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Design Method and Fatigue Strength of Large-Span Concrete Filled I-Beam Grid Deck

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Summary

Recently, a tendency to make slab span more wide in bridge construction is growing in Japan from rationalization of structural systems and construction cost . Also high durability of slabs is required. To match the tendency, concrete filled I-beam grid deck has been planned to expand the maximum available span length by rolling a new large I-beam of 20cm height. Then, the design method and fatigue durability were discussed through many analysis and fatigue tests. This paper introduces the expanded design method with some based analytical results and fatigue phenomena and strength of the grid decks obtained by the fatigue tests by the Wheel Running Machine.

1. Introduction and Outline of Concrete-Filled I-Beam Grid Deck

Reduction of the construction cost and period in bridge construction is a recent great subject in Japan. One of the solution is to reduce the number of main girders and to use prefabricated slabs such as precast slabs and composite decks. But until now, as the maximum span length for RC slabs is limited to 4m by the Japanese Specifications for Highway Bridges, the ordinary design method available for the limited span length has to be modified or expanded.

As the slab is a important structural member to directly support wheel loads of traffic, it has been required to have the enough durability. Many damages , however, were reported in the ordinary RC slabs and steel orthotropic decks. Also, there are some problems on those ordinary RC slabs and steel decks such as weight or fabrication cost, respectively. Therefore, some kinds of precast PC slabs or composite decks are focused as innovated deck types.

The concrete-filled I-beam grid deck, which is a kind of steel-concrete composite decks and has too much construction records over 1,000 bridges in Japan, is considered a useful composite deck for the large span decks and some revolutions are required.Before concrete casting, the I-beam grid deck is a semi-prefabricated steel grillage consisting of I-beams and the transverse distributing bars. Furthermore, galvanized steel plates of 1mm thickness are welded by a spot-welding method at the bottom surface as the form during concrete casting, as shown in Fig. 1. At the construction site the panels are placed on the girders, and after simple adjustment and some arrangement of reinforcements at the jointing parts of the panels, concrete is casted to fill and envelope the whole steel panels. After concrete hardening, the both concrete and steel members work together with composite action.The use of those prefabricated panels is making some reduction of field works and construction period of bridges and is gives improvement of bridge erection accuracy. Furthermore, the use of I-beams of high-rigidity instead of the main reinforcements in the ordinary RC slab makes it possible to reduce the slab thickness and the dead load.

The concrete-filled I-beam grid decks have been used for the conventional slab spans up to 4 m and have been designed by considering the orthotropy which is expressed with the section properties neglecting tension side concrete at the orthogonal cross sections. The bottom plates are disregarded for the bending rigidities. Furthermore, when the design of cross sections is carried out with the design bending moment formulae given at the Design Manuals of Steel Bridges[1)], Japan Road Association, a verification for fatigue is excused.

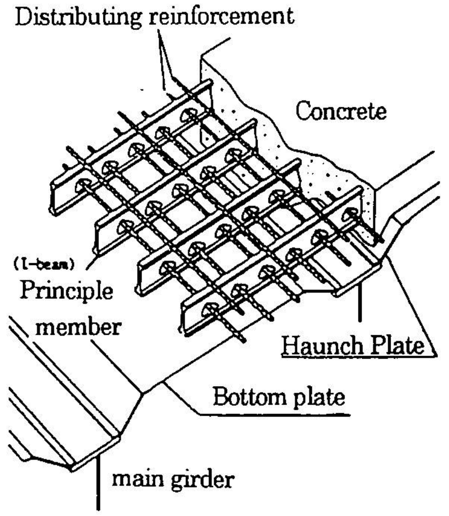

Fig.1 Structure of concrete-filled I-beam grid deck

When the use of the grid decks is expanded to more wider slab span, new problems will arise such as necessity of higher I-beam with larger moment of inertia, verification of the ordinary design method used for the maximum span length of 4m, fatigue strength increasing of I-beam in which fatigue failure occurs at the corners of punching holes in the web and rising up durability against fatigue and environment factors by modification of the orthotropy.To overcome those problems, the authors have carried out the design of new I-beams and realized the roll. Also, they carried out many analysis to arrange a new design method and to obtain a favorable punching hole in the web of I-beam to make pass through distributing bars. Furthermore, a series of fatigue tests on the concrete filled I-beam grid decks have carried out to check the fatigue strength of I-beams and to investigate the effects of expansive concrete, bottom form plates and punching hole shape. The paper reports those investigations' results on the concrete filled I-beam grid decks.

2. Design Method of Large-Span Concrete-Filled I-Beam Grid Deck

Generally, I-beams in the grid decks are installed in the direction perpendicular to main girders and distributing bars are arranged perpendicular to the I-beams through the punching holes in the webs. Due to weak bond between I-beam web and concrete and the difference of steel ratios in the both orthogonal direction, the bending rigidity, Dx of the cross section perpendicular to I-beams becomes more large than the one, Dy of the cross section perpendicular to distributing bars. Where, the tension side concrete is neglected at the calculation of the bending rigidities. Therefore, the deck behavior as orthotropic plate which is already recognized at many loading tests.

The degree of orthotropy, anisotropy, α is expressed by the ratio of the bending rigidities, Dy/Dx. Through the investigation on actual design data and experimental results, the ratios are scattering from about 0.4 to 0.5. But there are some cases of smaller ratio than 0.4 due to application of an allowable stress design method to decide the cross sectional properties. The almost ratios from 0.4 to 0.5 can be secured by the normal design bending moment formulae designated at the Design Manual which are calculated with the following ratios. Namely, the bending moment for the cross section perpendicular to I-beams was derived with the ratio of 0.4 and the other hand the one for the cross section perpendicular to distributing bars was derived with the ratio of 0.7. The use of different ratios seems to be rational to keep a good load distributing action to bridge axis by giving a large bending rigidity to the cross section perpendicular to distributing bars. Also, the ratio combination gives the orthotropy from 0.4 to 0.5 as expected and presumed.

In order to examine the influence of the difference in anisotropy, we analyzed the bending moment varying α from 0.3 to 0.7 by expanding the slab span length. Fig.2 shows the relationships between the slab span length and the bending moments in both orthogonal directions. As seen from Fig.2, the bending moments vary by the ratio of bending rigidities. When the bending moment, Mx of $\alpha = 0.4$ for the cross section perpendicular to I-beam and the bending moment, *My* of $\alpha = 0.7$ for the cross section perpendicular to distributing bar is, the latter bending moment seems to be too safety. But the ratio of bending rigidities calculated with the design cross sectional properties becomes automatically between 0.4 to 0.5. Those tendency was checked for the decks having longer span length. Therefore, two design methods can be recommended as follows:

(1) Following the ordinary design method using the different ratios for the both directions. In this case, the ratios of 0.4 and 0.7 are available even for longer span length.

(2) At first, the cross sections of both directions are design with the bending moment derived using one ratio, for example of 0.4. Then the cross section perpendicular to the distributing bars is checked to have the bending rigidity to fulfill the assumed ratio of α, for example 0.4.

In this study, the former method is kept because the change of design method will bring some troubles for the design works.

Table 1 shows the bending moment formulae derived from the present study by the authors. The formulae for simple span decks are the essential formulae obtained from the relations as shown in Fig.2. Those were calculated with FEM under the full loading of wheels as shown in Fig.3, namely, one vehicle in the longitudinal direction and unlimited number of vehicles in the transverse direction. The design formulae are decided by giving the safety margin of about 10-15% to the analytical results.

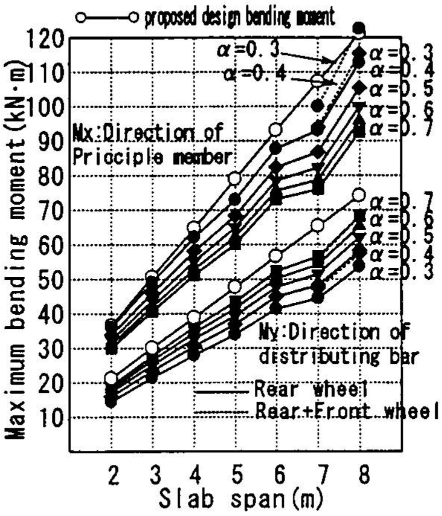

Fig.2 Relationships between slab span and maximum bending moment

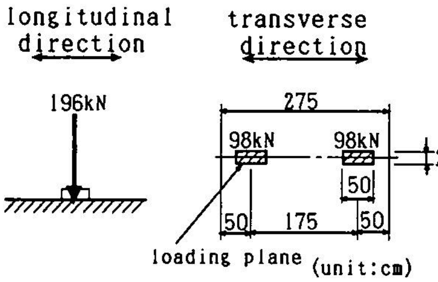

Fig.3 T-loading

Table 1 Design bending moment per unit width (1m) of slab due to T-loadings (include impact)

unit:kN·m/m(=kN·m/m)

Type of slab	Kind of bending moment	Direction of bending moment / Span of Slab (m)	For main member perpendicular to traffic: Bending moment for principle member	For main member perpendicular to traffic: Bending moment for distribution reinforcement
Simply supported slab	Bending moment through span	0<L≦8	1.2×(0.12L +0.07)P	0.9×(0.10L +0.04)P

where L:Span length of slab
P:Weight of one wheel of T-loading(=98kN)

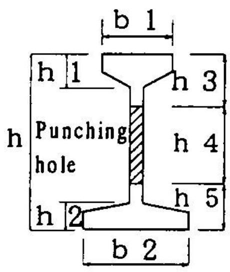

Table 2 Section properties of I-beam

	Dimensions (mm) h	b1	b2	t	h1	h2	h3	h4	h5	Properties (net section) Intertia (cm4)	Area (cm2)	Weight (N/m)
I-105	105	30	35	4	13.5	10.5	25	50	30	167	8.50	71.3
I-130	130	30	40	4.5	14	12	35	65	30	319	9.98	88.6
I-150	150	35	50	5	14	10	55	65	30	489	11.8	104
I-200	200	50	60	6	15	12	35	135	30	1650	20.4	193

In ordinary design method, the spacing of I-beams and distributing bars is limited by the maximum and minimum values. For example, the minimum spacing of I-beams is 10cm and the maximum one is 25cm. Also the deck thickness is limited not to increase the dead weight. When a design of cross sections of longer span deck is carried out considering such limitations, the design becomes impossible and a new I-beam is required. Last year, the authors have designed the cross section to I-beam for longer span deck until 8m. The new I-beam was rolled with the cross section as shown in Table2. Table 2 shows the section properties of the I-beams including old ones.

3. Fatigue Phenomena and Improvement of Fatigue Strength of Concrete-Filled I-Beam Grid Deck

Through various kinds of fatigue tests on the concrete-filled I-beam grid deck[2)], the predominant fatigue failure of the deck is ascertained as the fatigue fracture of I-beams at the corner of web holes which are provided to arrange distributing bars. Welding at the points to make fix the distributing bars to I-beams seems also to affect the fatigue fracture. In order to secure the stiffness to keep the panel shape during the transportation and erection, the welding is required at some points. But those fixing points are the weak points in fatigue and have to be modified.

3.1 Fatigue strength of I-beam and its improvement by I-beam itself

In order to clarify the essential fatigue strength of I-beams, a series of fatigue tests were conducted on simple necked I-beams. The test was conducted by giving a pulsating load at the span center on the I-beams as shown in Fig. 4. On all the specimens tested, fatigue cracks occurred at the corner of the supporting side of each punching hole. The corner of a hole in the shear span develops complex stress states by the combination of bending stress and secondary bending stress by shearing force and stress concentration by geometric aspect. Paying attention to the shape of punching holes and the welding of distributing bars, the fatigue tests were conducted on three kinds of I-beams as shown in Fig.5 and Table 3.

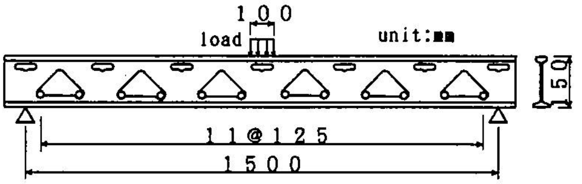

Fig.4 I-beam fatigue test

By a FEM analysis the stress concentration states were compared by changing the hole shape and welding position to fix the distributing bar. Regarding to the hole shape, type B decreased the stress concentration. Also the welding at the side seems to be favorable than the welding from bottom side. Those stress decreases can be recognized by the increase of fatigue lives at the fatigue tests in the order.

Table 3 Specimens for I-beam fatigue test

Specimen	Cross point welding (Welding type)	Type of punching hole
I-1	No welding	Type A
I-2	Type 1	Type A
I-3	Type 2	Type B

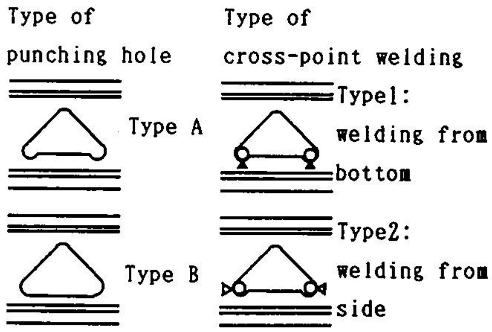

Fig.5 Details of punching hole and crosspoint-welding

Fig.6 is the S-N results and mean S-N curve about the crack initiation at the hole corner. As seen the figure, when the fatigue data were plotted by the stress range, all data can plotted around a curve. The curve is the essential S-N curve of I-beam.

3.2 Stress expression of I-beams in deck and improvement of fatigue durability

3.2.1 Specimens and loads

In order to study the fatigue life of the I-beams, how express the stress at the fatigue initiating corners in a concrete-filled deck and to compare the effect of modified points, a series of fatigue tests on deck specimens were carried out using a wheel running machine. Five kinds of specimens were prepared. Main modified points by each specimen are the shape of punching holes of I-beam, casting concrete, the presence or not of the bottom form plate and the welding point for fixing distributing bar as shown in Fig.5 and Table 4. The specimen with 20cm thick was simply supported with the span length of 2.2 m. The direction of I-beams is perpendicular to the direction of wheel running. A given constant wheel load runs going and returning motion on the span center.

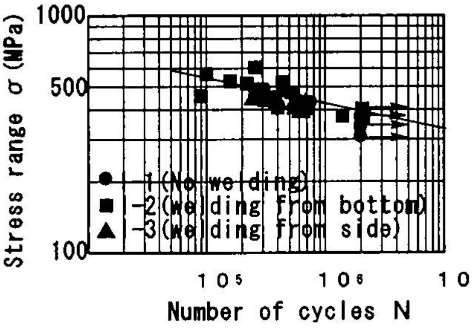

Fig.6 S-N curve for I-beam (crack initiation point)

Table 4 Specimens for wheel running test

Specimen	Type of concrete	Bottom plate	Cross point welding (Welding type)	Type of punching hole	Test load	Loading number
IS-1	normal	×	standard* (Type 1)	Type A	147kN	500, 000cycles
IS-2	expansive	×	standard (Type 1)	Type A	147kN	500, 000cycles
IS-3	normal	×	all point(left side of slab:Type 2, right side of slab:Type 1)	Type A	147kN (+177kN until slab fracture)	500, 000cycles
IS-4	normal	○	standard(Type 1)	Type A	147kN	100, 000cycles
IS-5	normal	×	standard(Type 2)	Type B	147kN (+177kN until slab fracture)	500, 000cycles

* standard:welding the cross point on 4 sides and some innner points of panel
design strength of concrete σ_{ck}=29. 4MPa, I-beam pitch:18cm(I-150:JIS SS400)
distributing bar pitch:upper 25cm, lower 12. 5cm(D16:JIS SD345)

The aimed load and number of cycles to give on each specimen were decided basically 147kN and 500,000 cycles. The wheel load of 147kN was determined as the maximum measured wheel load in Japanese and 500,000 cycles was enough ones over the equivalent cycles of 147kN wheel load during 50 years at the common urban expressway. For Specimen IS-4, only 100,000 cycles was given in order to confirm the effectiveness of the bottom plate. For specimens IS-3 and IS-5, after loading 147kN, 500,000 cycles, the loading with the increased load of 177kN was continued until to find out a remarkable fatigue failure.

3.2.2 Fatigue failure of the basic decks

All the specimens have endured to 500,000 cycles under the load of 147kN In the specimens IS-3 and IS-5 which were loaded until the occurrence of fatigue failure by increasing the load, the presumed fatigue failures have occurred at some I-beams. Those failures seemed to initiated at the punching holes near the edge of wheel where the highest shear force occurred. The number of cycles when the fatigue failures were found were 180,000 cycles in IS-3, and 260,000 cycles in IS-5, respectively. Also, the failured I-beams were the welded ones with distributing bars. From those fatigue failures, it can be said that welding of distributing bar at the I-beam hole makes weak for fatigue.

After the tests, all concrete was removed at the specimen IS-3 to check the fatigue cracks. Then, we can compared the difference of welding points that the fatigue cracking on the I-beam connecting distributing bars by Type 1 is more severe than the one by Type 2.

When comparing the fatigue lives of IS-3 and IS-5, the difference of the web hole shape is not clear.

Fig. 8 shows the deflection change to number of cycles with the slab center. In the figure, a clear difference can be seen. Namely, the specimens IS-1, IS-3 and IS-5, which have no bottom form plate, are developing large deflection and shows an increasing rate. On the other hand, deflections of the specimen IS-2 using expansive concrete and the specimen IS-4 having a bottom plate are very small and steady. The difference of deflection is about 2/3 at steady states. The effect of usage of expansive concrete seems to be due to chemical prestressing between I-beams and rising slab orthotropy. The effect of the bottom plate can be said due to composite action with the whole concrete deck. By the composite action, the orthotropy is rising, too.

Generally, as the concrete-filled I-beam grid deck is attached the bottom plate, it can not be presumed that such a fatigue failure as observed at the specimens without the plate will occur. Furthermore, when expansive concrete is used, a remarkable enlargement of fatigue strength of the deck will be expected.

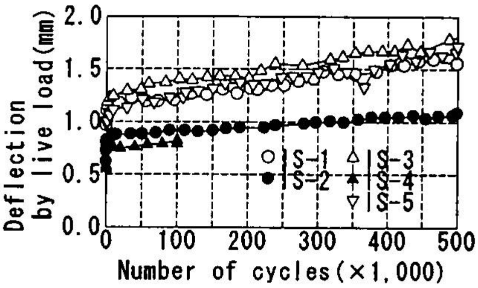

Fig.8 Deflection of the slab(at the slab center)

3.2.3 Stress expression of the hole corners

As seen in Fig.7, the deflection becomes steady after some cycles of about 10,000 cycles. The steady state is identified that the bending rigidities in the orthogonal two ways have dropped to the ones neglecting tension side concrete. So, through plate analysis of orthotropic plate theory, the bending moment and shearing force acting on I-beams can be calculated. Then calibrating the flange stresses just under the web holes and with the relation between stresses at the flange and hole corner in a composite beam, the stresses at the hole corners of the I-beams in a deck can be expressed with the section forces of bending moment and shearing force in the deck.

Equation 1 is the final expression for the hole corner where a fatigue crack will initiate. The numbers before the each term are stress concentration factors depending on hole shape. By the stress calculated with the equation and S-N curve as shown in Fig.6, fatigue life of crack initiation can be presumed.

$$\sigma_x = \alpha \frac{M}{I_V} Y_w + \beta \frac{y_w}{I_T} \cdot \frac{A_s}{\frac{B \cdot X}{n} + A_s} \cdot \frac{I_{TL}}{I_{TL} + I_{TU}} l_1 Q \quad \cdots (1)$$

where α, β:stress concentration coefficient by the punching hole shape,
M:Bending moment, Q: Shear force, I_V: Inertia of composite section, I_T: Inertia of I-beam,
I_{TU}: Inertia of compression side of I-beam, I_{TL}: Inertia of tension side of I-beam,
Y_W: Distance between neutral axis and the corner of I-beam in composite section,
y_W: Distance between neutral axis and the corner in tension side of I-beam,
A_s: Area of I-beam(net-section), B: effective width of concrete, X: effective thickness of concrete
n: Young's modulus ratio, l_1: span of secondary bending moment by shear force

4. Conclusions

The present study is carried out to apply the concrete-filled I-beam grid deck to wider span length deck than the ordinary one. Therefore, a new large I-Beam is rolled to be applicable to decks of 8m span length. Then design bending formulae are prepared considering the orthotropy which is a feature of the grid deck. Furthermore, fatigue tests are carried out to make clear the fatigue strength of I-beams themselves and the I-beams in a deck. Through the tests the use of expansive concrete for the deck can be recommended.

References

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2) Y.Maeda, S.Matsui and K.Kushida: Fatigue Strength of Concrete-Filled Grillage Decks, IABSE Colloquium Lausanne 1982, pp.609-616.