigue Tests of SM58Q Steel

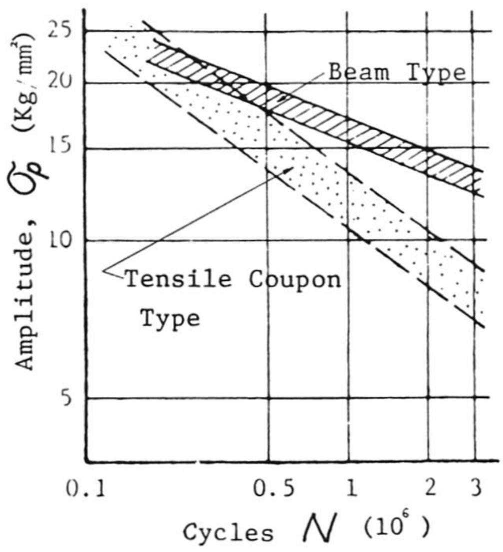



Fig.5 S-N Diagrams of Stud Shear Connectors

3.1 Non-Prestressed continuous composite beams

It was a common practice in Japan to prestress the negative moment regions of continuous composite beams, but it was not considered generally economical. At present, prestressed continuous composite beams are not used for highway bridges. In Japan, non-prestressed continuous composite beams with studs throughout their entire span have been applied to several highway bridges (Fig. 6). Static tests [3)] and fatigue tests [4)] showed that in such cases, if sufficient longitudinal reinforcements in the negative region are provided with, premature fatigue failure in a tension flange cannot occur and concrete slab crackings can be limited within nearly 0.2 mm in width. The rules of those investigations were incorporated into the 1973 Specifications. Furthermore , studies on non-prestressed continuous composite beams without shear connectors throughout the negative moment regions, have been proceeded also at Osaka University by the author.

3.2 Preflexed beams or pre-beams (Fig. 7)

The current fabricating techniques for preflexing were developed in Japan by KAWATA Industry Co. in a different way from the original Belgium patent. In Japan, preflexed beam is called "Pre-Beam." The Development Engineering Research Center, which is a Government Corporation, established "Recommendations for Design and Fabrication of Pre-beam Composite Girder Bridges" in 1975 [5)]. It should be pointed out that losses of prestress have been rather high after casting due to creep and shrinkage as with prestressed concrete.

3.3 Precast slab composite beams

Since 1964, static and fatigue tests of precast slab composite beams with high-strength bolts and channels as shear transfers and also with epoxy resins between slab and beams, have been conducted in Japan. Composite plates [6)] in which welded studs and high-strength bolts are used as the shear transfer between two flat plates and a sandwiched concrete slab, can make a composite beam with a steel beam which is connected to the composite plates with high-strength bolts. Also, an experimental study about a composite beam composed of an encased steel

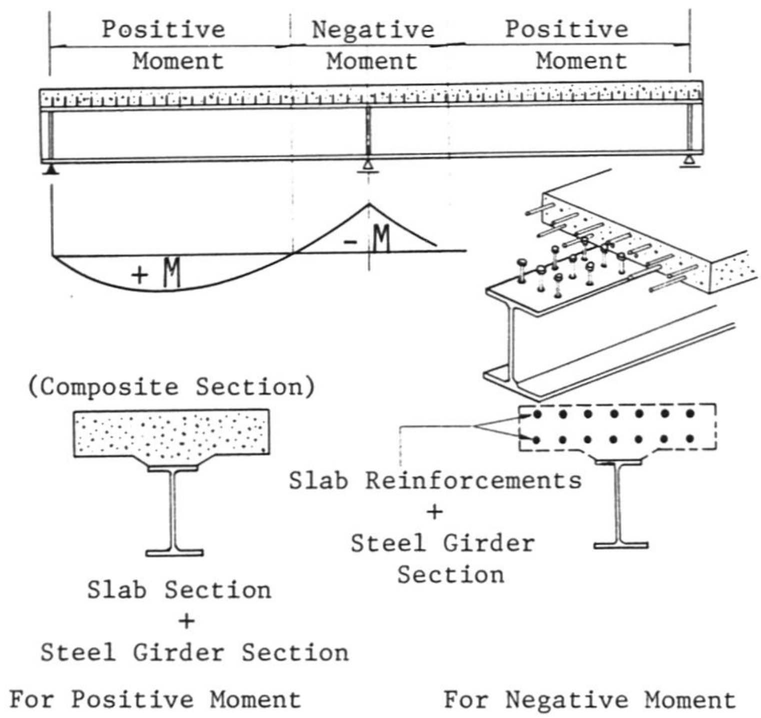



Fig.6 Design Model of Non-Prestressed Continuous Composite Girder

grating slab and inverted steel T-beams with the web welded to small I-beams in the slab grating, was reported [7]. Various precast slab composite beams have been developed in Japan and some of them were applied to actual bridges, but they have not been widely used yet.

3.4 Concrete encased steel beams

Any degree of encasement of a steel section increases its stiffness and energy absorption capacity, reduces the possibility of lateral-torsional instability, and eliminates the possibility of local buckling of the encased parts of the section. Partially encased steel beams for anti-noise structural members were tested, in which concrete was cast on the both sides of the web with bolts and studs. Fully-encased steel beams have not been used for highway bridges, except pre-beams.

3.5 Other types of composite beams

3.51 Composite hybrid girders

A study [8] showed that web yielding has only a local effect and the behavior of a composite hybrid girder differs little from that of an ordinary homogeneous composite girder. However, the allowable flange stress should be reduced to take into consideration web yielding. In Japan, two highway bridges [9] were built with composite hybrid girders. A. comprehensive tests of such girders were carried out at Osaka University by the author.

3.52 Steel plates-reinforced concrete composite beams

The ultimate static and fatigue tests on a composite RC beam with steel plates which were connected to the upper and lower sides of the beam with studs, were reported, but its practical application has not been experienced yet.

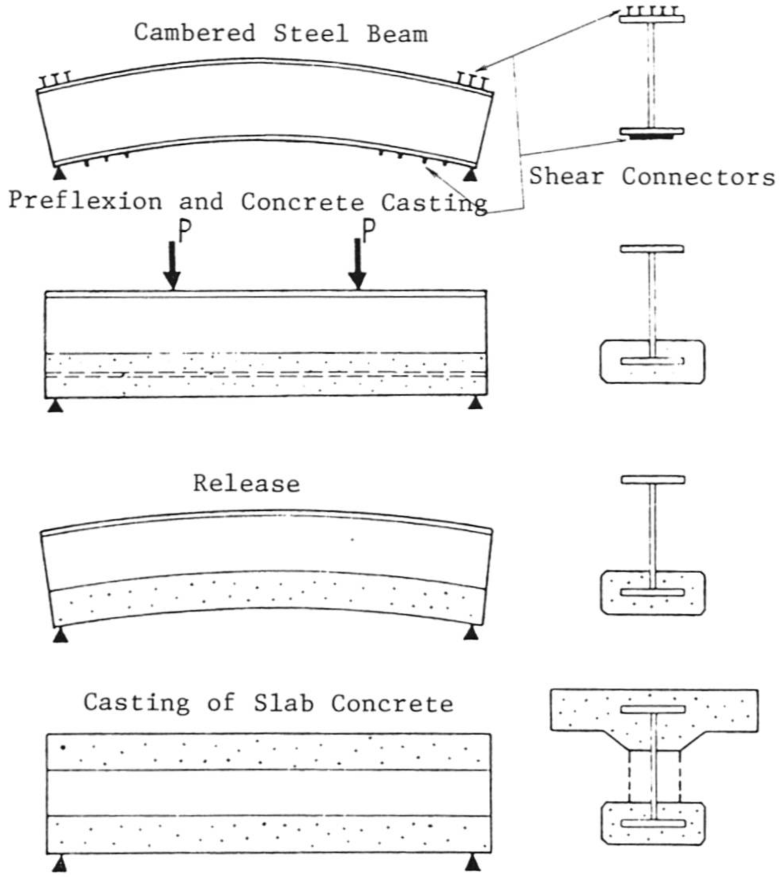



Fig.7 Fabrication Procedure of Pre-Beam Composite Girder

## 4. COMPOSITE SLABS AND PLATES

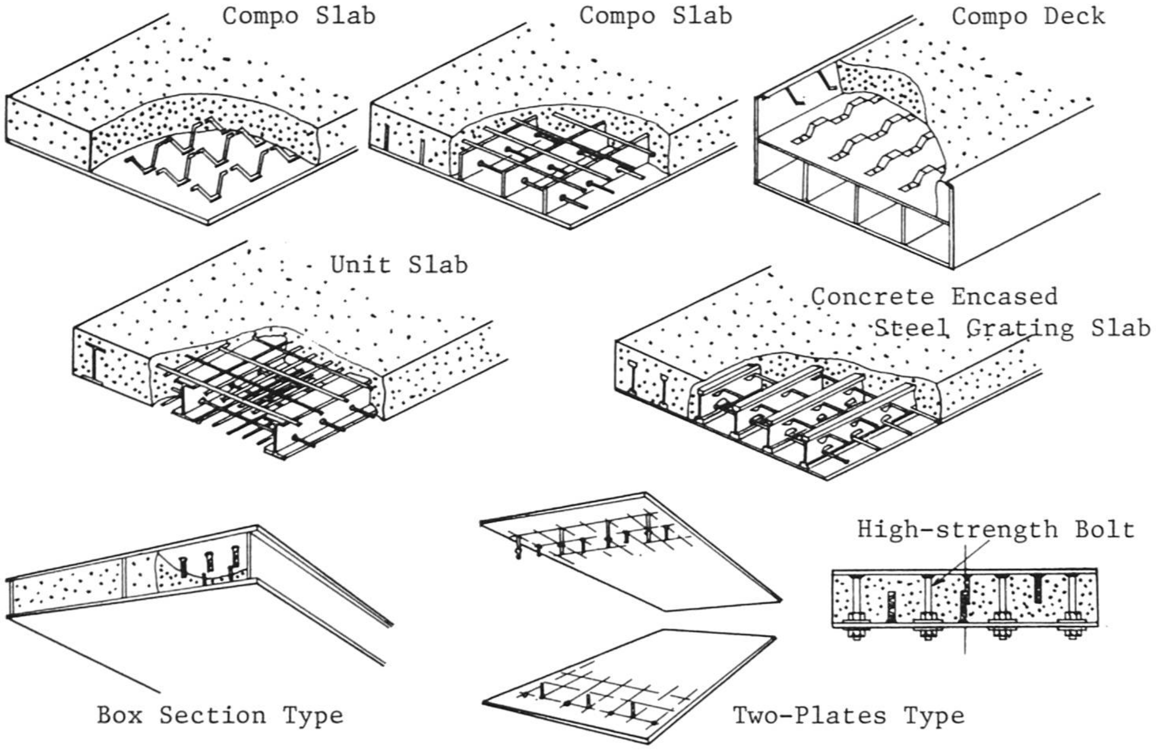
In order to improve ordinary RC slabs at highway bridges several new types of composite slabs and plates have been developed or proposed for practical use (Fig. 8).

### 4.1 Steel plate-concrete composite slabs

Proposals of composite slabs in which welded studs are used to provide with the shear transfer between a flat or deformed (corrugated) steel plate and a concrete slab, and their tests under static or dynamic loading were reported, showing great promise either in one-way or two-way slabs. One of the composite slabs is called "Compo Slab" (Fig. 8) commercially in Japan.

### 4.2 Concrete-encased steel beam composite slabs

Several types have been proposed after static or fatigue tests. H- or I-beams and hollow steel pipes or channel-shaped beams are used as steel beams, and they are encased ordinarily in reinforced concrete without shear connectors. As one of the proposed slabs, commercially named "Unit Slab System" (Fig. 8) was developed and used in Japan [10]. Encased small I-beam grating floors are used in Japan, particularly for long suspension bridges, in which I-beams are set perpendicularly to the bridge axis and its web hole can carry through reinforcements (Fig. 8). Their test results were reported by several research engineers [11),12)]. In such concrete-encased beam composite slabs, it will be required to clarify




Concrete Sandwiched Steel Deck Floor

Fig. 8 Composite Slabs and Deck Floor

the interaction between steel beams and concrete in stiffness and strength, and also the fatigue cracking around web holes of the beams.

### 4.3 Concrete-filled steel elements

Studies on steel deck plates sandwiching concrete were reported by the author [6]. They proposed two types (Fig. 8): One is a concrete-filled, flat box type steel with intermediate and end diaphragm web plates and with welded studs, and the other is a two-plates type in which two steel deck plates with studs are connected by welded bolts to hold a certain depth, and then concrete is filled in without reinforcements. Also, a jointing method of slab units at a job site was studied. These slabs have not been used for an actual structures, but they have great possibility for future use as far as fatigue cracking in a tension plate at stud welds can be avoided.

### 4.4 Composite slabs for temporary road paving

Recently, temporary pavings have been very often needed in Japan for undergraund construction works under roadways. Composite steel-concrete decking plates present a safe slip-proof surface with the minimum tire noise and at the same time inexpensive. I.H.I. Co. in Japan developed a new type of composite plates called "Compo Deck" 13) which is composed of a concrete slab and a hollow flat box steel beam, both connected by shear connectors (Fig. 8). Also, comprehensive static tests of composite decking plates for temporary paving were carried out at Osaka City University, in which concrete was filled in a rectangular flat box steel section stiffened with flat bars, H-beams or corrugated sheets [14].

## 5. COMPOSITE COLUMNS

Two types of composite steel-concrete columns have been used for substructures of bridges, foundation structures and timbering structures (Fig. 9).

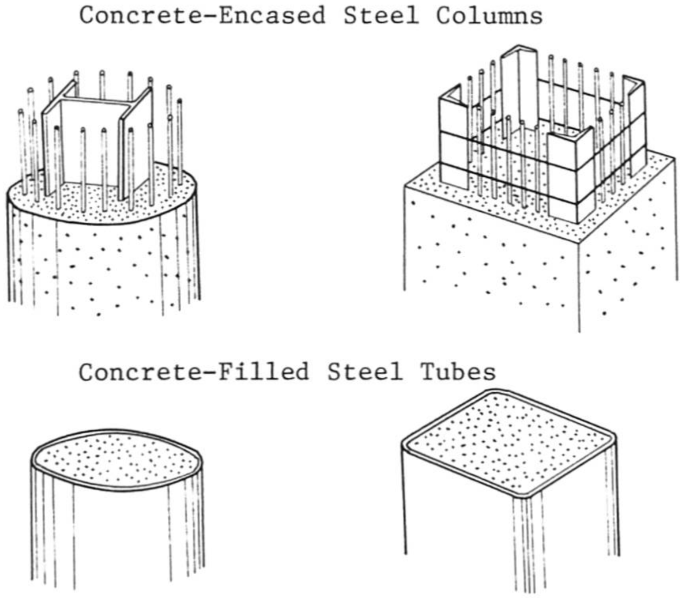



Fig. 9 Composite Columns

### 5.1 Concrete-encased steel columns

Encasing structural steel columns in concrete, which is originally intended for increasing their fire and noise resistance and for improving maintenance, is becoming a practice in Japan, but the increased column stiffness and strngth resulting from encasement have not been taken into positive consideration. Studies on composite concrete encased square or round steel tubes together with axial and hoop reinforcements and with or without studs, were reported. Also, the question of bond between the steel section and the encasement has been studied in encased columns against their anchoring.

### 5.2 Concrete-filled steel tubes

In addition to concrete-filled circular tubular sections, recently, square and rectangular tubing has entered the market. Studies on concrete-filled steel tubes were reported: compressive strength tests of hoop-reinforced concrete-filled steel pipes for tunnel timbering against earth pressure / ultimate strength tests and theoretical analysis of concrete-filled steel round or square tubes subjected to combined bending and axial load for foundation structures / ultimate strength tests of light-weight lower strength concrete-filled steel pipes for temporary erection works / bending, push-out and hammering tests of prestressing bars-reinforced concrete-filled pipes for piling which have been used for bridge or tower foundations.

### 5.3 Other types

For slabs and walls of caissons for submerged tunnels or off-shore structures, concrete-filled rectangular rigid frames composed of two plates provided with studs, were tested under compressive point loads on the four sides. To reinforce an existing RC column against earthquake, it was reported that expansive concrete was filled in between the column and a steel pipe which was set around the column.

## 6. CONNECTIONS

Compared to the research effort on composite elements, the attention to composite beam-to-column, beam-to-beam or beam-to-girder connections has not been nearly given. Although composite beams are frequently a part of a framed structure, a designer usally ignores the effect of composite action and continuity on the frame design, and the floor slab reinforcement at the columns and girders. It is the present situation in Japan that the study on connections of composite members-to-members has just started. Ultimate strength tests of the connection of a concrete-encased square steel tube column to I-beams and of the connection of precast beams to H-beams, etc. intended for the prefabrication of RC rigid frames, were reported. One interesting connection was reported [15] (Fig. 10) : a two-span continuous beam can be built by encasing the ends of two simply supported composite beams at the support into a reinforced concrete cross beam, which is also made continuous with the slabs of the two simply supported composite beams. Further studies on composite members' connection methods and on the strength and stiffness developed at the connection , will be expected.

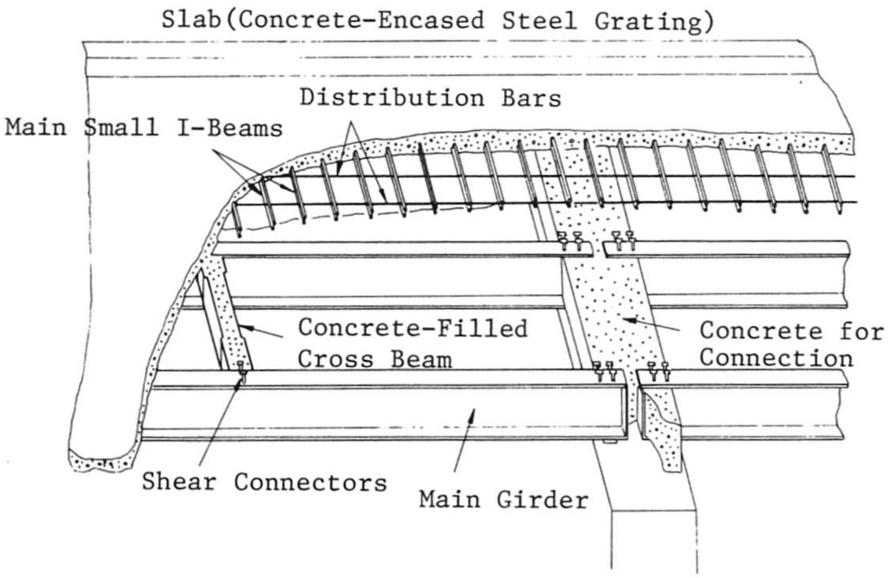



Fig. 10 Concrete-Encased Cross Beam and Connection of Simple Girders

## 7. COMPOSITE SUPERSTRUCTURES OF BRIDGES

While beam or girder bridges - both simple and continuous - are the most common types, composite steel-concrete construction has also been used for rigid frame bridges, cable-stayed bridges and flooring of suspension bridges. The following discussion will concentrate on bridge decks with particular emphasis on continuous slabs and special construction techniques.

### 7.1 Cast-in-place bridge decks

The majority of composite bridges in Japan are built as simple spans. The tendency toward continuous bridges had been observed as a result of a greater need to reduce material costs than to simplify fabrication and erection. Important savings achieved by eliminating the great number of joints and their maintenance, were desired strongly. Then, several continuous composite bridges were built with the maximum span length of 67.30 m, in which prestressed bridge desks were employed to eliminate or minimize slab cracking in the negative moment regions. This is termed complete or total prestressing. In Japan, however, since prestressing adds considerably to the cost of continuous composite bridges, the present trend is to avoid it unless some restrictions become controlling.
A slightly more liberal view, termed non-prestressing system, was substantially introduced into the 1973 Japanese Highway Bridge Specifications.
In continuous spans, the positive moment portion may be designed with composite sections as in simple spans. When shear connectors are provided in the negative moment portion, the reinforcement steel embedded in the concrete in the negative moment portion can be considered a part of the composite section together with a steel girder (Fig. 6). This design concept was introduced into the present Japanese Specifications after verified by extensive static and fatigue tests and design studies. In Japan 28 continuous composite highway bridges were built with this design method, and among them the maximum span length is 88.0 m [16]. There are, however, still argument against acceptance of the concrete cracking in tension in the negative moment portion and the maximum permissible amount of crack width of concrete slabs. On the other hand, studies on another design approach - partial composite - in which shear connectors are not provided in the negative moment portion, but additional connectors should be placed at points of contraflexure, are now carried out at Osaka University by the author.

### 7.2 Precast elements for bridge decks

After the cost of continuous formwork in bridge construction became very high, prefabricated deck sections of unit length came into use. Intermittent openings are left in the prefabricated elements to coincide with shear connectors welded to the steel girders. Shear transfer is provided, after the deck elements on one span or on all spans are placed, by filling the openings with concrete. In some instances, high-strength bolts are used instead of welded shear connectors. The large number of joints between precast deck elements makes careful fabrication necessary to avoid weak connections. Three different approaches have been explored to deal with the problem of weak joints: longitudinal prestressing, articulated joints and spliced joints. But, much more practical studies on the field joints are required in order to develop the same behavior as that of cast-in-place slabs in terms of slab continuity.

### 7.3 Application of special construction techniques

In addition to simple and continuous composite girders above mentioned, several special composite construction techniques have been applied to bridges.

7.3.1 Pre-beam bridges [5] : Since the preflex technique (Fig. 7) was developed in 1966 in Japan and introduced at the market, about 106 pre-beam composite girder bridges were built in Japan, one of which covers the maximum span length of 43.6 m. In those bridges, losses of the preflexing stresses due to creep and shrinkage of concrete have been examined by following up their deformations.

7.3.2 Steel prestressed concrete combine technique : A composite construction technique to encase a steel truss into concrete with cast-in-place and then to apply post-tensioning to the composite section with PC steel bars, was developed in Japan. This technique has been applied to a cantilever erection of the beam itself without temporary staging (Fig. 11)

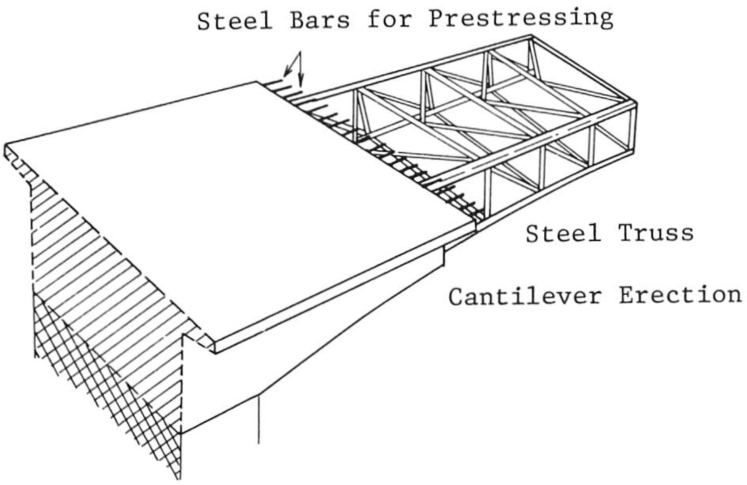



Fig. 11 Steel Prestressed Concrete Erection Method (SPC Method)

7.3.3 Cable-stayed continuous composite girder bridge [17] : A bridge composed of three spans ( 54.0 + 83.0 + 54.0 m ) continuous composite box girders stiffened by inclined cables was built in Japan, named Yamato Bridge (Fig. 12). In this system, adjustment of stresses was achieved by prestressing of cables arranged in a form similar with a cable-stayed girder bridge, so as to utilize composite action along the total span of the bridge. The main purpose of this construction was to provide the bridge with a small girder height of 1.75 m.

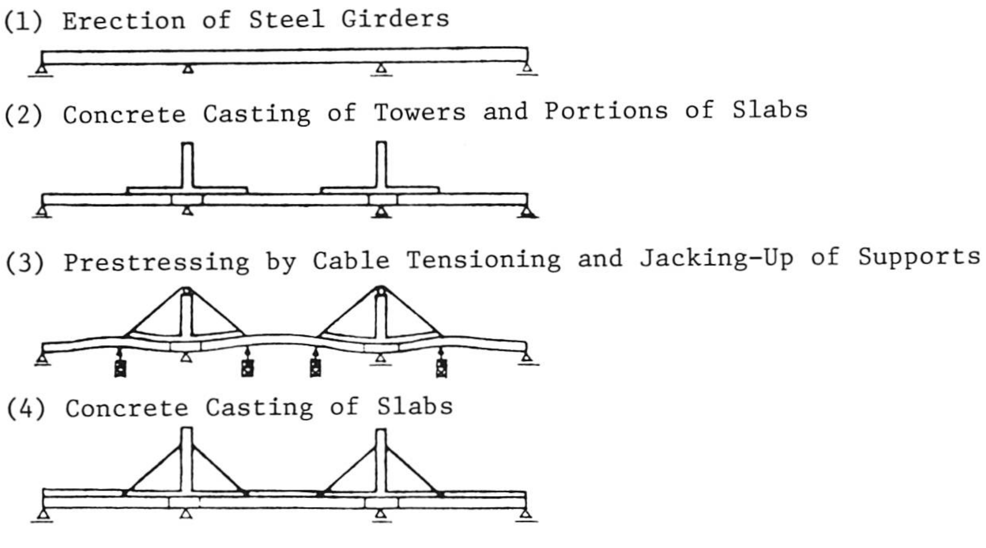



Fig. 12 Erection of YAMATO Bridge (Cable-Stayed-Type Continuous Composite Girders)

## 7.4 Design consideration for precast slab composite bridges

Two important factors should not be overlooked in connection with precast slab composite bridges. First, the safety of the structure has to be checked, and preferably, this should be based on the ultimate moment capacity of the bridge cross section. Secondly, the fatigue strength has to be checked. Appropriate care should be taken to consider the effects of live load on shear connectors, concrete cracking and joint behavior.

## 8. COMPOSITE BRIDGE-SUBSTRUCTURES AND FOUNDATION STRUCTURES

Various applications of composite construction to substructures of bridges were reported : prepacked concrete-encased steel footing which supports steel pipe piers (Fig. 13) / encasing the top of steel pipe piles and a prefabricated steel footing which is fixed at the top of piles, in underwater concrete or prepacked concrete [18] / underwater bridge piers of prepacked concrete-encased steel frames. In Japan, recently, submerged underwater tunnel constructions were experienced, in which steel pipe piles were used originally for temporary works during the construction. Then, to utilize these piles as a retaining wall as well as a structural member for a vertical shaft, these piles and reinforced concrete walls were made composite with shear connectors welded to the steel pipe piles.

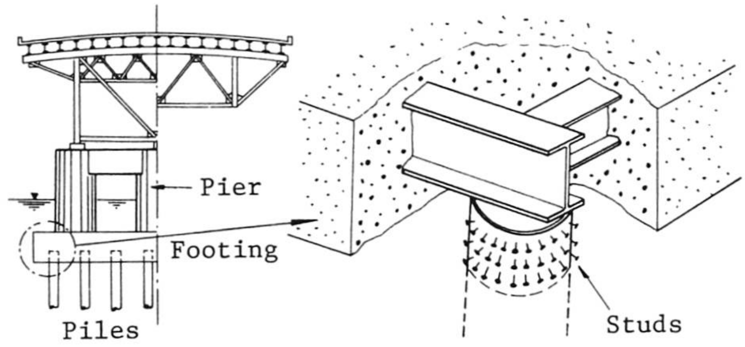



Fig. 13 Prepacked Concrete-Encased Steel Footing

### 8.1 Composite shells for tunnel lining

Commercially named "Composite Segment" [19] developed in Japan as lining elements for shield-tunneling, is a composite shell construction composed of a reinforced concrete segment faced on either inner or outer side with a steel skin-plate (Fig. 14). The two layers are solidly bonded together by shear connectors or zig-zag wires welded to the skin plate, both to be encased in the concrete layer. Specially strong joints of welded steel construction are provided with for bolting the segments end-to-end and side-by-side.

### 8.2 Composite walls for underground construction

At excavation works for poor subsoils in urban areas in Japan, it is extremely necessary to build retaining walls in high watertightness and great stiffness. Four kinds of construction methods were reported: underground reinforced concrete continuous walls / underground continuous lines of columns which are concrete encased H-shaped steels / underground continuous walls composed of H- or I-shaped steel columns and concrete walls cast by water concreting between steel columns / continuous composite underground walls of reinforced concrete encased steel pipes provided with shear connectors (Fig. 15). Each of them has its own advantages, but, if such temporary structures are also intended for permanent structural members, further studies are required for their earthquake resistance.

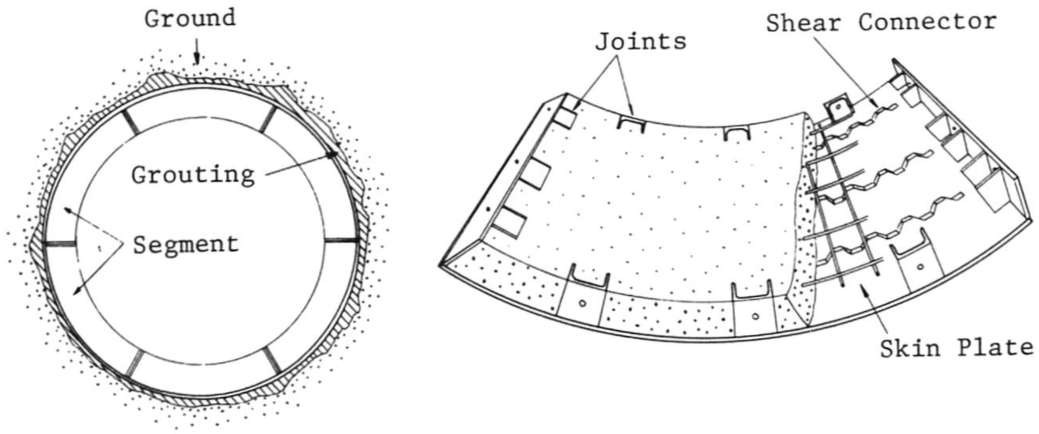



Fig. 14 Composite Segment

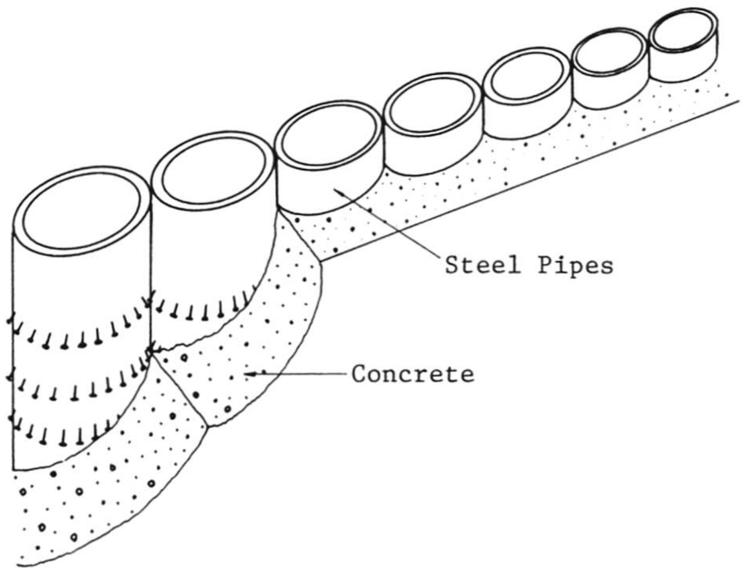


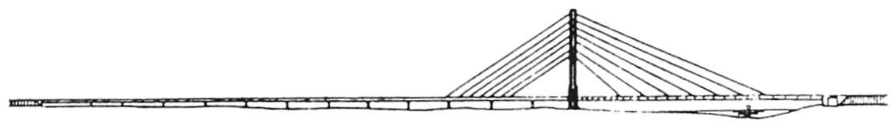

Fig. 15 Composite Continuous Underground Wall

## 8.3 Steel frame-reinforced concrete constructions (SRC Constructions)

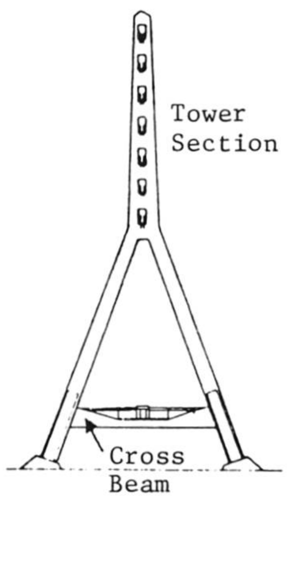
In future, the use of concrete encased steel frames will be required for substructures and foundations of bridges. Concrete-encased steel frames have been used for many years in the construction of multistory buildings around the world. In Japan, hot-rolled shapes and welded I- or H-sections have been used for the encased beams and columns. The concrete has been reinforced as in conventional reinforced concrete construction. Hence, this type of construction is known as "Steel-Rienforced Concrete Construction" (SRC Construction) in Japan. The 1963 Standard for Structural Calculations of SRC Construction formed by the Architectural Institute of Japan (AIJ), specified that allowable strength of the cross section of a concrete-encased beam or column may be calculated by superposition of the allowable strengths of the steel and concrete portions. This is called "Cumulative Allowable Stress Method" in Japan. The allowable strengths of the steel and concrete portions were to be calculated individually in accordance with requirements of the related Standards for steel construction and for reinforced concrete construction, respectively, except that the provisions for local buckling of steel members could be ignored. This simple design procedure was verified by the test data of many researchers. For substructures and foundations of bridges, Hanshin Expressway Public Corporation and Tokyo Metropolitan Expressway Public Corporation established the first Standard for Design of Steel Reinforced Concrete Constructions in 1970 and 1973, respectively. Recently in 1975, the Honshu-Shikoku Bridge Authority [20] formed the draft of the Standard for Design of Steel Reinforced Concrete Constructions. It specifies either of the two design methods: one is the Cumulative Allowable Stress Design Method as mentioned above, and the other is the Reinforced Concrete Allowable Stress Design Method in which the section of steel frames is transformed into the section of reinforcements. Systematic studies of the elastic-plastic behavior and hysteretic characteristics of the structure to formulate procedures for dynamic structural analysis have to be made. On the other hand, studies on details of anchoring steel reinforced concrete columns, design of slabs for caisson works composed of steel reinforced concrete, and calculation formulas of concrete crack width in such constructions, are currently in progress in Japan.

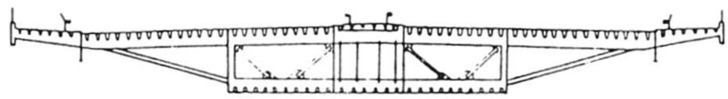
## 9. MIXED STRUCTURES

The combination of reinforced concrete members, prestressed concrete members and steel members, will make up so-called "Mixed Structures." Fig.16 shows Flehe Bridge built in West Germany in 1979 and it illustrates a mixed-structural bridge. As a means to stand against keen competition between steel bridges and concrete bridges, a mixed structure will be one of the most promising composite constructions (in a broad sense) in future.

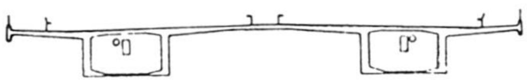


General View



Cross Section of Steel Box Girders



Cross Section of Prestressed Concrete
Girder Section at Non Cable-Anchoring Location

Fig.16 General View and Cross Section of Flehe Bridge

## 10. CONCLUDING REMARKS

The engineering level of steel-concrete composite constructions has been summarized including the author's recent researches, and the related problems on several subjects have been discussed.
Now, the author present his concluding remarks as follows:
Since the first-built composite bridge in Japan in 1953, the composite construction has been accepted generally for bridges. The design rules adopted were based principally on experiments on shear connectors and on simply supported beams. In recent years, investigators have embarked on studies of continuity through tests of continuous beams and shear connectors in the negative moment regions. It seems reasonable to expect that this work will proceed and lead to greater economy and safety through continuous composite design. Both the increased strength in terms of ultimate load carrying capacity, obtained inexpensively through continuity, and the increased stiffness due to composite action through the interaction between steel and concrete, will play an important role in the future progress of overall steel structures. It should be kept in mind, however, to follow up slab crackings, slab water-tightness, fatigue of shear connectors and losses of prestressing in structures after built.
Experience in Japan has shown clearly that encasing steel sections in reinforced concrete is particularly effective for earthquake resistant design. Although it is known that connecting a steel section to a concrete slab with shear connectors delays local buckling of the compression flange of the steel section and greatly increases resistance to lateral buckling of the steel section, the suitability of other types of composite elements than SRC structures for earthquake resistant structures is not known practically.
It has been also clarified that concrete-filled tubes and encased rolled shapes possess much higher shear strength than ordinary reinforced columns for the same size. It has been reported that the connections between columns and composite beams can be made very ductile in the same way as in ordinary steel frames.
It is the author's opinion, therefore, that further inverstigations on the response of composite beams, columns and frames to repeated loadings in both high cycles and low cycles would offer much promise for practical application in the future.
Another major aspect which has to be emphsized is the combination of steel sections with precast concrete elements. The advancement of precasting techniques and its inherent advantages show that especially the combined precast slabs with steel framing are to be expected to offer potential construction economy through their rapid erection and easy fabrication. Along this line there have been many new types of precast plates, slabs and walls developed and proposed in the market. However, some of them are just from an idea not supported by sufficient static and fatigue tests and analytical studies. It is suggested that practical experiences on new types of construction are much more needed. Particularly, the structural and physical behaviors of field joints of such precast units have to be examined carefully in a long term.
Among the many other subjects that require further investigation and study are: the static and fatigue behaviors of composite curved plate and box girder bridges, particularly on the response of composite girders to torsional loadings, composite beams with corrugated steel forms, composite continuous walls for underground construction, connections between steel columns and flat slabs, the design of studs and bolts for slab diaphragms under horizontal loadings and the behavior of composite plates subjected to repeated loadings due to traffic vehicles and temperature fluctuations.
Finally, the author wish that this present paper will contribute to stimulating further study and practical utilization not only of composite members and elements, but also of the overall steel-concrete composite construction.

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