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# Development of “KAKUTABASHI®”, Steel Deck Slab Bridge Using Square Tube

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## Abstract

***A steel-deck slab bridge using square tube is proposed for short span bridge market less than 15 m. The bridge consists of rolled steel square tubes as main members. The excellent features of the bridge are its lightweight, shallow depth, easy fabrication and quick construction time-frame. This paper describes the concept of the bridge and its structure. Load bearing capacity and fatigue resistance of the bridge are confirmed by actual size loading test. An example of design, fabrication and erection of the bridge is also described.***

## 1. Introduction

In recent years, in view of the aging of many of the existing bridges constructed in the years after the war, especially during the period of 1960’s economic booming, the importance of bridge maintenance is now widely recognized. On the other hand, efforts are being made to reduce the maintenance burden for road bridges in the years ahead. Under those conditions, when it comes to renovating existing bridges or constructing new bridges, it is necessary to meet increasingly diverse demands, including reduction of cost, saving of labor and shortening of construction period. According to a survey into the present state of bridges in Japan[1)], small bridges with a span of 15 m or less account for the great majority: they number about 540,000, or nearly 80% of the total number of bridges in Japan. Therefore, the need to develop technologies for rational renovation, reduction of cost, prolongation of service life, etc. of small bridges is especially strong.

In view of the above need, Nippon Steel has proposed a steel-deck slab bridge using square tubes (**Fig. 1**) as a new bridge construction method applicable to short spans of about 15 m or less. The steel-deck slab bridge consists mainly of square steel tubes arranged side by side. Steel pipes are inserted laterally into the array of square tubes at equal intervals and the panel is partially filled with concrete so that all the parts form a single Deck Slab unit. Thus, the salient characteristic of this bridge is that welding and bolts which tend to cause the durability problem of bridges are not used in the assembly work. The main purposes of development of this bridge are to reduce the girder height by having an array of square tubes play the roles of girder and floor slab at the same time, to cut the cost of construction by using shapes, and to shorten the construction period by adopting a simple structure.

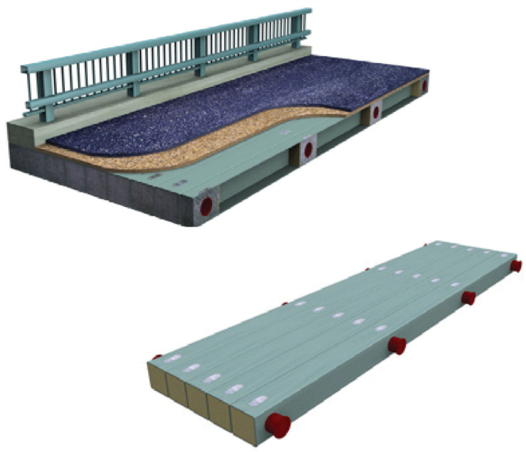

**Fig. 1 Steel deck slab bridge using square tube**

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## 2. Outline of KAKUTABASHI® Steel-deck Slab Bridge

In developing the steel deck slab bridge using square tubing intended for short-span bridges with a length of 16 m (span: 15 m) or less, an aim of the authors was to establish a highly economical and durable construction that allows for speedy replacement. The development concept that was worked out to that end was that cold-formed square tubing—our factory-made product—should be used as the main structural member of the bridge, that neither welded joints nor bolted joints should be used in the assembly of the major components, and that the bridge should be such that it could be fabricated at the factory and erected on site easily and speedily. Ordinarily, square tubes are manufactured by either the press-forming process or the roll-forming process. In terms of manufacturing costs, smaller square tubes (roughly 550 mm square or smaller) are made using the roll-forming process while larger equivalents are made using the press-forming process.

Because of the size and cost of the square tube used for the proposed bridge, the roll forming process was applied. Concerning the square tube material, it was decided to choose the optimum one from among BCR295 (MSTL-9021 approved by the Minister of Land, Infrastructure and Transport), steels for general structural purposes specified in JIS G 3466, and the weathering steel (BC-SMA400AW) that was newly developed for KAKUTABASHI (**Table 1**), according to the intended use and working conditions. Steel deck slab bridges using square tubing have the following features.

1) The girder height can be reduced

Since the square tubing used for the bridge is very stiff and light in weight (it has a hollow section about 250 to 550 mm sq.), it permits reducing the girder height as compared with ordinary steel bridges or PC bridges.

2) The dead load can be reduced

Since the main girder and floor slab are of a unit construction and the square tubing used has a hollow section, it is possible to reduce the dead load of the bridge.

3) The bridge can be constructed speedily

Since prefabricated floor slab panels are jointed together by a simple mechanism without requiring on-site welding or bolting, the bridge can be constructed in a comparatively short period of time. In addition, since the floor slab panels have high stiffness, heavy construction equipment can be used on the floor slab from the moment the floor slab is secured in place.

4) Construction can be carried out even in confined spaces

Since on-site ground preparation work is unnecessary, the bridge erection work can be carried out even in confined working spaces. In addition, since the panels are light in weight and can be erected using a small crane, it is possible to minimize the space required for installation of heavy construction equipment. Furthermore, since an entire bridge need not necessarily be constructed at the same time, it is not necessary to completely close the road to all traffic even during replacement of existing bridges.

## 3. Performance Confirmation Test of KAKUTABASHI

### 3.1 Load bearing capacity of KAKUTABASHI

In order to confirm the load bearing capacity of KAKUTABASHI, a load test was carried out using a full-scale bridge model. The model tested is shown in **Fig. 2**. It had a span of 15 m and a width of 2 m (five square tubes arranged side by side). The steel pipes for lateral jointing of the square tubes were inserted at intervals of 3 m. The square tubing used was STKR400 (400 mm square, 12 mm in wall thickness), and the steel tubing used was STK400 (216.3 mm in diameter, 5.8 mm in wall thickness). In addition, concrete with a designed strength of 24 MPa was used. It was decided to apply wheel loads to the bridge surface in accordance with the Road Bridge Specifications. However, in order to test the bridge under the severest conditions, a loading plate measuring 200 mm × 400 mm was placed on the bridge in such a manner that the test load concentrated on the single square tube in the center. The surface of the bridge was paved with two layers of asphalt (lower layer: mastic asphalt 40 mm in thickness, upper layer: dense-grade asphalt 40 mm in thickness).

A scene from the load test is shown in **Fig. 3**. **Fig. 4** shows the relationship between applied load and square tube deflection, obtained from the test. At first, the square tube deflection and strain increased linearly. They showed elastic behavior till the load reached 569 kN, which was equivalent to the nominal yield load. After that, when the load was increased above 600 kN, the strain on the lower flange of the square tube right under the loading point began to exhibit nonlinearity. At the same time, the strains on the other four square tubes showed a tendency to increase. The reason for this is assumed to be that the bending moment acting upon those square tubes increased as the lateral distributed load was applied to them at the lateral joints. Thus, it can be seen that even after the square tube right under the loading point yields, the square tubes as a whole display a large load-bearing capacity. It is not that only some of the square tubes begin to show plastic behavior. The maximum yield strength of KAKUTABASHI as confirmed experimentally was about three times greater than the design load and 1.63 times greater than the nominal yield load. Thus, it was confirmed that the bridge had

**Table 1 Specifications of steel square tube**

| Type code | Chemical compositions (%) | | | | | | Mechanical properties | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | C | Si | Mn | P | S | N | Yield strength or proof stress (N/mm²) | Tensile strength (N/mm²) | Elongation: Test piece | Elongation: Elongation (%) |
| BCR295 | Max. 0.20 | Max. 0.35 | Max. 1.40 | Max. 0.030 | Max. 0.015 | Max. 0.006 | Min. 295 | 400 to 550 | No. 5 | Min. 23 |
| STKR400 | Max. 0.25 | - | - | Max. 0.040 | Max. 0.040 | - | Min. 245 | Min. 400 | No. 5 | Min. 23 |
| STKR490 | Max. 0.18 | Max. 0.55 | Max. 1.50 | Max. 0.040 | Max. 0.040 | - | Min. 325 | Min. 490 | No. 5 | Min. 23 |
| BC-SMA400AW* | Max. 0.18 | 0.15 to 0.65 | Max. 1.25 | Max. 0.035 | Max. 0.035 | | Min. 245 | Min. 400 | No. 5 | Min. 23 |

* BC-SMA400AW represents weathering steel square tubes that meet both the chemical composition specifications for hot-rolled weathering steel for welded structures SMA400AW (JIS G 3114) (contains Cu 0.30-0.50, Cr 0.45-0.75 and Ni 0.05-0.30 in addition to the elements shown above) and the mechanical property specifications for square tubing for general structural purposes STKR400 (JIS G 3466).

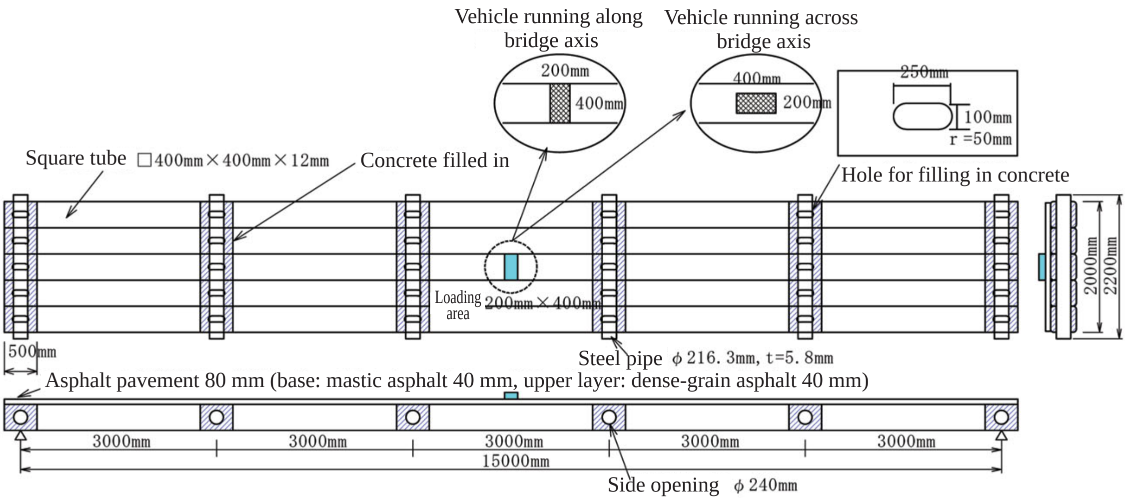



**Fig. 2 Actual size specimen for loading test**

**Fig. 3 Loading test condition**

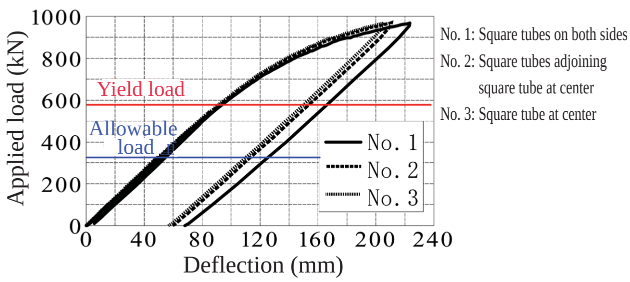
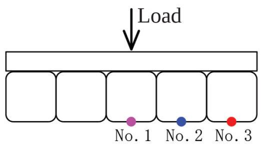



**Fig. 4 Load displacement relationship**

**Table 2 Load distribution factor of experiment or analysis**




| | Load (kN) | Strain along bridge axis (μ) | | |
|---|---|---|---|---|
| | | No. 1 | No. 2 | No. 3 |
| Test results | 340 | 630 (0. 241) | 526 (0. 201) | 466 (0. 179) |
| Type-1 | 340 | 732 (0. 277) | 486 (0. 184) | 470 (0. 178) |
| Type-2 | 340 | 692 (0. 275) | 455 (0. 181) | 455 (0. 181) |
| Type-3 | 340 | 573 (0. 226) | 530 (0. 209) | 453 (0. 178) |

Figures in parentheses indicate the load distribution factors calculated from the strains.

sufficient strength.

The load distribution factors obtained from the load test are shown in **Table 2**. Here, the load distribution factor indicates the proportion of the load borne by each of the square tubes. It can be obtained by dividing the strain on a specific square tube by the sum of the strains on all the square tubes. In the present load test, the maximum load distribution factor was always approximately 0.25 regardless of the span length. In a past load test (five 300 mm sq. tubes arranged side by side; 3.6 m span; lateral joint interval 1.2 m), the maximum load distribution factor when the load was applied to the central square tube was also 0.25[2-4]. Even though the lateral joint interval was increased to 3 m in the present test, the load distribution factor of each individual square tube remained almost the same as in the previous test. Thus, it was confirmed that sufficient load distribution performance could be secured even when the lateral joint interval was 3 m.

In order to confirm the load distribution performance and load-bearing mechanisms of the bridge model used in the present load test, we carried out a linear elastic FEM analysis to simulate the test results. The analytical code used was a general-purpose structural analysis program (MARC20038). In view of the symmetrical structure of the bridge tested, a quarter-scale model was subjected to the analysis. The boundary conditions set were as follows: the model is linearly supported at the bearing points assuming the span as 15.0 m and the boundary surfaces along and across the bridge axis are geometrically symmetric. It was decided to apply the test load under displacement control so that a surface load could be evenly applied to an area 400 mm in width and 200 mm in length in the center of the model. Concerning the structural elements of the model, the square tubes and the steel pipes for lateral jointing were shell elements and the concrete was a solid element. The steel-concrete interface was made to share nodes so as to secure perfect composition.

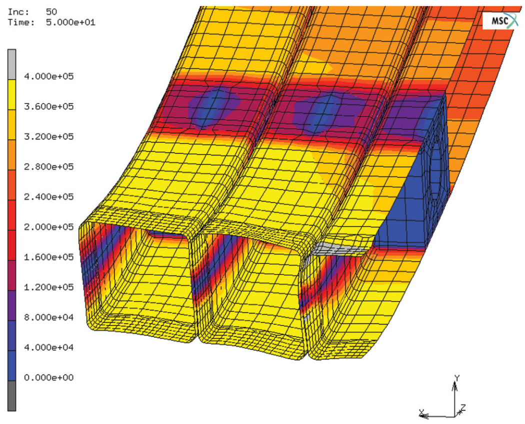



**Fig. 5 Counter map of stresses at the mid span at a maximum loading**

Three types of models of the contact surface between square tubes that influences the load distribution were used in the analysis. They were: (1) a model with the contact between square tubes left out of consideration, (2) a model taking into consideration the friction at the contact surface between square tubes, and (3) a model fixing the contact surface between square tubes. The analysis results were compared with the test results as shown in Table 2. The Type-3 model that fixed the contact surface between the square tubes best simulates the test results. The analysis was continued with the conditions varied widely. As a result[5], it was confirmed that in the elastic region, the model that fixed the contact surface between square tubes is valid and accurately permits evaluation of the load distribution performance.

**Fig. 5** shows the deformation conditions of the square tubes in the center of the span and the contour lines of the corresponding stresses. According to the present analysis, the central square tube to which the test load was applied deformed markedly and as a result, deformation due to torsion occurred with the adjoining square tubes. From the conditions of these deformations too, the mode of load distribution can be seen. The condition of deformation of the bridge tested resembles that of the Type-3 model: the central square tube deformed markedly and, as a result, the adjoining square tubes deformed.

### 3.2 Load test of field-jointed parts

In the proposed method, panels consisting of several square tubes jointed side by side are fabricated at the factory and these panels are jointed together by steel pipes at the construction site as shown in **Fig. 6**. The jointing procedure is as follows. First, panels consisting of several square tubes are fabricated at the factory and transported to the construction site. Then, the first panel in the prescribed position is set and a jointing square tube which is provided with openings in the side is fitted to the panel via the lateral jointing steel pipes projected from the panel. Next, the lateral jointing steel pipes projecting from the second panel are inserted into the openings in the side of the jointing square tube. This procedure is repeated until the prescribed width is obtained. After installing all the panels, fill the joints of the jointing square tubes with concrete to make all the components into one solid unit.

In order to clarify the strength of the field-jointed parts of the KAKUTABASHI bridge shown in **Fig. 7**, the authors took out only field-jointed parts from assembled panels cut across the bridge axis and subjected them to a load test. As a result, the following facts were determined[6].

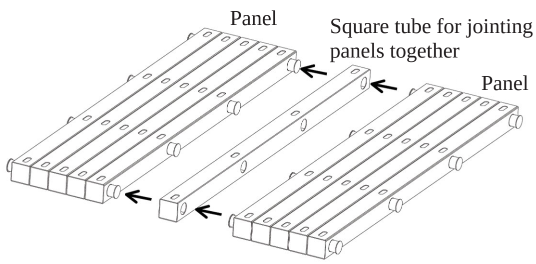



**Fig. 6 Field joint procedure on site**

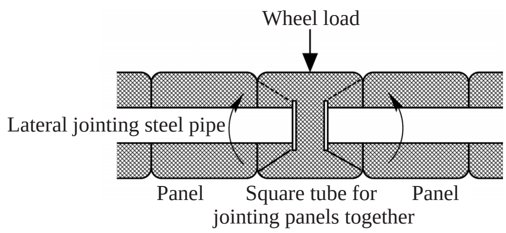



**Fig. 7 Structural detail of field joint part**

(1) Joints cut out from assembled panels were subjected to a flexural shear test. As a result, it was confirmed that the proposed joint structure is effective and that it imparts sufficient yield strength to the jointed parts.
(2) When a flange plate is fitted to the steel pipe end, an anchor effect is produced. Namely, a compressive force acts upon the interface between the square tubes where the filled-in concrete is discontinuous. As a result, the jointed part acts against the bending force as if it were almost a section evaluated in terms of the combination of steel pipe and compressive-side concrete.
(3) As a result of measurement of the shear force acting upon each lateral jointing steel pipe, it was found that the shear strain on the lateral jointing steel pipe at the interface between square tubes where the shear force is concentrated agrees well, in the elastic region, with the strain calculated on the assumption that only the lateral jointing steel pipe is effective. From this fact, it was confirmed that the design concept that the lateral jointing steel pipes alone are made to support the shear force is almost valid.

From the results of the above discussions, we have confirmed that the proposed field-jointed structure has sufficient strength, that it works quite satisfactorily as a panel-jointing mechanism, and that the shear force acting upon it can be calculated accurately in the design.

### 3.3 Study of skewed steel deck slab bridge using square tubing

There are quite a few bridges which are skewed because of limitations set by a nonlinear road or some obstacle. Concerning a skewed bridge, it is already known that the reaction force is not uniform and that the mode of load distribution differs from that of a straight bridge. In order to experimentally ascertain the influence of skewing of the proposed bridge on its load distribution performance and yield strength, the authors fabricated a bridge model with a skew angle of 60 degrees (**Fig. 8**) and subjected it to a load test[7].

(1) Reaction force
Although the reaction force distribution across the width of the bridge becomes uneven, it does not pose any practical problems which impair the usability or load bearing capacity of the bridge.
(2) Concerning the influence on the mode of load distribution, dispersion of load across the square tube axis was observed. The

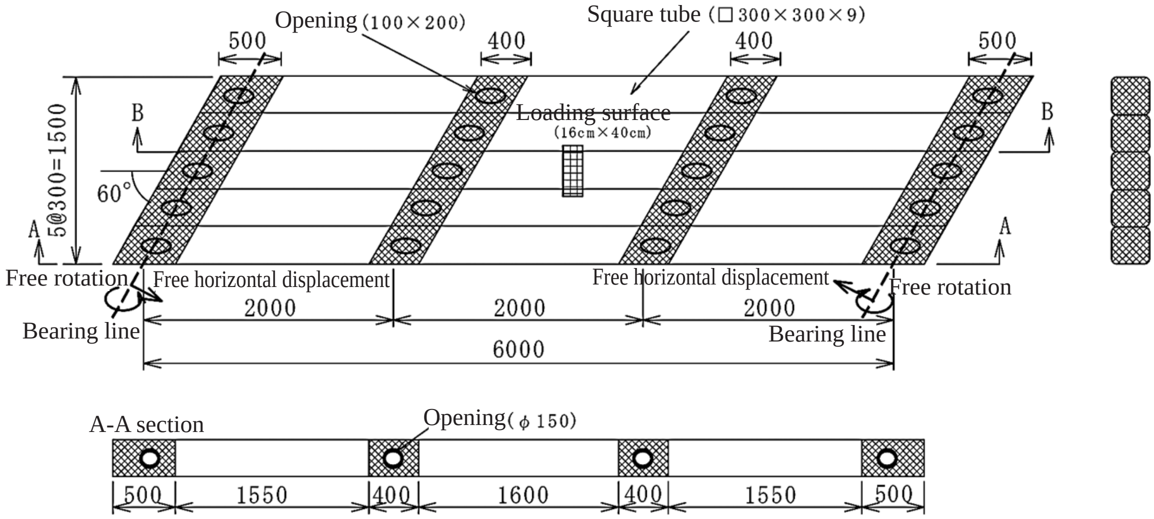



**Fig. 8 Skewed specimen**

mode of load distribution was almost uniform across the width of the bridge, and the load distribution factor of each square tube was 25%, nearly the same as in the case of a straight bridge. Thus, it was confirmed that even if the proposed bridge is skewed, it has sufficient load distribution performance.

(3)Yield strength and deformation performance

The maximum load obtained from the load test was 1.4 times the yield load estimated from the material strength stated in the mill sheet. Thus, it was confirmed that the bridge model had sufficient yield strength, even though it had a skew angle of 60 degrees which is considered the critical limit from the standpoint of practical use.

### 3.4 Fatigue test of steel-slab bridge using square tubing

The main members of the proposed steel-slab bridge are assembled without using welded joints or bolts which cause stress concentration and fatigue failure. Basically, therefore, the proposed bridge is considered to have good resistance to fatigue. However, in the case of a steel-slab bridge having a short span, the dead load component is relatively small, whereas the stress amplitude under a live load, or a variable stress, is large. Therefore, in order to confirm the fatigue strength of the proposed steel-slab bridge, a full-scale bridge model was subjected to a fatigue test in which the test load was applied to fixed points. As shown in **Fig. 9**, the bridge model tested consisted of five square tubes (400 mm sq., 12 mm in wall thickness) arranged side by side, with steel pipes (216.3 mm in diameter, 5.8 mm in wall thickness) inserted into the square tubes at intervals of 3 m and filled with concrete in the joints. It was simply supported at a span of 6 m. When it comes to erecting an actual bridge, it is necessary to fit hanging pieces to the bridge. Therefore, in order to confirm the influence of the hanging pieces on the fatigue strength of the bridge model, hanging pieces were first welded to the sides of the square tubes on both sides of the bridge at the center of the span, and then they were removed and the parts from which the hanging pieces had been removed were smoothed off using a grinding machine.

As the wheel load, the load applied by a large vehicle with twin axles and double tires was considered. On the assumption that the load would be applied to four points corresponding to the tire positions, arrangements were made so that the load center was placed at the center of the bridge model.

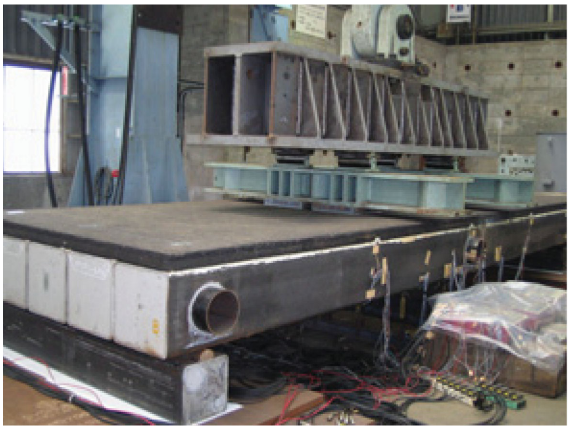


**Fig. 9 Fatigue test set up**

Since the proposed steel-slab bridge does not use welding to joint its main structural members, it is considered to have good resistance to fatigue. However, the actual fatigue resistance of the proposed bridge has yet to be verified by a suitable test. For the proposed bridge, the following points, including the square tubing material and the joint structure using concrete, were taken up as items to be heeded in the fatigue test.

(1)Cold-formed corner of square tube

(2)Longitudinal seam-welded part during production of cold-straightened square tube

(3)Openings in square tube near joints

(4)Durability of concrete-filled joints

(5)Parts from which hanging pieces are removed.

Estimated using the B live load specified in the Road Bridge Specifications, the maximum stress that occurs in the square tubing under the live load is about 100 N/mm$^2$. Therefore, it was decided that in the present fatigue test, a load of 1,000 kN should be repeatedly applied two million times so that the stress amplitude at the surface of the lower flange at the center of the span would become about 100 N/mm$^2$. The facts determined from the fatigue test are summarized below[8].

(1) Throughout the two million applications of the test load, the bridge model showed no abnormal conditions, suggesting that stress amplitudes around 100 N/mm$^2$ would not cause fatigue failure of the proposed bridge. The stress amplitude of 100 N/mm$^2$ and the number load applications clear those of Class D of the JSSC fatigue design curve.
(2) With respect to the points ((1) through (5)) in the fatigue test mentioned above, the bridge model exhibited no damage due to fatigue. Thus, they do not constitute any weak point in terms of fatigue strength.

## 4. Design and Construction of KAKUTABASHI

In constructing the steel-slab bridge using square tubing, steel-slab bridge panels consisting of several square tubes jointed together and jointing square tubes provided with holes in the prescribed positions are fabricated at the factory. By prefabricating the main structural members of the bridge at the factory (**Fig. 10**), it is possible to reduce labor at the construction site and shorten the construction period. The prefabricated panels and jointing square tubes are transported to the construction site, where one of the panels is installed at the prescribed position using a crane. After that, one of the jointing square tubes is fitted to the panel via the lateral jointing steel pipes projecting from the panel side. Thereafter, the installation of a panel and a jointing square tube is repeated until the prescribed bridge width is obtained. After erecting the bridge, the joints of the jointing square tubes are filled with concrete. Then, the ground cover and handrails are installed and the bridge is paved with asphalt. This completes construction of the bridge.

By way of reference, **Table 3** presents the design conditions for Kosawada Bridge[9]. Basically, the bridge was designed in accordance with the Road Bridge Specifications. The allowable stress-based design was applied to the bridge. However, since the bridge was a new type, some of the items required of the bridge were not provided for in the Road Bridge Specifications. Concerning those items which were not provided for, specifications were decided based on relevant test results, etc.

In the construction of Kosawada Bridge, the entire bridge was divided into several sets of three panels and two square tubes to joint them together because of the limitations set by transport facilities. Since the point of erection was in a densely populated area, it was impossible to secure a yard on which to make necessary arrangements for the erection. Besides, since there were many overhead electric cables crisscrossing the vicinity of the construction site, vertical working space was also very limited. Therefore, the prefabricated panels were transported piece by piece on a truck from the factory to the construction site and each of the panels was hoisted from the truck by a rafter crane (capacity: 25 ton) and installed directly to its prescribed position. The maximum panel weight was about 8.5 tons.

**Fig. 10 Panel members composed of steel square tubes**

**Table 3 Design specifications of Kosawada bridge**

| | |
|---|---|
| Bridge type | Road bridge |
| Length (girder length) | 8.55 m (8.5m) |
| Span length | 8.0 m |
| Overall width<br>(effective width) | 6.2 m<br>(5.0 m) |
| Skew angle | Left 85 ° 0 ° 0 ° |
| Live load | A |
| Snow load | 1 kN/m$^2$ |
| Pavement | Asphalt 7 cm |
| Crosswise gradient | 2% divided into a straight line |
| Lengthwise gradient | 1 % parabola |
| Plane linearity | R = ∞ |
| Applicable standard | Road bridge specifications (2002.3) |

**Fig. 11 Completed Kosawada bridge**

Despite the severe working conditions (confined ground space, limited head clearance, etc.), the bridge was completed without any serious problems. The time required to install each panel was 15 to 20 minutes and all the panels could be installed in one day. Concerning the work precision, dimensional tolerances were set based on the manufacturing precisions of structural members specified in the Road Bridge Specifications. In a dimension inspection conducted after erection of the bridge, it was confirmed that there were no problems in terms of work precision.

**Fig. 11** shows the completed Kosawada Bridge. The ratio of the girder height to the span length of this bridge is about 1:23. Thus, the bridge is very slender compared with average PC bridges with spans of about 8 m and subject to A-live loads (girder height to span ratio: 1:20) or H-beam steel bridges (about 1:13). In addition, the weight of the girder itself could be reduced to about 0.56 ton/m$^2$, about 60% that of the average PC bridge (about 0.9 ton/m$^2$).

## 5. Conclusion

As has been described in this paper, various matters were studied for the development and application of the proposed steel-slab bridge using square tubing and an actual bridge of the proposed type was designed and constructed based on the study results. The proposed bridge can be evaluated as having achieved the original aims of development?reduction of weight, reduction of girder height-to-span ratio, saving of labor, shortening of construction period, construction within limited confines, etc., all of which are required of replacement bridges. In addition, through the application of the new bridge type to an actual bridge, the authors collected valuable data about the applicability of the proposed bridge. It is considered that the characteristics of the proposed bridge are helpful not only for replacement bridges, but also bridges to be newly constructed. In the future, in order to promote the proposed new bridge structure, the authors intend to accumulate records of construction and make various improvements and thereby improve the reliability of the new bridge structure and contribute to the maintenance and renewal of social capital in the field of short-span bridges.

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