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Mechanical Joints for Composite Construction

Joints mécaniques pour constructions composites

Mechanische Verbindung für Verbundkonstruktionen

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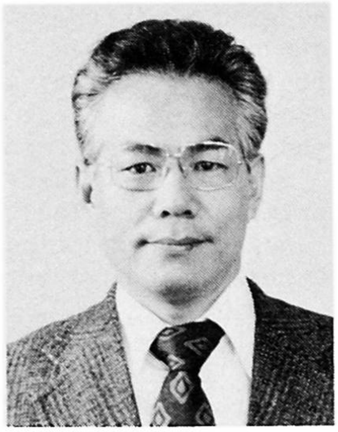

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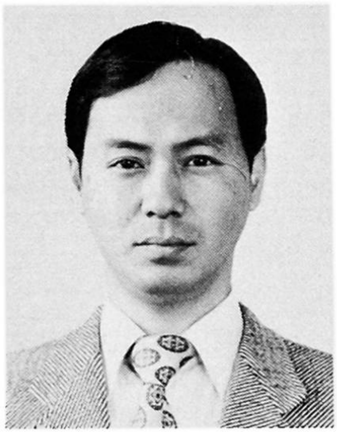

SUMMARY
A new type of composite construction in steel and concrete has attracted special interest recently, because of its economic and structural advantages. In order to find the most suitable joint structure for the above construction, several mechanical joints were investigated and a series of bending tests were carried out on composite beams and slabs with the proposed joints. In addition, an analysis of the joint on the basis of the semi-rigid connection theory is described.

RESUME
Un nouveau type de construction en acier et en béton a créé un intérêt particulier récemment, par ses avantages économiques et structurels. Pour déterminer le type le mieux approprié de ce genre de joints, divers types de joints mécaniques sont proposés, et une série d'essais à la flexion sont effectués sur des poutres et des dalles, avec les joints proposés. De plus, une analyse des joints basée sur le principe de connexion semi-rigide est décrite.

ZUSAMMENFASSUNG
Eine neue Verbundkonstruktion aus Stahl und Beton hat wegen seiner wirtschaftlichen und baulichen Vorteile eine besondere Aufmerksamkeit erregt. Um die zweckmässigste Verbindungsart zu erhalten, wurden mehrere mechanische Verbindungen untersucht und eine Reihe von Biegeversuchen an Verbundträgern und -platten durchgeführt. Eine analytische Behandlung der Stossfugen mit Hilfe der Theorie halbstarrer Verbindungen wird beschrieben.

1. INTRODUCTION

Mixed steel-concrete construction is very interesting and attractive to bridge engineers, who are eager to promote technological innovation. The advent of Düsseldorf-Flehe Bridge [1] in West Germany may be considered as one of the symbolical works in this field. Modern cable-stayed bridges are usually self-anchored as shown in Fig.1(a). For these bridges, the mixed girder system in Fig.1(c) may be more reasonable because large compressive forces act on the main girders in the vicinity of the towers (See Fig.1(b)). The joint of mixed construction needs to have a sufficient capability in transfer of bending moment, axial and shearing forces. The development of connecting methods is required for the practical application. Technological and design information about joint structures, however, is still limitted.

The purpose of this study is to provide general information with regard to the optimum method of connection for the composite structures in a broad sense. Several mechanical joints including a bolted joint applied to steel-prestressed concrete beams are investigated experimentally, and an analytical method is proposed for the bolted joint. Practical problems of the connection for the precast composite slab decks are also discussed in this paper.

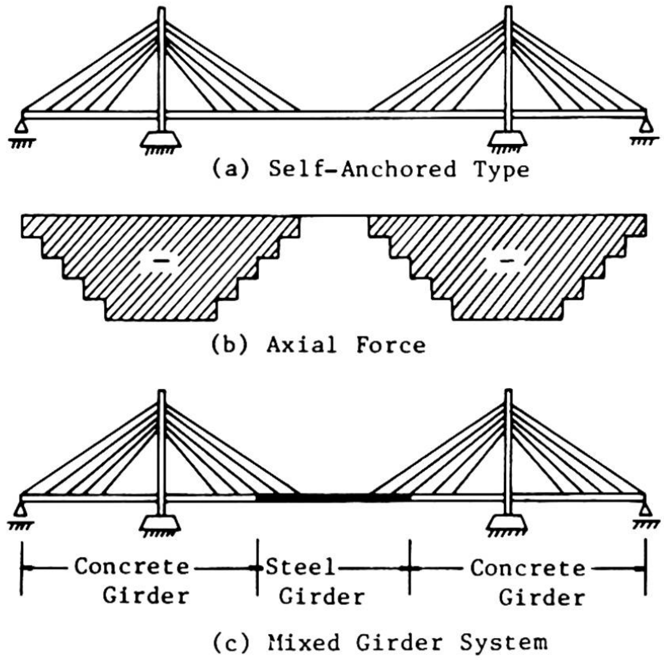

Fig.1 Cable-stayed bridge

2. MECHANICAL JOINTS APPLIED TO STEEL-PRESTRESSED CONCRETE BEAMS

2.1 General

The mechanical joints such as used in Flehe Bridge and Mosel Bridge [2] play an important role in the creative design of mixed structures. Fundamental research related to the joint of mixed structures is little presented, whereas the practical application has been extensively made in several countries.

A new mechanical joint as shown in Fig.2 is proposed herein, which can be applied to mixed steel-prestressed concrete beams subjected to bending moment. In order to investigate strength and flexural rigidity of the joint, a series of failure bending tests are carried out. Attention is also paid to slip and separation on the steel-concrete contact surface.

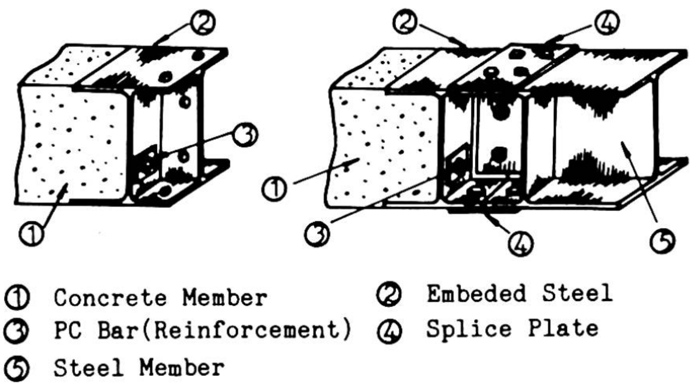

Fig.2 Mechanical joint with channel steel

2.2 Test and Discussion

Three mechanical joints were herein investigated. As shown in Fig.3, Joint-R consists of a channel steel with 3 anchor bars, Joint-S installs 6 studs on the upper and lower plates of the channel, and the concrete of Joint-B is connected tightly to the channel with 2 H.T.bolts. Loads were transmitted through a spreader girder to the test beam in order to create two equal concentrated loads. The beams were simply supported and of 2.00 m span.

Fig.4 shows load-midspan deflection relationships. Under the loads greater than the decompression load of 35 kN, the slip on the steel-concrete contact surface in Joints-B and S increased gradually with the increase of load, which resulted in significant reduction of the flexural rigidity. However, Joint-R retained a sufficient stiffness up to almost the failure load, and the test deflections agree well with the theoretical deflections based on the elasto-plastic beam theory [3].

Cracking and ultimate moments for the test beams are given in Table 1, where theoretical values of $\overline{Mcr}$ and $\overline{Mu}$ imply the cracking and ultimate moments prescribed in Specifications for Japanese Highway Bridges [4]. Little cracks were produced in the joint concrete region of Joint-R before failure. The failure occurred due to crushing of concrete. The experimental cracking and ultimate moments agree well with the theoretical moments. For Joints-B and S, however, cracks initiated in the joint region at small loads and the test beams failed in concrete crush at the joint end. Especially, the experimental cracking moment for Joint-S was 26 % less than the theoretical cracking moment.

However, the results do not directly mean that Joints-B and S are essentially inferior to Joint-R. This difference of capability is obviously caused by the difference of resisting mechanisms which resulted from the dimensions of the joint components. Joint-S has been successfully used in Flehe Bridge and other bridges, while the similar types to Joint-B have been widely used as the connection of segmental structures. As far as authors' opinion about the results is concerned, joints combined together with Joints-R and B may be more desirable and reliable for such mixed structures from the standpoint of fatigue safety. Thus, research of the resisting mechanism and the reasonable design method of bolted joints is required for the further practical application.

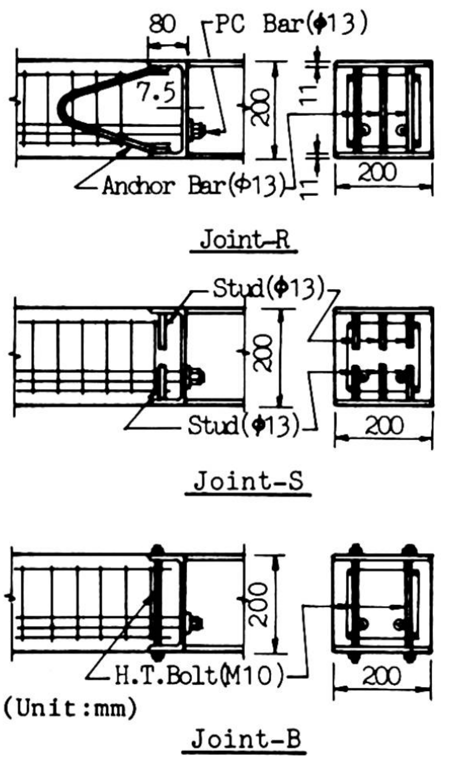

Fig.3 Details of test joints

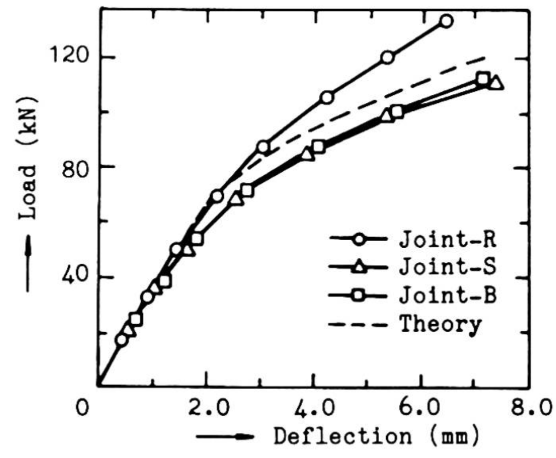

Fig.4 Comparison of load-deflection relationships

Table 1 Cracking and ultimate moments

Type of Joint	Cracking Moment (kN·m) Test Mcr	Theory $\overline{Mcr}$	$\frac{Mcr}{\overline{Mcr}}$	Ultimate Moment (kN·m) Test Mu	Theory $\overline{Mu}$	$\frac{Mu}{\overline{Mu}}$
Joint-R	20.6	20.4	1.01	54.8	52.3	1.05
Joint-S	15.6	21.0	0.74	47.0	51.5	0.91
Joint-B	20.6	21.2	0.98	49.4	51.7	0.95

3. BOLTED STEEL JOINT IN TRANSFER OF BENDING MOMENT

3.1 Test

A series of the statically and fatigue bending tests were carried out on 16 steel-reinforced concrete beams and 11 reinforced concrete beams, which were connected together by the bolted steel joint. Parameters for the joint of the present test beams were (1) tension in bolt, (2) use of mortar and bonding agent fillers on the contact surface, (3) additional reinforcement in the joint, and (4) length and thickness of the horizontal plate of the joint.

Fig.5 shows load-midspan deflection relationships for the effectively jointed beam and the corresponding monolithic beam. This beam had a rectangular section of 10 x 20 cm and a joint consisted of 9.0 x 1.0 cm holizontal steel plate, M12 bolts, bonding agent filler and longitudinally additional reinforcement. The test result shows that no significant crack occurred in joint concrete and that the flexural rigidity of the jointed beam was higher than that of the monolithic beam. Photo.1 shows the failure mode.

From the test results, it may be emphasized that the present bolted steel joint retains a sufficient capability in preserving the interconnection as well as in transfer of bending moment.

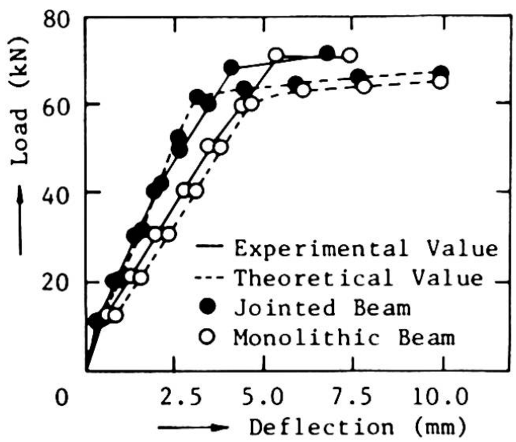

Fig.5 Comparison of load-deflection relationships

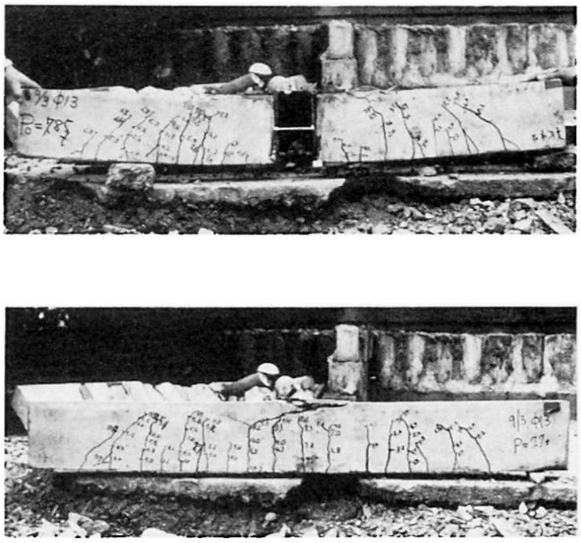

Photo.1 Failure mode of test beams

3.2 Analysis of Bolted Steel Joint (Semi-Rigid Connection Theory)

Equilibrium equations for the semi-rigid connection of the bolted joint due to the slip and separation are derived on the basis of the following assumptions.

1) The joint is a composite cantilever system consisting of upper and lower horizontal plates and of rigid concrete beam, as shown in Fig.6.

2) The beam is connected rigidly with the holizontal plates only at the bolted portions (Points A and B).

3) Elastic deformations of concrete and vertical plate are neglected for the rigid rotational deformation of the beam.

4) The end slip is expressed by F/kA_o , where F is total shear acting on the surface area (A_o) of lower holizontal plate and k is constant related to the slip.

When a concrete beam rotates rigidly as much as ϕ under bending moment M_o , the equilibrium equations of resultant forces Y_A , Z_A , M_A and Y_B , Z_B , M_B at Points A,B are expressed as (See Fig.7),

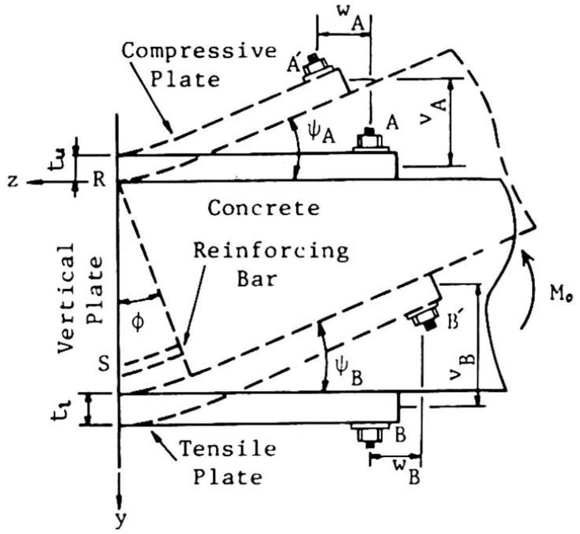

Fig.6 Idealization of bolted joint subjected to bending moment

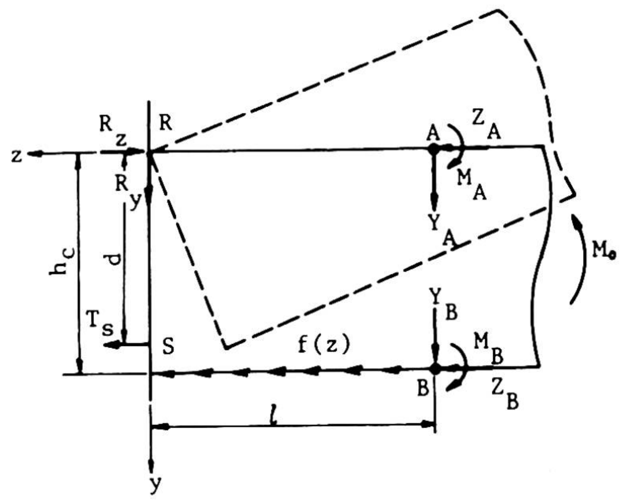

Fig.7 Forces acting on the contact surface

$$\left.\begin{aligned} &Y_A + Y_B + R_y = 0 \quad , \quad Z_A + Z_B + F + T_s - R_z = 0 \\ &M_A + M_B + (Y_A + Y_B)l + (Z_B + F)\ h_c - T_s\, d = 0 \end{aligned}\right\} \qquad (1)$$

And assumning Point R as the center of the rotation, the compatibility equations for the deformation are,

$$\left.\begin{aligned} &v_A = -\,t_u\,(1-\cos\phi\,)/\,2 + l\,\sin\phi \quad , \quad v_B = (h_c + t_l/2)(1-\cos\phi\,) + l\sin\phi \\ &w_A = -\ l\,(1-\cos\phi) - t_u \sin\phi \quad , \quad w_B = -\,l\,(1-\cos\phi) + (h_c + t_l\,/2)\sin\phi \\ &\psi_A = \phi \qquad\qquad , \quad \psi_B = \phi \end{aligned}\right\} \qquad (2)$$

Strain energies W_u and W_l stored in upper and lower holizontal plates are, respectively,

$$\left.\begin{aligned} &W_u = \int_0^l \frac{Z_A{}^2}{2E_s S_s} dz + \int_0^l \frac{(M_A + Y_A z)^2}{2E_s I_s} dz \\ &W_l = \int_0^l \frac{(Z_B + F\,z^2/l^2)^2}{2E_s S_s} dz + \int_0^l \frac{(M_B + Y_B\,z - Ft_l z^2/2l^2)^2}{2E_s I_s} dz \end{aligned}\right\} \qquad (3)$$

in which E_s , S_s and I_s are modulus of elasticity, sectional area and moment of inertia of the holizontal plate, respectively.

Based on Castigliano's theorem, the deformations at Points A and B can be given as,

$$\left.\begin{aligned} &v_A = \partial W_u\,/\,\partial Y_A \ , \quad w_A = \partial W_u\,/\,\partial Z_A \ , \quad \psi_A = \partial W_u\,/\,\partial M_A \\ &v_B = \partial W_l\,/\,\partial Y_B \ , \quad w_B = \partial W_l\,/\,\partial Z_B \ , \quad \psi_B = \partial W_l\,/\,\partial M_B \end{aligned}\right\} \qquad (4)$$

Eqs.(1),(2) and (4) yield the semi-rigid property, K_s , equal to M_o/ϕ in the following form.

$$K_s = \frac{8E_sI_s}{l} + \frac{E_sS_s(h_c + t/2)h_c}{l} + kA_oh_c(\frac{5t}{12} + \frac{2h_c}{3}) + \frac{E_rS_rd^2}{l} \tag{5}$$

in which the thickness t_u and t_l are equal to t ,and E_r and S_r are modulus of elasticity and sectional area of reinforcement, respectively.

Figs.8 and 9 illustrate moment-deflection relationships at the joint and moment-strain relationships of the holizontal joint plate, respectively, obtained from the test and theory. These figures also indicate that accuracy of the semi-rigid connection theory is sufficient for analysis of the deformation of the joint, and that the full-rigid connection theory considerably underestimates the deformation.

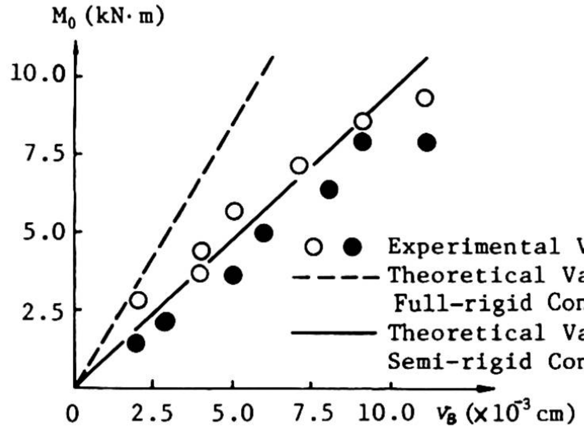

Fig.8 Comparison of moment-deflection relationships at bolted portion

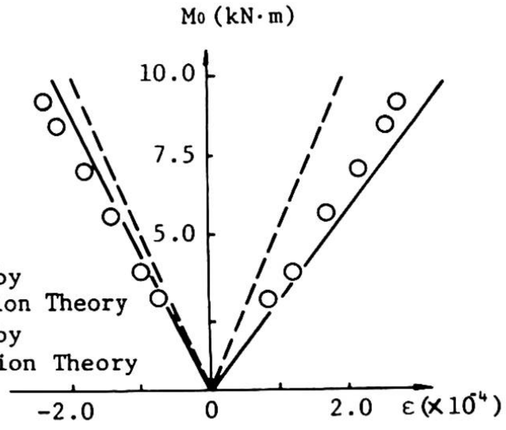

Fig.9 Comparison of moment-strain relationships of holizontal plates

4. MECHANICAL JOINTS APPLIED TO PRECAST COMPOSITE SLABS

4.1 General

A significant deterioration of concrete slab decks has been recently observed in highway bridges due to fatigue under excessive loads, and the complete replacement of these decks is often required. Precast composite slab decks are used as a conventional and quick replacement. The precast slab has a disadvantage of unfavorable discontinuous construction joints between precast and cast-in-place concrete parts. A fairly large amount of concrete is placed in the lapped portion of reinforcing bars developed from decks, as shown in Fig.10.

Two mechanical joints are proposed for connecting precast composite slab decks on the steel girder. Six composite slabs having proposed joints and a lapped joint and two corresponding monolithic slabs are tested in order to study joint capability in transfer of negative bending moment.

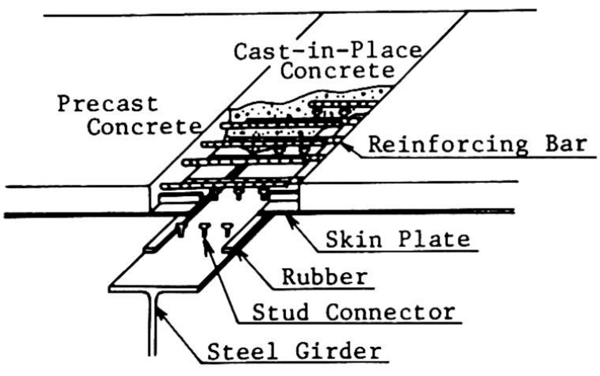

Fig.10 Existing connection of precast composite slabs on steel girder

4.2 Test and Discussion

Fig.11 illustrates details of the proposed joints. A steel joint, called Joint-CT, is spliced with the flange of steel cut T-section and main reinforcing bars are anchored to the steel and tightened with nuts. Joint-FB consists of two flat bars for anchoring main reinforcing bars. The other joint is a lapped joint, called Joint-LP, whose lap length was determined about 30 times the diameter of main reinforcing bars. Notations for the composite slabs such as Slab-CT are called after the slabs having Joint-CT. In addition to these composite slabs with joint, two corresponding monolithic slabs without joint were also tested and are called Slab-NJ.

Test slabs were loaded upside down to create negative bending in the joint. The loads were applied over the full width of the slabs simply supported at a span of 2.00 m.

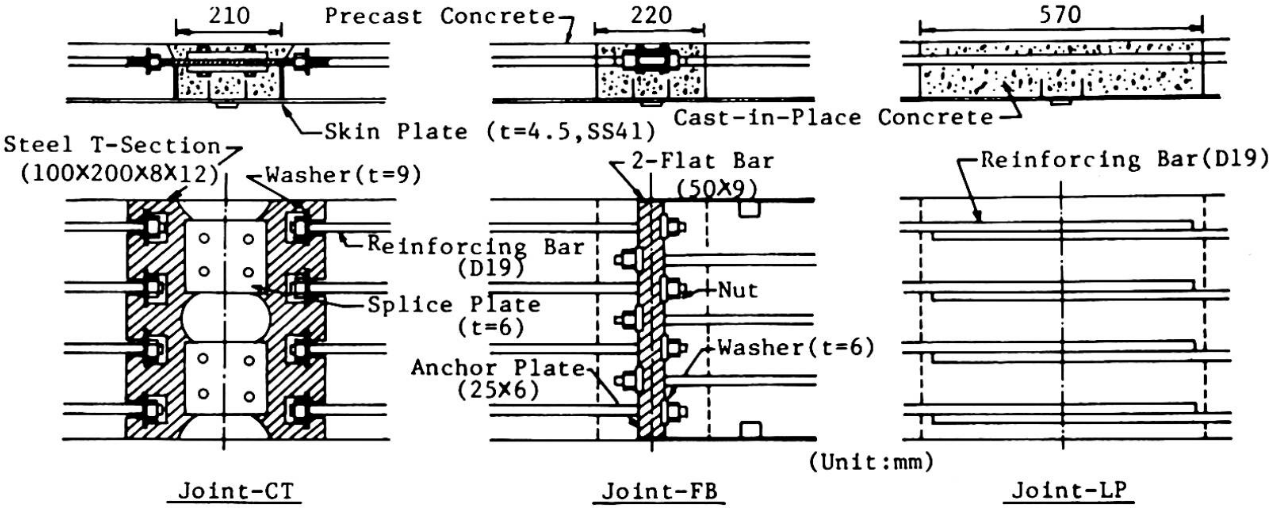

Fig.11 Details of test joints

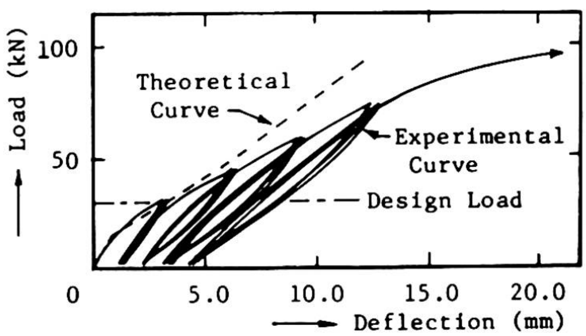

Fig.12 Load-deflection relationships for Slab-CT

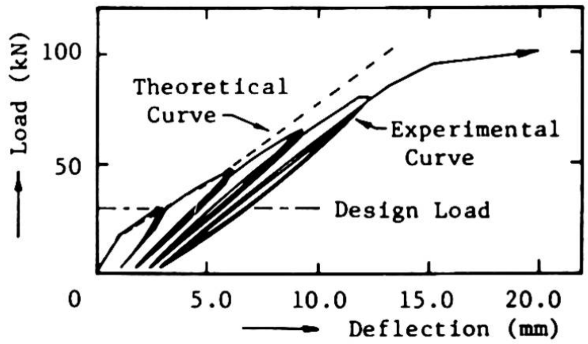

Fig.13 Load-deflection relationships for Slab-FB

Figs.12 and 13 illustrate load-midspan deflection relationships for Slabs-CT and FB obtained from test, including theoretical results. There are no significant differences in deflection among these test slabs, and the test results are close to the theoretical results under loads lower than the design load of 29.4 kN. At the design load, the maximum crack width in the joint region reached approximately 0.15 mm. But, the deflections of Slabs-CT and FB gradually increased with the number of repetitions of the maximum loads of two and three times the design load, respectively. In Joint-CT, a significant crack due to stress concentration was observed at the notch of the steel flange, in which reinforcing bars were anchored, under the loads greater than the design load. This defect must be improved in practical use.

Table 2 Comparison of ultimate moment

Type of Specimen		Ultimate Strength Pu(kN)	Ultimate Strength Mu(kN·m)	$\frac{Mu}{Md}$ 1)	$\frac{Mu}{\overline{Mu}}$ 2)	$\frac{Mu}{Mun}$ 3)
CT	No.1	102.9	38.6	3.53	0.92	0.94
	No.2	105.4	39.5	3.61	0.94	0.96
FB	No.1	105.0	39.4	3.61	0.93	0.96
	No.2	105.8	39.7	3.63	0.94	0.97
LP	No.1	111.0	41.7	3.81	0.99	1.01
	No.2	118.2	44.3	4.05	1.05	1.08
NJ	No.1	108.1	40.6	3.71	0.96	0.99
	No.2	110.9	41.7	3.81	0.99	1.01

1) Md:Design Moment (=10.93kN m)
2) $\overline{Mu}$:Theoretical Ultimate Moment (=42.1kN·m)
3) Mun:Average Ultimate Moment of Specimens NJ

Ultimate strengths of all test slabs are given in Table 2, where the definition of $\overline{Mu}$ is the same as that in Table 1. All test slabs failed in a typical flexural faillure and had the ultimate moments approximately 3.5 to 4.0 times the design moment. The test values of jointed slabs were nearly equal to the values of monolithic slabs both in experiment and theory. This implies that a certain degree of the stiffness reduction at joint little affects the ultimate strength of the jointed slabs.

5.CONCLUSIONS

Mixed steel-concrete construction is expected to be one of the most attractive structural systems of the bridges, from the standpoints of structural rationality, construction cost, maintenance and repair. The joint of mixed construction needs to have a sufficient resisting capability to external forces. The development of joint structures has been desired for the further practical application.

This study provides some instructive information about several mechanical joints in transfer of bending moment. The proposed bolted steel joint is desirable and reliable for such mixed structures from the test results. Analytical equations of the bolted joint are derived on the basis of the semi-rigid connection theory. This analysis provides sufficient accuracy.

Two mechanical joints are also proposed for the precast composite slab decks in highway bridges. These joints can reduce a fair amount of joint length and can be used as a structural element.

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