Development of Aluminum Decks for Highway Bridges

Ichiro OKURA
Associate Professor
Osaka University
Suita, Osaka, Japan
okura@civil.eng.osaka-u.ac.jp

Syogo OSAWA
Graduate Student
Osaka University
Suita, Osaka, Japan
shogo-o@civil.eng.osaka-u.ac.jp

Masakazu TAKENO
Graduate Student
Osaka University
Suita, Osaka, Japan
take-no@civil.eng.osaka-u.ac.jp

Nobuyasu HAGISAWA
Senior Manager
Nippon Light Metal Co., Ltd.
Shizuoka, Japan
nobuyasu-hagisawa@nikkeikin.co.jp

Toshiyuki ISHIKAWA
Research Associate
Osaka University
Suita, Osaka, Japan
t-ishi@civil.eng.osaka-u.ac.jp

Summary

In Japan, the amendment of the design vehicle load from 196 kN to 245 kN in 1994 urges concrete decks and girders of existing bridges to be reinforced. To cope with this issue, we put forward an idea of reducing the weight of the roadway by replacing concrete decks with aluminum ones. To realize this idea, we fabricated an aluminum deck by the friction stir welding. In this paper, we discuss the following topics: (1) Design of aluminum decks of open-hollow sections. (2) Connections of an aluminum deck to a steel girder. (3) Composite effects of an aluminum deck on a steel girder.

Keywords: aluminum alloy; deck; friction stir welding; fatigue; plate-bending stress; connection; composite effect; steel girder.

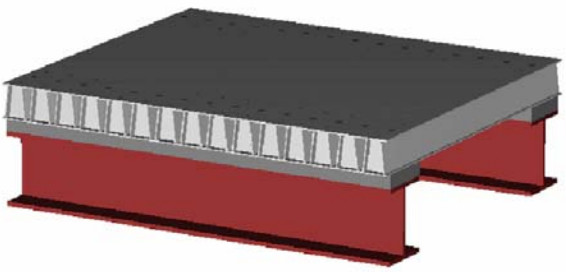


Fig. 1 *Aluminum deck of hollow sections*

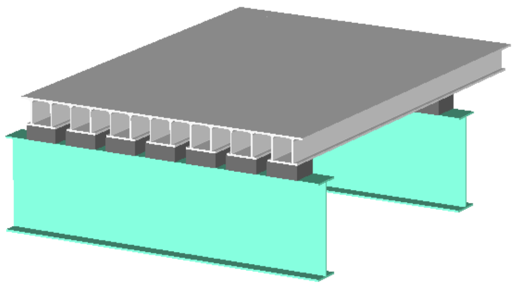


Fig. 2 *Aluminum deck of open-hollow sections*

1. Introduction

In Japan, the amendment of the design vehicle load from 196 kN to 245 kN in 1994 urges concrete decks and girders of existing bridges to be reinforced. To cope with this issue, an idea of reducing the weight of the roadway by replacing concrete decks with aluminum ones was put forward. Then an aluminum deck shown in Fig. 1 was introduced at the 8th INALCO [1]. The deck was fabricated by joining the top and bottom flanges of adjacent extrusions with the friction stir welding (FSW). However, since the deck consisted of hollow sections, it was impossible to examine visually the back surface of the FSW-joints. The Japanese Guideline for Quality Inspection of Aluminum Joints by Friction Stir Welding specifies that the visual inspection of the FSW-joints is mandatory [2].

To solve this problem, an aluminum deck of open-hollow sections was newly designed, where conducting FSW on the open sections made the visual inspection of the back surface of the FSW-joints possible. In this paper, the design procedure of the deck and the method to connect the deck to a steel girder are presented. The structural behavior of the aluminum deck laid on the steel girders is investigated by loading tests. Then the composite effects of an aluminum deck on a steel girder are examined by loading tests.

2. Design of aluminum deck of open-hollow sections

Fig. 2 shows the newly designed aluminum deck on steel girders. The longitudinal direction of the extrusions spans between the steel girders. As shown in Fig. 3, the ends of the overhangs of the extrusions were butted, and FSW was done there. Therefore, it is possible to inspect visually the upper and lower surfaces of the FSW-joints.

The aluminum deck was designed so as to be applicable to the spacing not greater than 4 m between steel girders. First the top flange of the extrusions was designed, and later the bottom flange and the webs were done. The aluminum alloy used for the extrusions was A6061S-T6. The thickness of the extrusions could not be over 15 mm, because of the product quality of the extrusions and the capability of the FSW machine.

In the design of the top flange, the thickness t_u and the intervals B_c and B_o notified in the Fig. 3 were determined according to the following requirements:

(1) The maximum stress produced on the top flange by the design wheel load 137.3 kN of a truck, specified in the Japanese Specifications for Highway Bridges (JSHB) [3] does not exceed the allowable stress. The design wheel load 137.3 kN is the sum of one wheel load 98.1 kN and its impact load 39.2 kN. The loading area of the design wheel load is a rectangle of 500×200 mm.

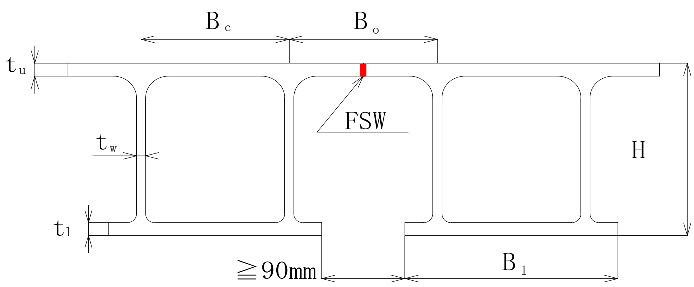


Fig. 3 *FSW at the ends of the overhangs of extrusions*

(2) The stress range produced on the top flange by the passage of the design wheel load does not exceed the fatigue strength.

(3) The out-of-plane deflection of the top flange created by the design wheel load is less than or equal to $B/300$ so as to exert no bad influence on the asphalt paving. Here B is B_c or B_o, that is, the interval between the adjacent webs.

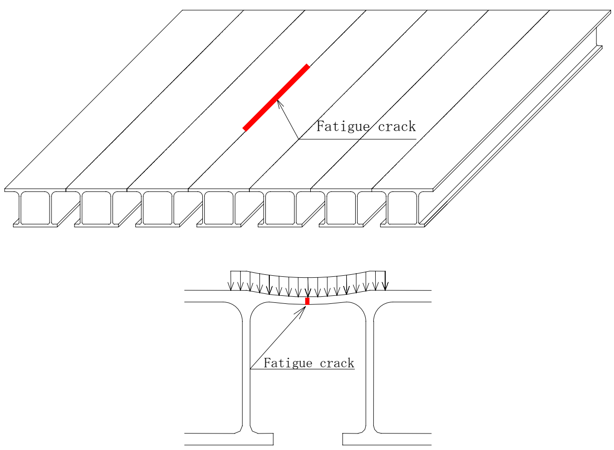


Fig. 4 *Fatigue crack initiated along the FSW-joining line of a top plate*

The fatigue crack considered in the item (2) is initiated along the FSW-joining line of the top plate of the aluminum deck, as shown in Fig. 4 [1]. The crack is caused by the plate-bending stress in the bridge-longitudinal direction. The stress is produced by the local out-of-plane deformation of the top plate just under the wheel load.

In the design of the bottom flange and the webs, the flange thickness t_l and width B_l and the web thickness t_w

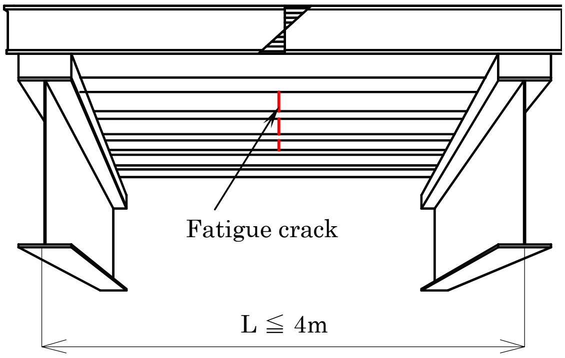


Fig. 5 *Fatigue crack initiated on bottom flanges in the bridge-longitudinal direction*

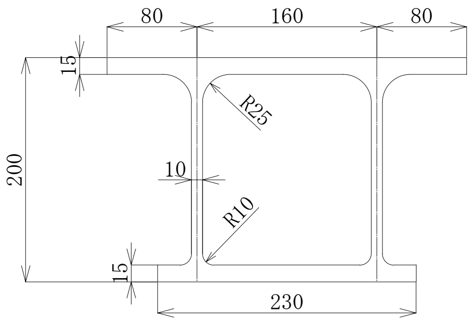


Fig. 6 *Cross section of the extrusion*

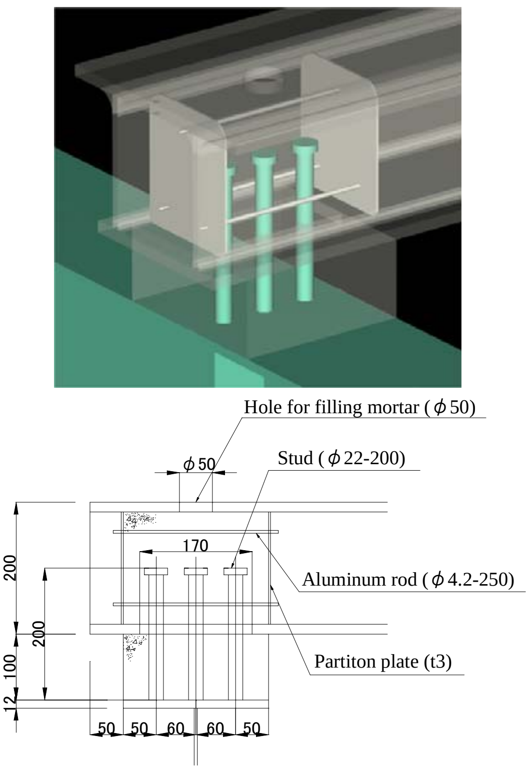


Fig. 7 *Connection of the aluminum deck to the top flange of the steel girder*

and height H shown in Fig. 3 were determined according to the following requirements:

(1) The size of an extruding die limits the height H of the extrusions.

(2) The FSW-tool needs a clearance not less than 90 mm between the adjacent bottom flanges.

(3) The maximum stress produced on the bottom flange by the design truck loads specified in the JSHB [3] does not exceed the allowable stress. The design trucks are laid side by side in the bridge-transverse direction wherever possible.

(4) The maximum stress obtained in the item (3) does not exceed the fatigue strength, either.

(5) The vertical deflection of the bottom flange is less than or equal to $L/300$ to prevent an excessive vertical deflection of the aluminum deck. Here, as shown in Fig. 5, L is the steel girder spacing, which is not greater than 4 m.

The fatigue cracks taken into account in the item (4) are initiated on the bottom flanges in the bridge-longitudinal direction, as shown in Fig. 5 [1]. The cracks are induced by the membrane stress in the bridge-transverse direction, which is produced by the global bending moment.

The FEM analysis of aluminum decks gave us the cross section of the extrusion shown in Fig. 6, which met the above requirements.

3. Connection of aluminum deck to steel girder

The connection of the aluminum deck to the top flange of a steel girder is shown in Fig. 7. Three steel stud shear connectors of 22 mm in diameter were welded to the top flange of the steel girder in one row in the bridge-transverse direction. A formwork was laid surrounding the studs to leave the supporting mortar between the top flange of the steel girder and the bottom flange of the aluminum extrusion. The studs were inserted inside the extrusion through a rectangular cutting on the bottom flange. The non-shrinkable mortar was filled through the hole on the top flange of the extrusion. The two aluminum plates which were tied with three aluminum rods were installed inside the extrusion to prevent the mortar from

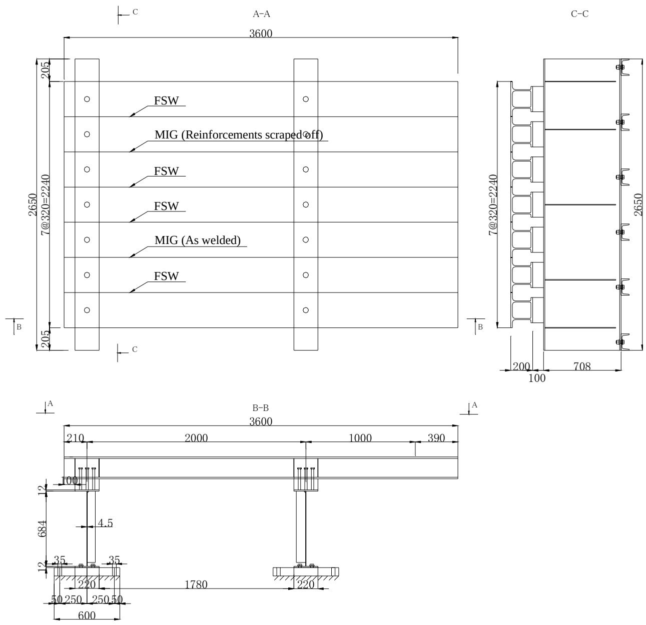


Fig. 8 *Test specimen*

Fig. 9 *View of loading tests*

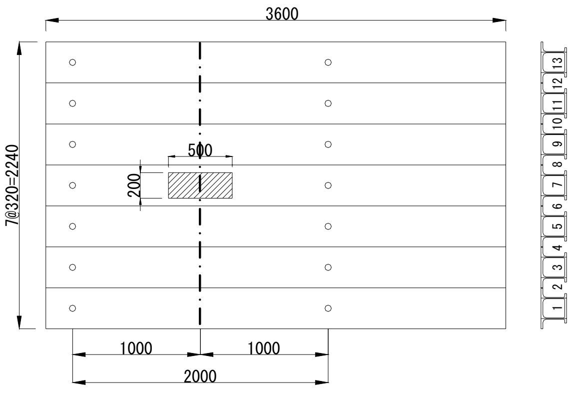


Fig. 10 *Loading on the span*

running out.

The supporting mortar is necessary to absorb the camber of the steel girders, which is created when existing concrete decks are replaced by aluminum decks. Besides it prevents the electric corrosion of aluminum, since it avoids the direct contact of the aluminum extrusions with the steel girders.

The loading tests showed that the connection was a rigid one, and the fatigue tests demonstrated that it has sufficient fatigue durability [4].

4. Structural behavior of aluminum deck of open-hollow sections

Fig. 8 shows the test specimen consisting of the aluminum deck of open-hollow sections and the steel girders [5]. Because of the capability of the FSW machine, the number of the extrusions which could be joined by FSW was three and below. First the upper half of the overhangs of the extrusions was joined by FSW and next the lower half was done after the extrusions were turned over. The overlaps on the upper and lower surfaces of the FSW-joints were scraped off by a grinder. As shown in Fig. 8, the FSW-joined panel of three extrusions and those of two extrusions were connected by MIG welding. The reinforcements on the upper and lower surfaces of one MIG-weld were scraped off by a grinder, but another one is as-welded.

The hollow sections of the aluminum deck were connected to the top flange of the steel girders with the method mentioned in Chapter 3. The deck is supported by the steel girders placed at an interval of 2 m and it overhangs 1.39 m from the right-hand steel girder.

Fig. 9 presents the view of the loading tests. A load is applied to the deck through a hard rubber plate of 500×200×15 mm. The shape of 500×200 mm is the same with the loading area of the design wheel load of a truck specified in the JSHB [3]. As shown in Fig. 10, the loading tests were carried out on

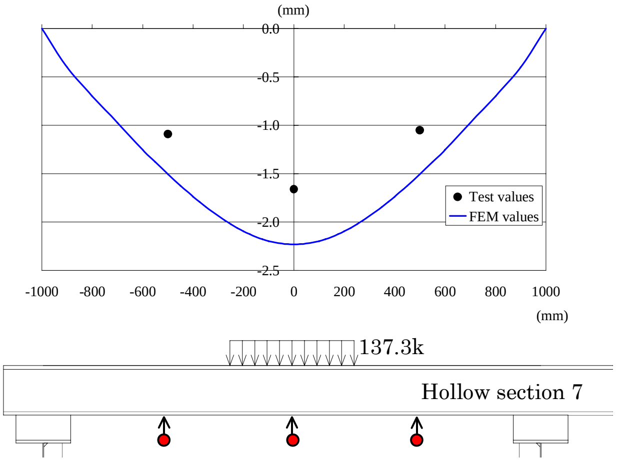


Fig. 11 V*ertical deflection of the bottom flange of the aluminum deck [Hollow section 7]*

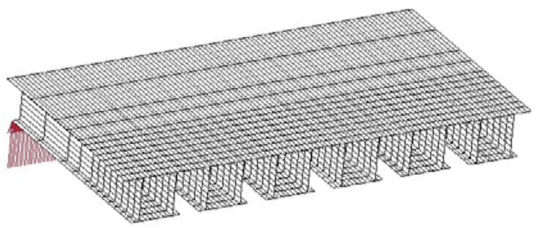


Fig. 12 *Mesh division*

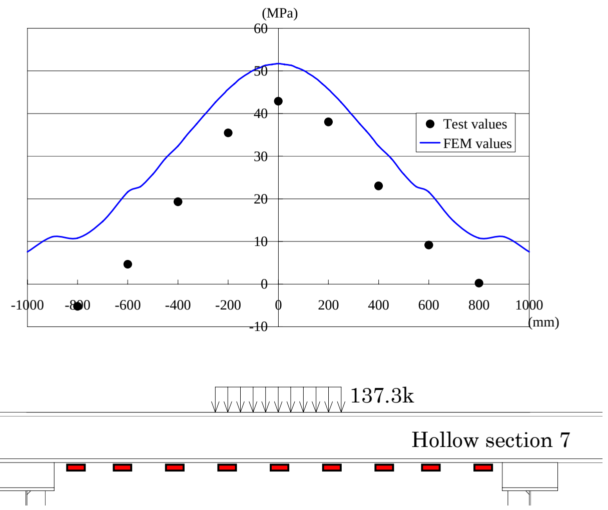


Fig. 13 *Bridge-transverse stress on the bottom flange of the aluminum deck [Hollow section 7]*

the span in the middle between the steel girders. The load was applied statically until 137.3 kN, after moving the hard rubber plate at every 20 mm interval in the bridge-longitudinal direction.

Fig. 11 shows the vertical deflection of the bottom flange of the aluminum deck when the load of 137.3 kN is located on the hollow section 7 in Fig. 10. In the figure the curve is given by the FEM analysis for the mesh division shown in Fig. 12. The test values are smaller than the FEM ones. Since the steel girders are not considered in the FEM analysis, it may be the reason that the deck is restrained rotationally by the steel girders.

Fig. 13 shows the distribution of the bridge-transverse stress on the bottom flange. The test values are smaller than the FEM ones. The reason for this may be the same as mentioned for the vertical deflection of the bottom flange.

Fig. 14 presents the distributions of the bridge-transverse and -longitudinal stresses on the upper surface of the top plate on the hollow section 7 in Fig. 10 when the load of 137.3 kN is located on the same section. Fig. 15(a) provides the distributions of the bridge-transverse stress on the upper and lower surfaces of the top plate on the open section 8 in Fig. 10 when the load of 137.3 kN is located on the same section. Fig. 15(b) does for the bridge-longitudinal stress.

As shown in Figs. 14 and 15(a), the bridge-transverse stress is a plate bending stress just under the load. Except this area, it is a membrane stress. As shown in Figs. 14 and 15(b), the bridge-longitudinal stress is a plate-bending stress, which is very high within the loading area, and decreases rapidly outside the loading area. This stress is produced by the local out-of-plane deformation of the top plate just under the load. In each figure of Figs. 14, 15(a) and 15(b), the test values agree well with the FEM ones. This means that the plate-bending stress is not influenced by the existence of the steel girders.

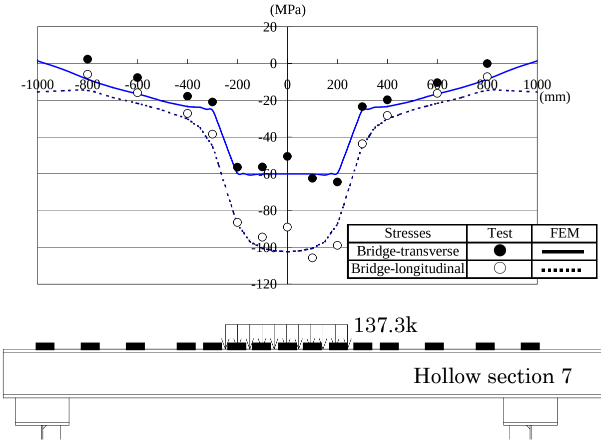
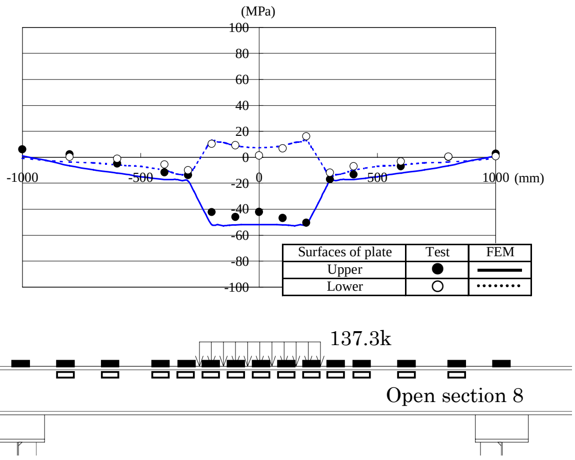
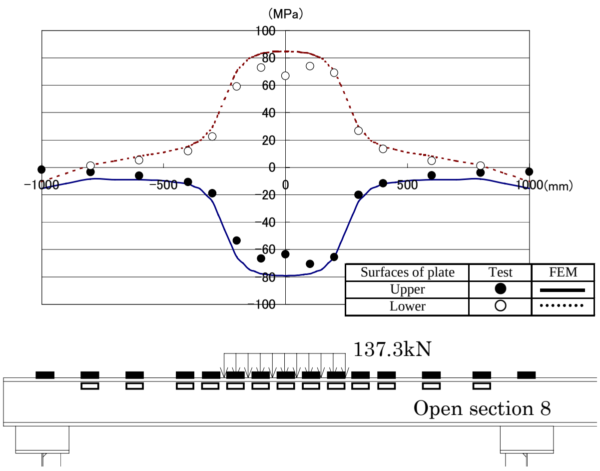


Fig. 14 B*ridge-transverse and -longitudinal stresses of the top plate of the aluminum deck [Hollow section 7]*



(a) *Bridge-transverse stress*



(b) *Bridge-longitudinal stress*

Fig. 15 *Bridge-transverse and -longitudinal stresses of the top plate of the aluminum deck [Open section 8]*

5. Composite effects of aluminum deck on steel girder

5.1 Incomplete composite theory

Since stud shear connectors are used in the connection of an aluminum deck to a steel girder, composite effects are produced between both in the bridge-longitudinal direction. Referring to Fig. 16, the shear force H on the top flange of the steel girder is assumed to have the following relation to the gap δ between the top plate of the aluminum deck and the top flange of the steel girder [6]:

$$H = k\delta \tag{1}$$

where k : elastic spring.

Based on Eq. (1), the axis force N of the top plate of the aluminum deck or the steel girder is expressed in the following differential equation [6]:

$$\frac{d^2N}{dx^2} - \lambda^2 N = -rM + k\Delta_t \tag{2}$$

where M : bending moment and Δ_t : difference between thermal strains of the top plate of the aluminum deck and the steel girder. The coefficients λ and r are given by

$$\lambda = \sqrt{\frac{kaI_v}{E_a a_a A_a \left(I_s + \dfrac{I_a}{n} \right)}} \tag{3}$$

$$r = \frac{ka}{E_s \left(I_s + \dfrac{I_a}{n} \right)} \tag{4}$$

where I_v, I_a, I_s, E_a, E_s, A_a, a, a_a, n : see Fig. 16. Here note that A_a and I_a are the sectional area and the moment of inertia of area, respectively, of the top plate of the aluminum deck.

5.2 Loading tests

Fig. 17 shows the test specimen to investigate the degree of the composite effects of the aluminum deck on the steel

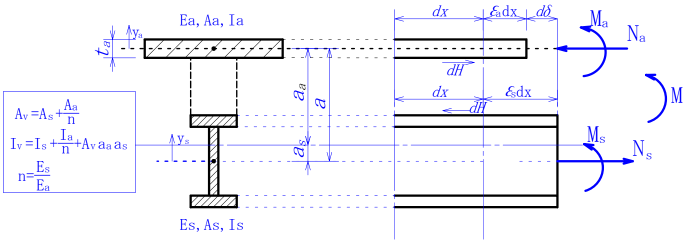


Fig. 16 *Symbols used in the incomplete compoiste theroy*

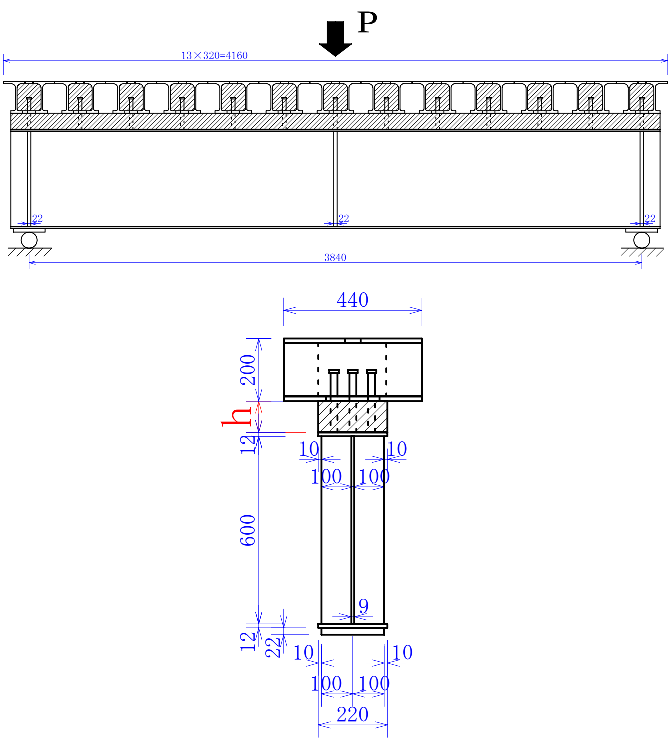


Fig. 17 *Test specimen*

Table 1 *Test specimens*

Specimen	*h* (mm)	Aluminum Deck
I	100	not provided
II	30	provided
III	60	provided
IV	100	provided

girder. As listed in Table 1, Specimen I has the concrete of 100 mm in thickness, but an aluminum deck is not provided. The other specimens have an aluminum deck provided, but the thickness of the concrete is different among the specimens. A concentrated load is applied to the span center. Fig. 18 presents the view of the loading tests.

Fig. 19 shows the relation between the load and the deflection at the span center. The maximum strength of Specimens II, III and IV is 1.49, 1.59 and 1.68 times larger than that of Specimen I, respectively. This means that the aluminum deck has large composite effects on the steel girder.

The strain on the bottom flange of the steel girder is given by the following equation:

$$\varepsilon_s = \frac{P}{2}\left[S_s x - T_s \frac{\sinh(\lambda x)}{\lambda \cosh\left(\frac{\lambda L}{2}\right)} \right] \qquad (5)$$

where ε_s: strain on the bottom flange of the steel girder, P: load, L: span length of the steel girder and S_s, T_s: coefficients. The values of λ are determined by adjusting Eq. (5) to the measured strains of the test specimens. Substituting the λ values into Eq. (3) gives 0.320, 0.445 and 0.422 kN/mm^2 to the elastic spring λ of Specimens II, III and IV, respectively. Fig. 20 shows the distributions of the strain on the bottom flange of the steel girder. The distribution given by Eq. (5) is located on the measured values, and it is near to the line corresponding to the complete composite effects.

6. Conclusions

The design procedure of an aluminum deck of open-hollow sections and the method to connect the deck to a steel girder were presented.

A very high plate-bending stress is produced on the top plate of the aluminum deck just under the wheel load.

The composite effects of an aluminum deck on a steel girder are expressed in terms of the

Fig. 18 *View of loading tests*

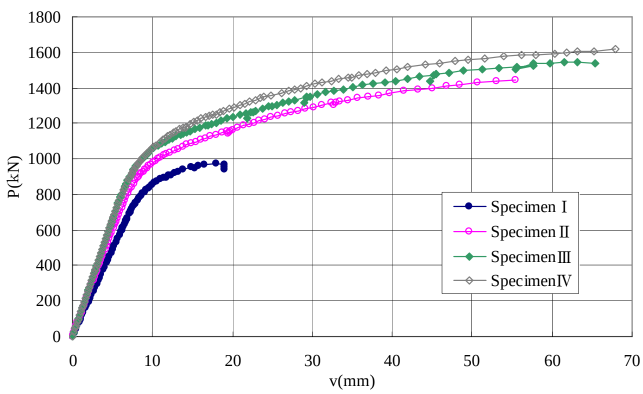


Fig. 19 *Relation between load and deflection at the span center*

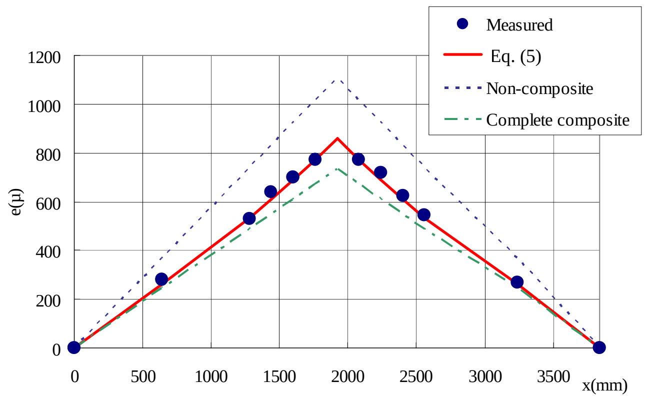


Fig. 20 *Distributions of strain on the bottom flange of the steel girder[Specimen IV, P=495kN]*

incomplete composite theory. The composite effects of an aluminum deck on a steel girder are near to the complete composite ones.

Acknowledgements

This work was supported by the Grant-in-Aid for Scientific Research (B), No. 15360241, provided by the Japan Society for the Promotion of Science, and by a research grant by the Frontier Research Center of Osaka University.

References

[1] OKURA I., NARUO M., VIGH L.G., HAGISAWA, N. and TODA H., "Fatigue of Aluminum Deck Fabricated by Friction Stir Welding", 8th International Conference on Joints in Aluminum (INALCO), Munich, Germany, 2001, pp.4.1.1-4.1.12.

[2] JAPAN ALUMINUM ASSOCIATION, COMMITTEE OF STRUCTURES, *Japanese Guideline for Quality Inspection of Aluminum Joints by Friction Stir Welding*, Draft, January, 2004. (in Japanese)

[3] JAPAN ROAD ASSOCIATION, *Japanese Specifications for Highway Bridges, Part 2 Steel Bridges*, 2002. (in Japanese)

[4] OKURA I., HAGISAWA N., OKADA O. and YAMAGUCHI S., "Static and Fatigue Behavior of the Connections of Aluminum Decks to Steel Girders", Proceedings of the 19th U.S.-Japan Bridge Engineering Workshop, Public Works Research Institute, Independent Administrative Institutions, Japan, 2003, pp.105-116.

[5] OKURA I., OSAWA S. and HAGISAWA N., "Development of Aluminum Decks for Highway Bridges", the 5th International Forum on Aluminum Ships, Tokyo, Japan, 2005, pp.93-101.

[6] HAWRANEK A. and STEINHARDT O., *Theorie und Berechnung der Stahlbrucken*, Springer-Verlag, 1958. (Japanese translated version, pp.472-475)