STATIC AND FATIGUE BEHAVIOR OF THE CONNECTIONS OF ALUMINUM DECKS TO STEEL GIRDERS

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ABSTRACT

A connection of aluminum decks to steel girders is developed. Specimens of a simple beam type and of an overhang type are provided for statically loading and fatigue tests. The aluminum beam of hollow section is joined to the top flange of steel girders, using stud shear connectors of steel and non-shrinkable mortar. A concentrated load is applied at the span center for the simple beam type specimens, and at the beam end for the overhang type ones. The statically loading tests show that the connection developed is a rigid one. The fatigue tests demonstrate that the connection has sufficient durability, although some shear connectors experience fatigue cracks.
Keywords: aluminum deck, steel girder, static and fatigue behavior, shear connector, non-shrinkable mortar

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 was fabricated by the friction stir welding, and its fatigue behavior was investigated. This was presented at the 17th Japan-US Bridge Engineering Workshop[1)].

Since then, as shown in Fig. 1, an aluminum deck was adopted for the sidewalk to widen the roadway of the Shin-Kakogawa bridge in Hyogo prefecture. The aluminum deck used is about 4 m in width and about 400 m in length.

To put aluminum decks to practical application to roadway bridges, the connections of the aluminum decks to steel girders have to be developed. In this research, a connection is proposed, and its static and fatigue behavior is investigated by statically loading and fatigue tests.

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Figure 1. Aluminum deck of the Shin-kakogawa bridge

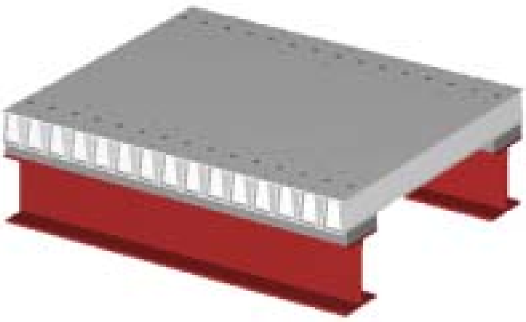


Figure 2. Aluminum deck on steel girders

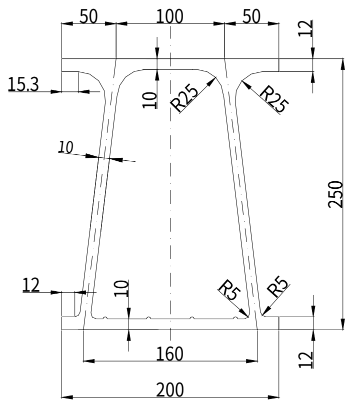


Figure 3. Dimensions of extrusion

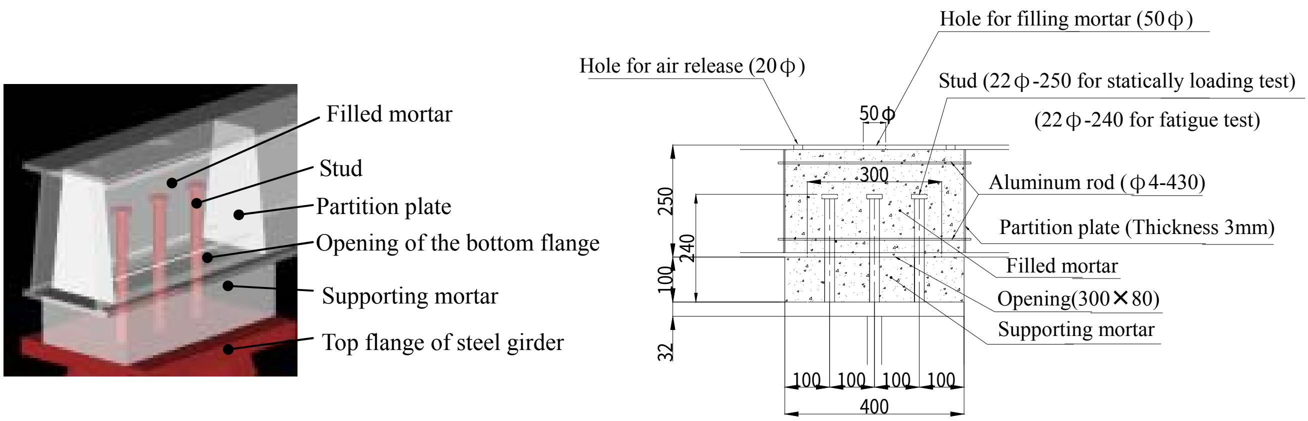


Figure 4. Connection of aluminum deck to steel girder

2. TEST SPECIMENS

Figure 2 shows a general view of an aluminum deck on steel girders. The aluminum deck consists of the extrusions connected parallel. The longitudinal direction of the extrusions spans between steel girders. Only one extrusion is enough to understand the static and fatigue behavior in the bridge-transverse direction of the connections of the aluminum deck to the steel girders.

Figure 3 presents the cross section of the extrusions used for the specimens. The aluminum alloy of the extrusions is A6N01-T5. Its mechanical properties are given in Table 1(a). The aluminum lot is different between the statically loading and fatigue tests.

As shown in Fig 4, 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 running out. The mechanical properties of the studs and the mortar used are listed in Tables 1(b) and (c), respectively.

The supporting mortar is necessary to absorb the camber of the steel girders, which is created when existing concrete slabs 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.

A simple beam type specimen and an overhang type one are shown in Fig. 5. The former models the decks between steel girders, and the latter does the overhang decks.

3. STATICALLY LOADING TESTS

3.1 Simple Beam Type Specimen

3.1.1 Outline of test

As shown in Fig. 6, the load was applied at the span center of the aluminum beam. The base plates of the connections were fixed to the test floor with high strength steel bars. The vertical deflection at the span center and the strains on the lower surface of the bottom flange and the upper surface of the top flange as well as the strains on the sides of the supporting mortar and the strains on the studs were measured. The strain gauges were glued on the studs before the mortar was filled.

First the load was increased to 294 kN and unloaded. Second it was increased to 618 kN, which is the capacity of the loading machine, without failure. The load was again increased to 618 kN, and the test was terminated.

3.1.2 Relation between load and deflection

Figure 7 presents the relation between the load and the vertical deflection at the span center. The load is taken on the vertical axis, and the vertical deflection is done on the horizontal axis. The thick solid line represents the FEM results for the fixed conditions at both the ends of the beam of 2m in length, and the thick broken line does for the simply

Table 1. Mechanical properties

(a) A6N01S-T5 alloy

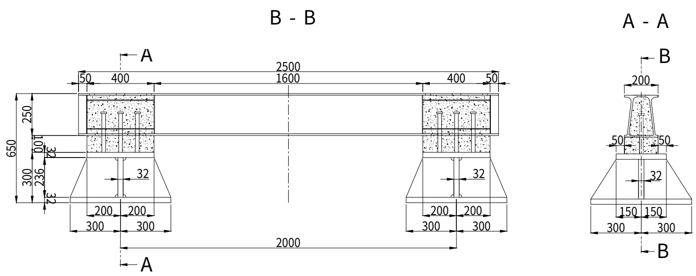
Tests	Tensile strength (MPa)	0.2% proof stress (MPa)	Elongation (%)	Young's modulus (GPa)	Poisson's ratio
Statically loading	325	299	16.6	71.5	0.32
Fatigue	308	289	16.0	71.0	0.31

(b) Steel studs

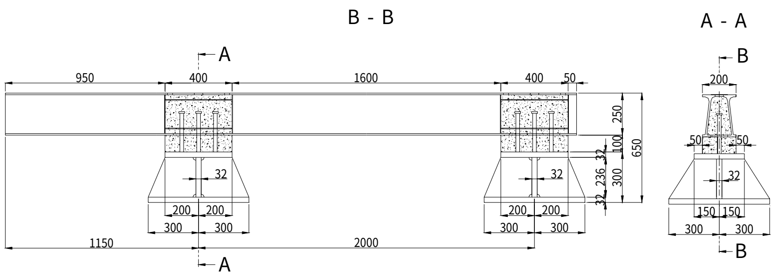
Tests	Statically loading	Fatigue
Yield stress (MPa)	283	296
Tensile strength (MPa)	443	469
Elongation (%)	26	27

(c) Mortar

Tests	Statically loading	Fatigue
Material age (day)	100	187
Compression strength (MPa)	77.4	78.1
Young's modulus (GPa)	29.4	28.9
Poisson's ratio	0.213	0.204



(a) Simple beam type



(b) Overhang type

Figure 5. Specimens

supported conditions.

For the first loading to 294 kN, the residual deflection is almost zero. The curve for the second loading to 618 kN is not on the unloading curve, leaving a residual deflection. Since the curves for the first and second loadings have almost the same slope as that of the thick solid line, the degree of the connection of the aluminum extrusion to the steel girder is near the fixed conditions at both the ends.

3.1.3 Relation between load and strains of stud shear connectors

Figure 8 shows the relation between the load and the strains of the stud shear connectors. The strains are an average of the two strain gauges which are glued symmetrically about the axis of the studs. The tensile force is produced in the central and outside studs, and the compressive force is done in the inside stud. The compressive force of the inside stud decreases at the load 300 kN. While the increase in strain of the outside stud stops above the load 520 kN, the strain of the central stud increases. Accordingly the share of the load shifts from the outside stud to the central and inside ones.

3.1.4 Relation between load and strains on the sides of supporting mortar

Figure 9 shows the relation between the load and the strains in the vertical direction on the sides of the supporting mortar. The compressive strain is created only at the strain gauge C1. The rate of increase in the strain of the strain gauge C1 decreases over the load 300 kN, and the stain decreases around the load 500 kN. This is the reason the strain is released due to cracking of the supporting mortar around the strain gauge C1.

The tensile force of the studs and the compressive one at the edge of the supporting mortar develop a moment, which makes the connection rigid.

Figure 10 shows the appearance of the cracks on the side of the supporting mortar after the loading to 618 kN. Since the width of the cracks is too small to see, the cracks are exaggerated by a marker.

3.2 Overhang Type Specimen

3.2.1 Outline of test

As shown in Fig. 11, the load was applied at the point 1 m away from the middle of the north connection. The vertical deflection just under the loading point and the strains on the lower surface of the bottom flange and on the upper surface of the top flange of the aluminum beam as well as the strains on the sides of the supporting mortar and the strains on the stud shear connectors were measured.

Cyclic loadings were repeated 5 times with a gradual increase at each loading. The maximum loads were 98 kN, 138 kN and 178 kN at the first, second and third loadings, respectively. At the load 334 kN in the fourth loading, the edge on the loading side of the supporting mortar of the north connection was crushed. At the load 326 kN in the fifth loading, a crack started at the edge of the air-release hole of the top flange on the loading side of the aluminum extrusion. Then the statically loading test was terminated.

3.2.2 Relation between load and deflection

Figure 12 presents the relation between the load and the vertical deflection just under the load. The test results are the values for the forth loading. The thick solid line is the FEM

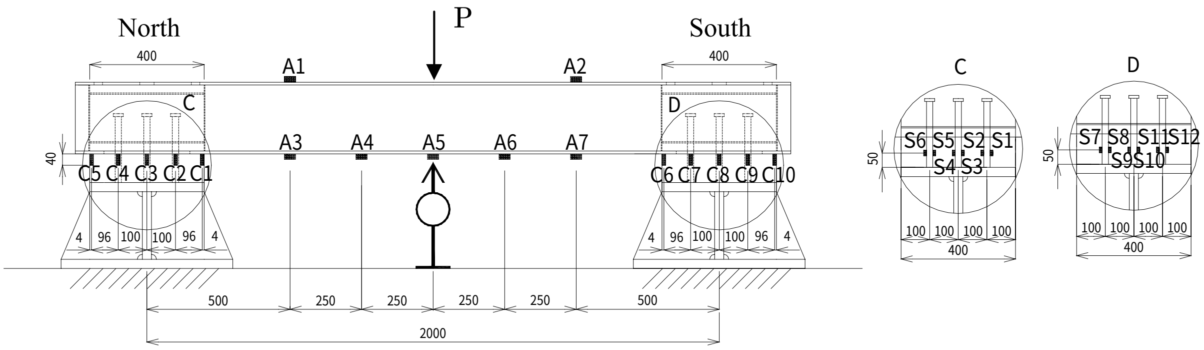


Figure 6. Loading point and measuring points of deflection and strains in simple beam type specimen

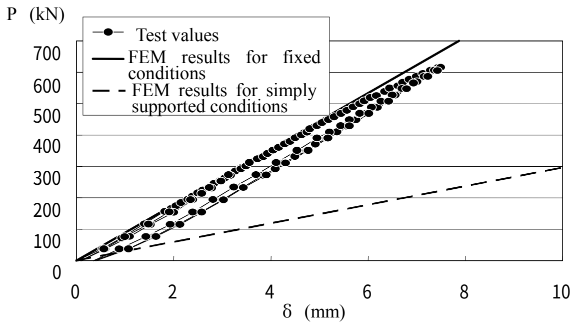


Figure7. Relation between load and deflection at span center

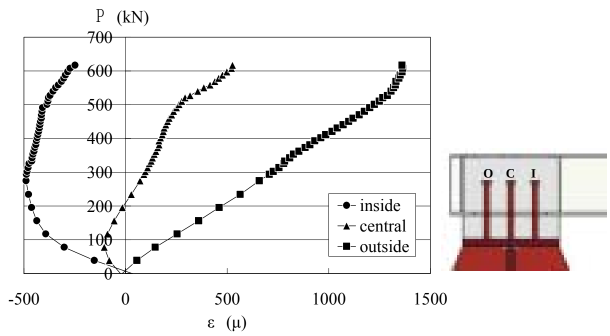


Figure8. Relation between load and strains of studs [North connection]

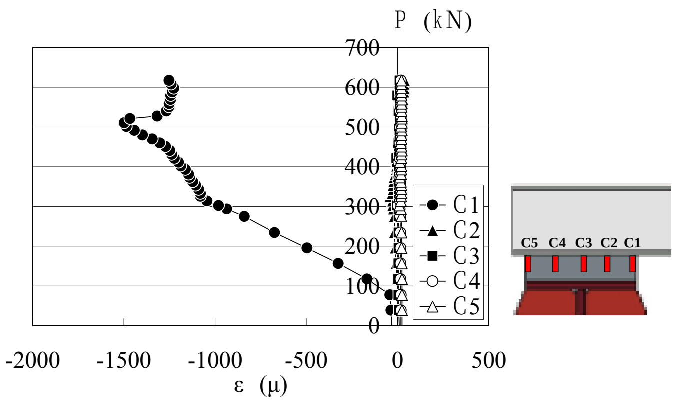


Figure9. Relation between load and strains on the side of supporting mortar [North connection]

Figure10. Appearance of cracks of supporting mortar of simple beam type specimen [North connection, Back side]

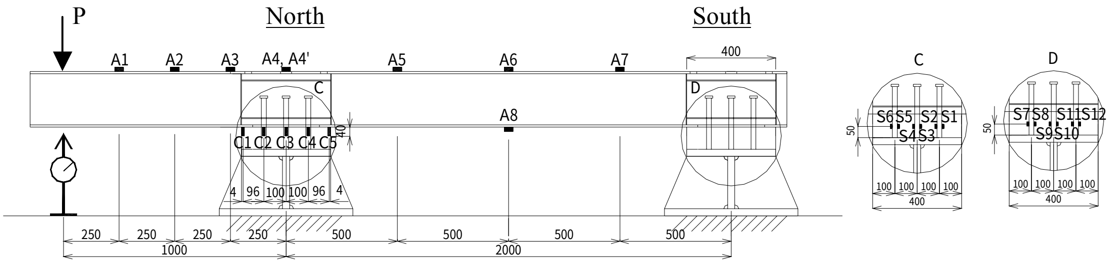


Figure 11. Loading point and measuring points of deflection and strains in overhang type specimen

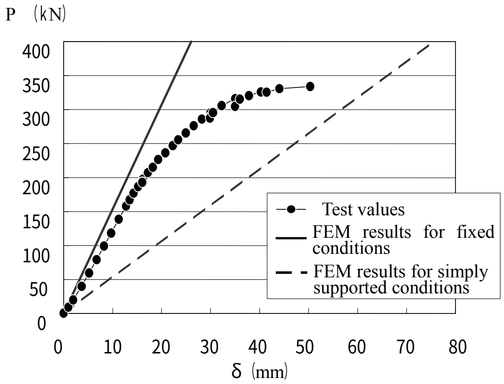


Figure 12. Relation between load and deflection

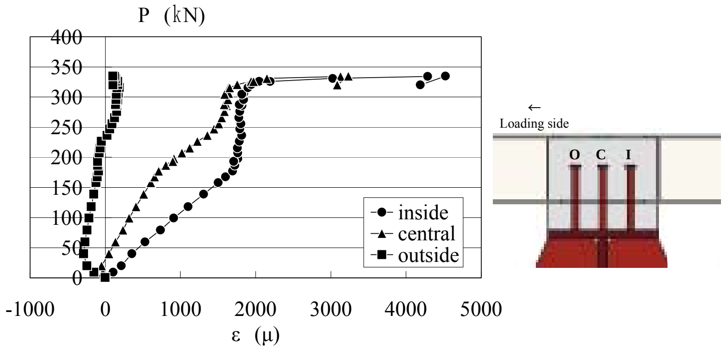


Figure13. Relation between load and strains of studs [North connection]

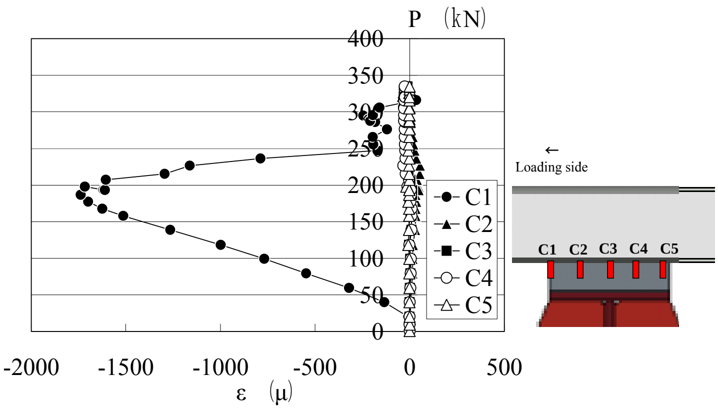


Figure14. Relation between load and strains on the side of supporting mortar [North connection]

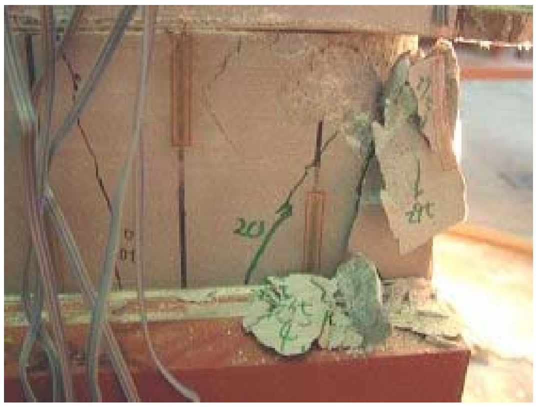


Figure15. Crushing of supporting mortar in overhang type specimen[North connection, Back side]

results for the cantilever beam of 1 m in length, and the thick broken line is those for the overhang beam of 1 m in length with the simple beam of 2 m in length. The test values vary linearly until 207 kN. The test values are closer to the FEM results for the cantilever beam than those for the overhang beam. From this, as in the simple beam type specimen, the connection of the overhang type specimen is also rigid.

3.2.3 Relation between load and strains of stud shear connectors

Figure 13 shows the relation between the load and the strains of the stud shear connectors. The strains are the axial strains, that is, the average strain mentioned in Subsection 3.1.3. The tensile force is developed in the central and inside studs. In the outside stud, the force is compressive until 220 kN, and after that, it is tensile. While the increase in strain of the inside stud stops at the load 177 kN, the strain of the central stud increases. As in the simple beam type specimen, the force shifts from the inside stud to the central and outside ones.

3.2.4 Relation between load and strains of supporting mortar

Figure 14 shows the relation between the load and the vertical strains on the sides of the supporting mortar. The compressive strain is developed only at the strain gage C1. The values of the strain gage C1 decreases at the load 190 kN, since the strain of the supporting mortar around the strain gauge is released due to cracking.

As in the simple beam type specimen, the tensile force of the studs and the compressive force at the edge of the supporting mortar develop a moment, which makes the connection rigid.

Figure 15 shows the appearance of crushing of the supporting mortar after the loading to 334 kN.

4. FATIGUE TEST

4.1 Simple Beam Type Specimen

4.1.1 Outline of test

For the specimen with the same dimensions as the simple beam type specimen in the statically loading test, the load of the upper limit 245 kN and the lower limit 24.5 kN was repeated at the span center with the frequency of 1 Hz. Expecting that the fatigue strength of the outside stud will be the grade E in the Japanese Fatigue Design Guideline[2)], the range of the load was determined for the stud to break at 5×10^5 cycles. In the middle of the fatigue test, the repeated load was stopped, followed by the statically loading test to measure the deflection at the span center and the strains of the studs, and to observe the fatigue cracks of the studs and the cracks of the supporting mortar. The locations of the strain gauges glued to the studs were the same as in the statically loading test.

4.1.2 Relation between deflection and number of cycles

Figure 16 shows the relation between the deflection at the span center and the number of cycles. On the vertical axis, the deflection at the upper load 245 kN is taken, and on the horizontal axis, the number of cycles is done. In the figure, the horizontal line represents the deflection given by the FEM for the beam of 2 m in length with both the ends fixed.

The deflection at the first loading was identical to the FEM value. The deflection suddenly increased at 5.7×10^5 cycles and 7.95×10^5 cycles, since the outside studs of the south and north connections broke at these numbers of cycles, respectively. The deflection increased moderately from 7.95×10^5 cycles to 2.59×10^6 cycles. After 2.59×10^6 cycles, the deflection did not vary.

4.1.3 Fatigue cracks of studs

Table 2 summarizes the fatigue cracks initiated in the studs. At 5.7×10^5 cycles, the axial strain of the outside stud of the south connection suddenly dropped to zero, followed by failure of the stud. At that time, the deflection of the beam increased rapidly and the hair-like cracks of the supporting mortar grew.

Similarly, at 7.95×10^5 cycles, the axial strain of the outside stud of the north connection dropped to zero, the stud broke, and the cracks of the supporting mortar propagated. The initiation of the fatigue cracks of the studs made the strain of other undamaged studs increase. This is because instead of the cracked studs, the undamaged studs take over the pulling force.

After 7.95×10^5 cycles, the initiation of cracks of the supporting mortar diminished. At 1.12×10^6 cycles and 2.85×10^6 cycles, fatigue cracks were initiated in the central studs of the north and south connections, respectively. Since the strain gauges showed a certain degree of strain, these studs did not break. After 1.12×10^6 cycles, the crack initiation was not detected in the supporting mortar. The fatigue test was not terminated until 3.19×10^6 cycles. Even if fatigue cracks are induced in the studs, the durability of the connections is high.

4.1.4 Fatigue strength of studs

The range of the axial stress of the studs is calculated, using the axial strain by the following equation:

$$\Delta\sigma_m = E\Delta\varepsilon_m \tag{1}$$

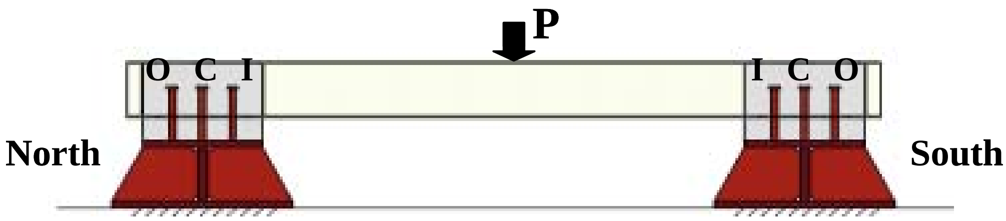
where E = Young's modulus of the studs (=206 GPa)

$\Delta\varepsilon_m$ = range of axial strain of the studs

Figure 17 shows the range of axial stress of the studs and the number of cycles when the studs broke due to fatigue cracking. The range of axial stress of the studs is taken on the vertical axis, and the number of cycles is done on the horizontal axis. The design S-N curves specified in the Japanese Fatigue Guideline[2)] are also presented in the figure. The

Table 2. Summary of fatigue cracks of studs

Cycles	Connections	
	North	South
0.57×10^6	————	Failure of outside stud
0.795×10^6	Failure of outside stud	————
1.12×10^6	Initiation of crack in central stud	————
2.85×10^6	————	Initiation of crack in central stud
3.19×10^6	Fatigue test terminated	



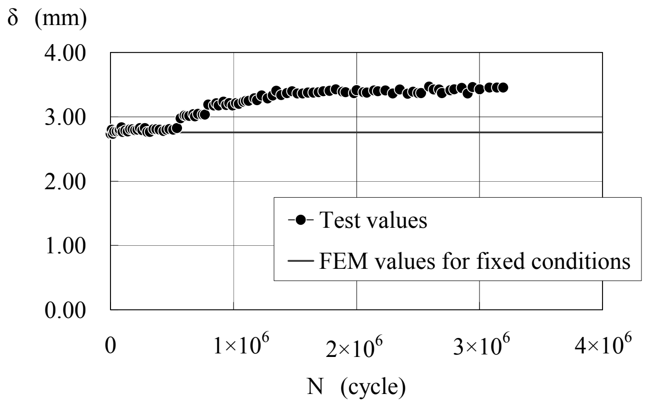


Figure 16. Relation between deflection at span center and number of cycles

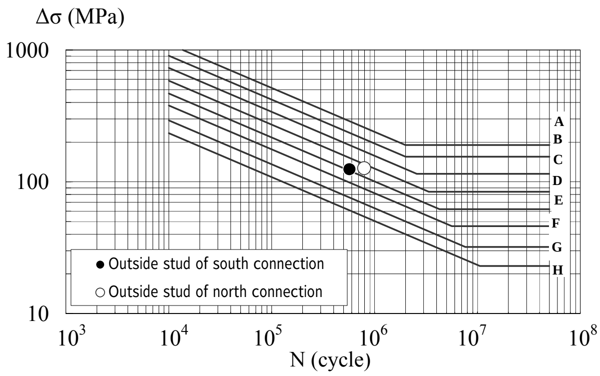


Figure 17. S-N relation of studs

Figure 18. Fatigue crack initiated at the air-release hole of the top flange of the aluminum beam

fatigue strength of the studs used in the connections is compatible with the grade E, as was predicted.

4.2 Overhang Type Specimen

For the specimen with the same dimensions as the overhang type specimen in the statically loading test, the repeated load of the upper limit 98 kN and the lower limit 9.8 kN was given at the point 1 m away from the middle of the north connection with the frequency of 1 Hz. Since it was revealed that in the fatigue test of the simple beam type specimen, the fatigue strength of the studs was the grade E in the Japanese Fatigue Guideline[2)], for the overhang type specimen, the range of the load was determined for the inside stud to break at 5×10^5 cycles in the grade E.

At 1.2×10^5 cycles, as shown in Fig. 18, a fatigue crack was initiated at one edge of the air-release hole of the top flange of the aluminum beam on the loading side in the north connection, and at 1.43×10^5 cycles, a fatigue was produced at another edge of the hole. At 1.88×10^5 cycles, the fatigue cracks propagated to both the edges of the top flange. At 1.89×10^5 cycles, when the load was statically loaded to measure the deflection and the strains, the top flange of the aluminum beam broke at the load 94 kN.

To avoid the cracks at the air-release hole, it is required to move the location of the hole or to change the shape of the hole to an ellipse.

5. CONCLUSIONS

In this research, the connection of aluminum decks to steel girders was proposed, and the static and fatigue behavior of the connection was investigated. The main results are as follows:

(1) The proposed connection of aluminum decks to steel girders is a rigid one. The compressive force is developed at the edge on the loading side of the supporting mortar, and the tensile force is induced in the central stud and the one far from the loading side. These two forces develop a moment, which makes the connection rigid.
(2) The static strength of the connection is governed by crush of the supporting mortar.
(3) The fatigue strength of the connection is governed by that of the studs. The fatigue strength of the studs is the grade E in the Japanese Fatigue Guideline. Even if the stud far from the loading side has fatigue failure, the durability of the connection does not decrease, since the tensile force shifts to other studs.
(4) In the fatigue test of the overhang type specimen, fatigue cracks are initiated at the air-release hole on the top flange of the aluminum beam. It is required to move the location of the hole or to change the shape of the hole to an ellipse.

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