# Development of the Link-Type Expansion Joint for the Akashi Kaikyo Bridge

by

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## Synopsis

*Long-span bridges require road expansion joints capable of large amounts of expansion and contraction in order to absorb the bridge displacement caused by temperature changes, live load variations, wind, earthquakes, etc..*

*Sumitomo Metal Industries, Ltd., has developed a road expansion joint utilizing a link mechanism as the load supporting mechanism, which is called "Link-Type Expansion Joint", for use in long-span bridges.*

*In the Akashi Kaikyo Bridge, which was opened on April 5th, 1998 and which is currently the longest suspension bridge in the world, these Link-Type Expansion Joints were adopted for actual installation.*

*This paper provides an outline of the Link-Type Expansion Joint developed for the Akashi Kaikyo Bridge.*

## 1. Introduction

Long-span bridges require road expansion joints capable of large amounts of expansion and contraction in order to absorb the bridge displacement caused by temperature changes, live load variations, wind, earthquakes, etc..

Sumitomo Metal Industries, Ltd., has developed a road expansion joint utilizing a link mechanism as the load supporting mechanism, which is called "Link-Type Expansion Joint", for use in the long-span bridges.

In the Akashi Kaikyo Bridge, which was opened on April 5th, 1998 and which is currently the longest suspension bridge in the world, these Link-Type Expansion Joints were adopted for actual installation.

The problems that needed to be solved before use were : the ability to provide the world's largest amount of expansion and contraction of 1450mm, with which no past experience was available ; the noise reduction required from an environmental point of view (particularly on the Kobe side) ; and the need to eliminate interference with the wind tongue on the center span side of the main towers. However, we confirmed that these problems were solved after carrying out technological developments and performance verification tests using actual scale prototypes, and we then carried out full scale production and have safely delivered and installed these expansion joints.

In the following, we report the details of our development of the Link-Type Expansion Joints for the Akashi Kaikyo Bridge, with particular emphasis on the outlines of the design and the results of the performance verification tests.

## 2. Outline of the Link-Type Expansion Joint

### 2.1 Basic Structure

The basic structure of the Link-Type Expansion Joint is shown in **Fig. 1**. To provide responsiveness to displacement and ease of installation and maintenance, the standard individual unit of the Link-Type Expansion Joint has a width equal to one half of the vehicle-lane width and consists of the fingers, two end beams, one middle beam, links, vertical shoes, and two universal joints.

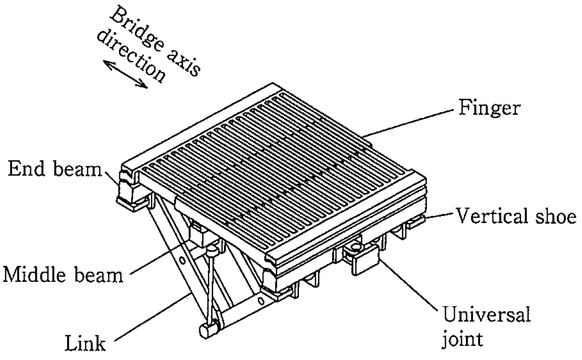


Fig. 1 Construction of the Link-Type Expansion Joint

### 2.2 Features

The features of the Link-Type Expansion Joint are :

(1) Compactness combined with capability for large amounts of expansion and contraction.

The unit uses a link mechanism as the load supporting mechanism, thereby the fingers are supported in a movable manner by the middle beam at the center of the unit, so the unit is compact yet can easily respond to very large movements.

(2) Responsiveness to displacement in all directions.

The unit and the bridge girders are linked by only one pair of universal joints, so the unit can smoothly respond to displacement of the bridge girder in all directions.

(3) Ease of installation.

The expansion joints are assembled as entire units in the factory and can be easily, quickly and accurately installed in the site by merely fastening the coupling bolts of the universal joints.

(4) Superior vehicle travel characteristics.

The expansion joint is always flat regardless of the direction of bridge girder displacement, providing excellent vehicle travel characteristics.

(5) Excellent durability.

Materials with excellent resistance to wear and fatique have been used for the sliding parts and the hinge parts, giving the expansion joint excellent durability.

### 2.3 Displacement Following Function

This unit is supported on the edge part of the bridge girder via the movable vertical shoes at its four corners, and the links, vertical shoes and the universal joints move in mutual linkage in relation to the displacement of the bridge girder because of the supporting mechanism that connects with the bridge girder (or the abutment) through only the universal joints. Therefore, the mechanism can smoothly follow the displacement of the bridge. This displacement following function is described briefly in **Table 1**.

## 3. The Link-Type Expansion Joint for the Akashi Kaikyo Bridge

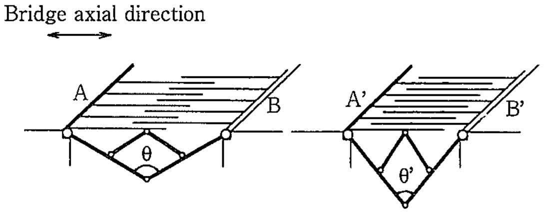
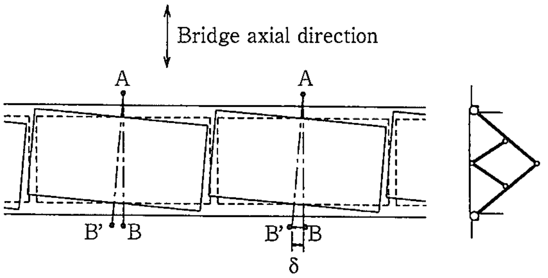
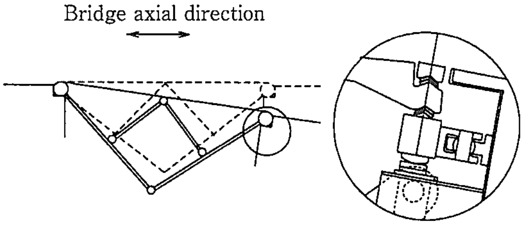
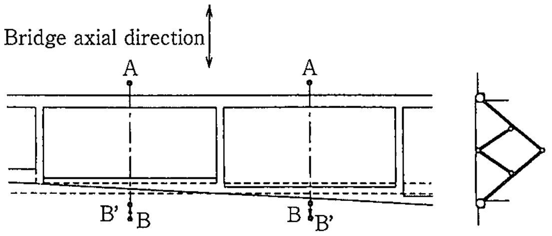
### 3.1 Outline

The Akashi Kaikyo Bridge belongs to the Kobe-Naruto Route of bridges linking mainland Japan with Shikoku island, and spans the Akashi Strait, well known as an international sea route with an extremely heavy ship traffic and very severe weather and sea behavior conditions. It links Kobe city in Hyogo Prefecture with Awaji island and is a three-span two-hinged stiffening girder system suspension bridge with an overall span of 3911m (center span between towers is 1991m). It is longer by 580m than the previous world's longest bridge [Humber Bridge] and is currently the suspension bridge with the world's longest center span between towers.

The Link-Type Expansion Joints used in the Akashi Kaikyo Bridge are of three types with expansion and contraction amount of +/−450mm on the abutment side, +/−600mm on the side span side of the main towers, and the world's largest displacement of +/−1450mm on the center span side of the main towers. The installation positions of these three types of expansion joints are shown in **Fig. 2**.

As shown in **Fig. 3**, these expansion joints are divided into 8 units in each steel deck in the east and west sides (16 units in one line). The four joints at the center (that is, two joints each on the east and west sides) on the center span side of the main towers are special joints in that all four of them constitute an integral structure.

Table 1 Bridge displacement following function

| Displacement | Outline description | Explanatory drawing |
|---|---|---|
| Displacement in the bridge axial direction | When the distance between A and B changes due to expansion/contraction of the bridge girder, the expansion joints follow it by changing the link inclusion angle θ. |  |
| Displacement perpendicular to the bridge axis direction | For the relative displacement δ(B-B') between the bridge girder and abutment (or bridge girder), the expansion joints rotate in the horizontal plane, pivoting around the universal joints and thereby following the displacement. |  |
| Angular rotation in the vertical plane | For the angular rotaion and displacement in the vertical direction of the bridge girders, the expansion joints follow the displacement by rotating the link and the fingers pivoting around the hinge connecting them to the end beam. |  |
| Angular rotation in the horizontal plane | For the angular rotation of the bridge girders in the horizontal plane, the expansion joints follow them by converting such displacement into differences in the amounts of expansion or contraction of the neighboring expansion joints. |  |

Installation positions of Link-Type Expansion Joints

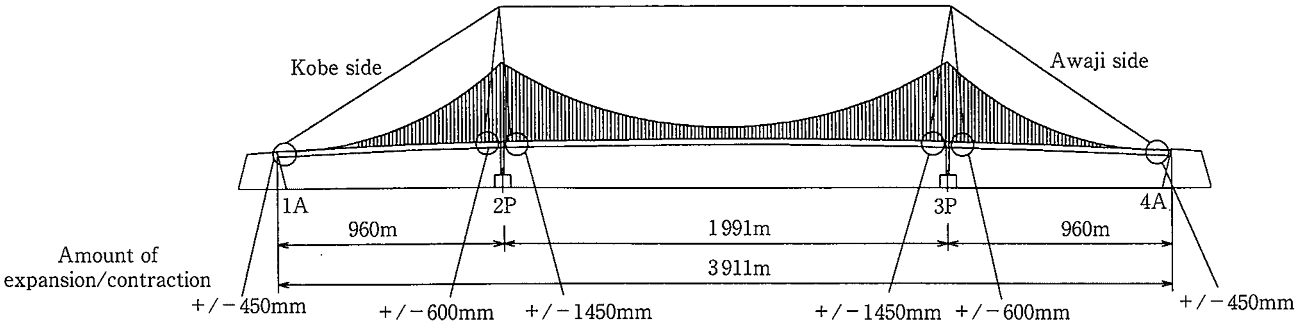
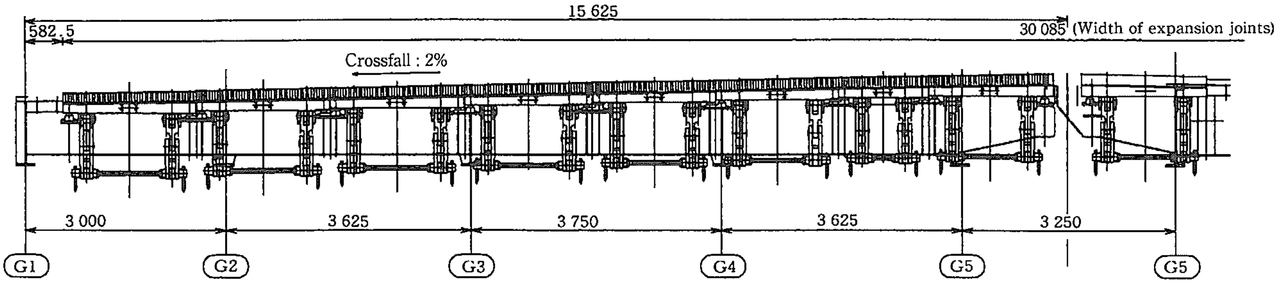


Fig. 2 Installation position of Link-Type Expansion Joints in the Akashi Kaikyo Bridge



G4 – G5 : Location of stringers of deck

Fig. 3 Unit arrangement of expansion joints (On abutment)

## 3.2 Design

### 3.2.1 Design dimensions

**Table 2** shows the design dimensions of the expansion joints for the Akashi Kaikyo Bridge.

Table 2 Design dimensions of expansion joints for the Akashi Kaikyo Bridge

| | Abutment section | Tower section | |
|---|---|---|---|
| | | Side span | Center span |
| Bridge class (Road specification) | 1st class bridge (1st grade, 2nd class, 6 lanes) | | |
| Overall width | 31.250m | | |
| Crossfall | 2.0% | | |
| Load | B Live load | B Live load | B Live load TT-43 |
| Shock coefficient | I=1.0 | | |
| Design amount of expansion/contraction (mm) | ±450 | ±600 | ±1450 |
| Design calculation amount of expansion (mm) | ±100 | ±250 | ±700 |
| Amount of movement in the horizontal direction (mm) | ±50 | ±30 | ±55 |
| Angular rotation in the vertical plane | ±20/1000 | ±20/1000 | ±20/1000 |
| Angular rotation in the horizontal plane | ±25/1000 | ±30/1000 | ±60/1000 |

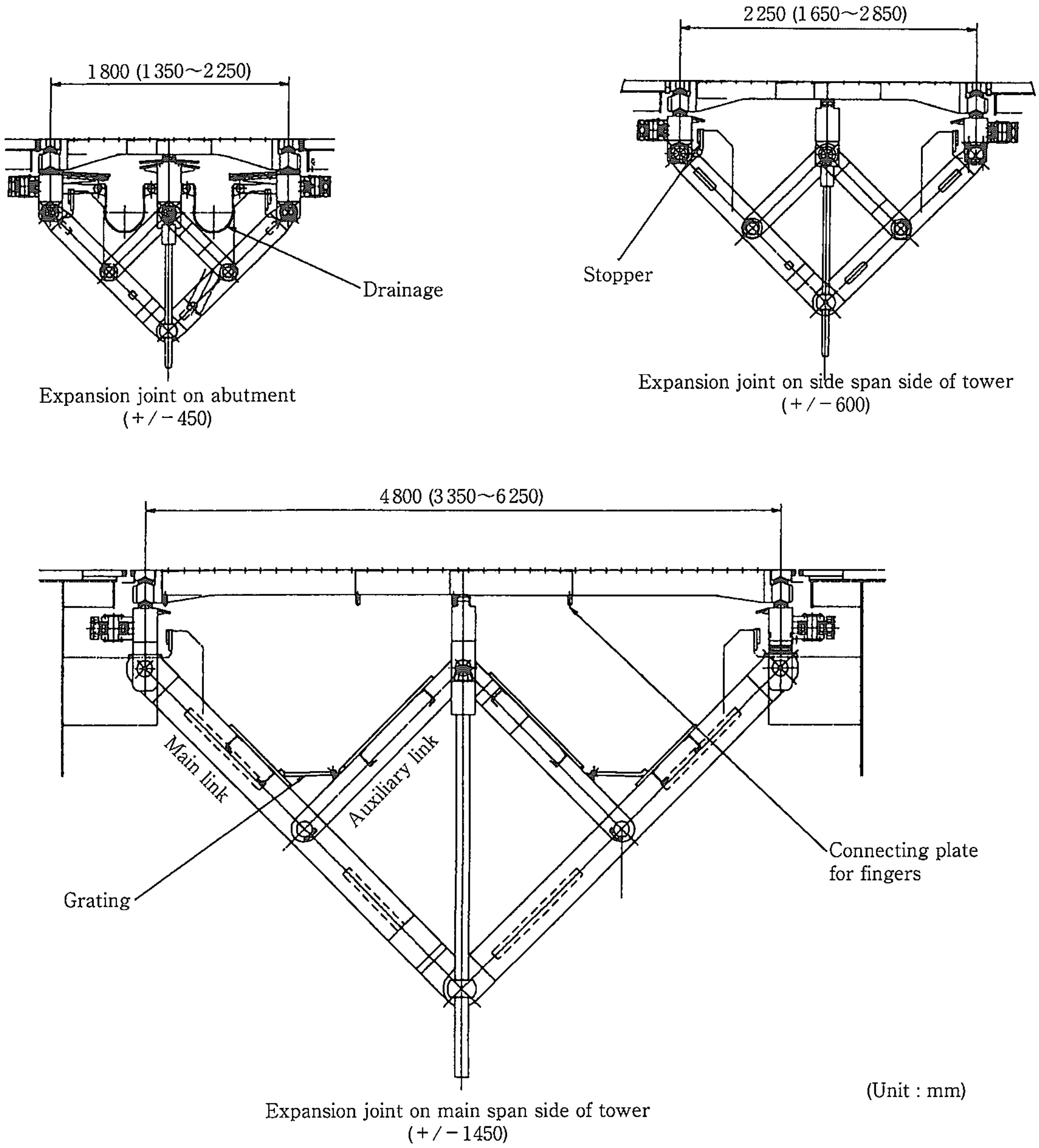
### 3.2.2 Structure

(1) Standard cross-section

The cross-sections of the expansion joints are shown in **Fig. 4** for the three expansion and contraction amounts of +/−450mm, +/−600mm, and +/−1 450mm. Although the basic structures of these three types are the same, rubber water drainage is provided for each entire expansion joint on the abutment side (expansion/contraction amount of +/−450mm) and waterproof zippers are provided at the junctions between units. Since the fingers in the expansion joints on the center span side of the main towers (expansion/contraction amount of +/−1 450mm) are as long as about 3.2m, connecting plates for sway prevention are provided under the ends of the fingers. Also, the size of the expansion joint becomes large, so gratings are provided on the upper side of the main links and on the auxiliary links for the inspection foot-path in order to simplify inspection inside the joints. In addition, stoppers are provided for all expansion joints in order to prevent dislocation from the supporting brackets overhanging from the end plates of the steel deck.

(2) Special units of the expansion joints on the center span side of main towers (expansion / contraction amount of +/−1 450mm).

As shown in **Fig. 5**, in the center span side of the main towers, the portal beams of the main towers have wind tongues that prevent the stiffening girders of the suspension bridge from shifting in the direction perpendicular to the bridge axis. Since the main links of the two units in the central part interfere with the wind tongue vertically if the normal shape of Link-Type Expansion Joints is used, the link structure of the central two units is changed to only maintain the rectangular shape without carrying out load transfer, thereby avoiding the interference, and the middle beam is integrated with the two units on either side of the central two units, and this special shaped expansion joint was developed so that the load is transferred by the links of the two outermost units. Further, the spacing of the links for load trans-



Expansion joint on abutment
(+/−450)

Expansion joint on side span side of tower
(+/−600)

Expansion joint on main span side of tower
(+/−1450)

Fig. 4 Cross section of Link-Type Expansion Joint

fer provided at the units on the two outermost units is 6m, compared to the 4m width of the wind tongue, in order to prevent interference between them.

In addition, while the middle beam has an integrated structure for four units, the end beams and fingers are made separate for each of the four units, similar to other lines ; if the end beams and fingers are also integrated for all four joints, the overall width becomes too large and the radius of rotation of the unit pivoting around the universal joint also becomes too large when there is a horizontal displacement of the bridge girder, thereby making the gap between the unit and the bridge girder insufficient.

In view of this, the end beams and the fingers are separated into four units, as in the case of other lines, and universal joints are provided for each of these four units, making the required gap equal to that of the general units. Because of the above structure, the distance between the links at the middle beam differs from that between the links at the end beams when there is a horizontal displacement of the bridge. Damper rubber bushings are provided at the pivots where the links are connected to the middle beam so that above difference in the distance between the links is absorbed.

(3) Gap amount

a. Finger gap

The finger gap should be as narrow as possible to

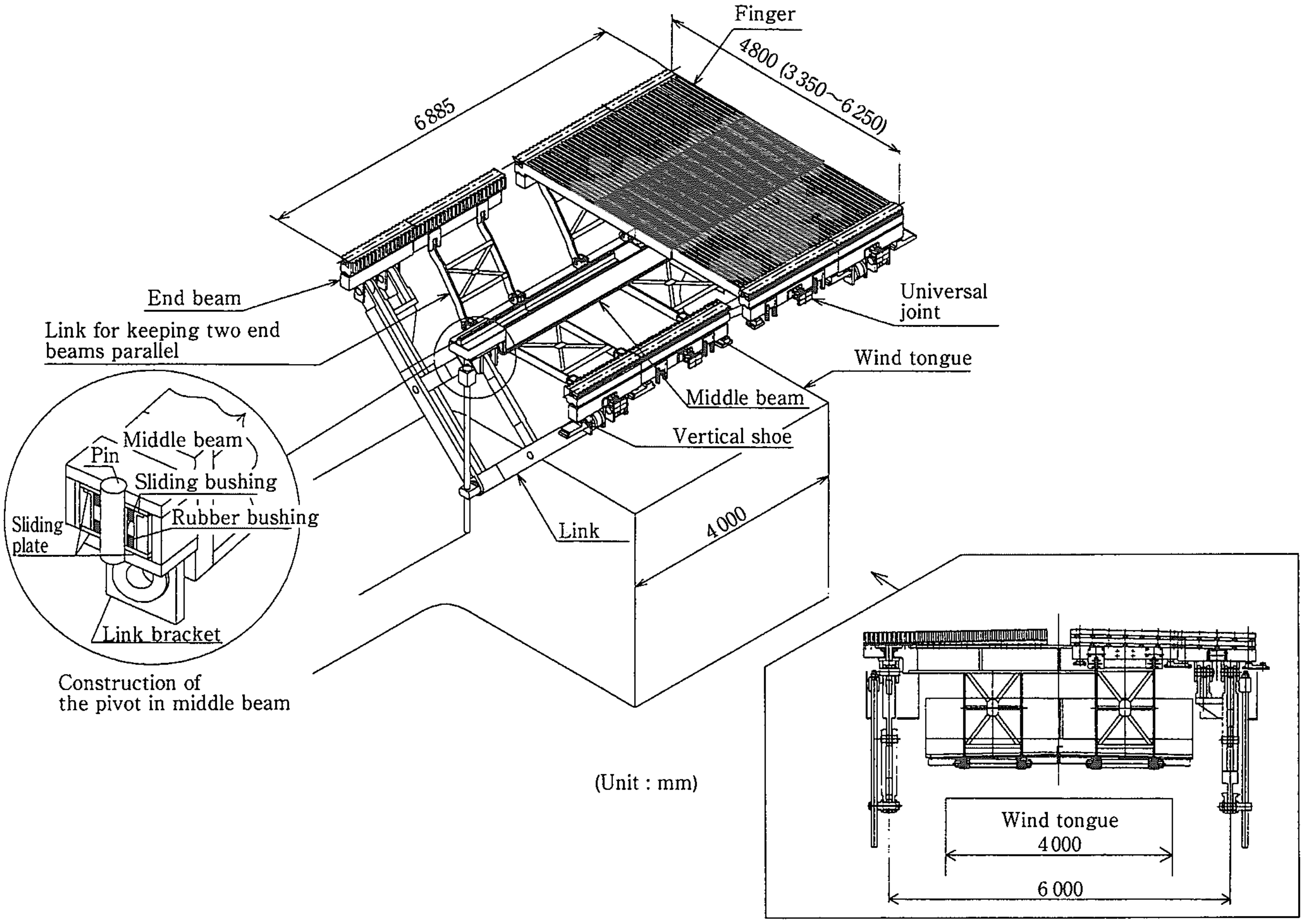


Fig. 5 Special expansion joint on center span side of tower

avoid hindering the vehicle (two-wheeler) travel characteristics.

In the general finger type expansion joints, the finger thickness is normally 40mm and the space between neighboring fingers is 5mm, and hence the finger gap will be 50mm.

As shown in **Fig. 6**, in order to improve the two-wheel vehicle travel characteristics in the Link-Type Expansion Joints, the finger thickness is 35mm, making the finger gap 45mm ; this type was also adopted for the Akashi Kaikyo Bridge.

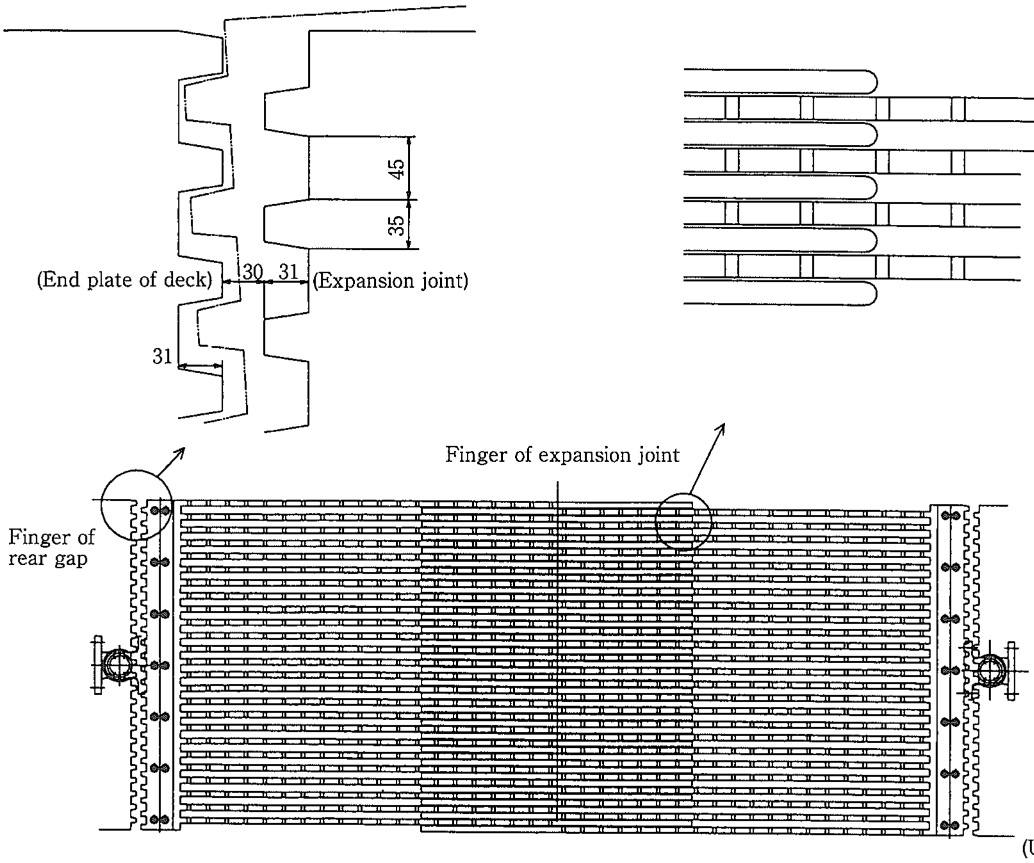
b. Rear gap

In the Link-Type Expansion Joints, when there is a rotational displacement in the horizontal plane of the deck end, the entire unit rotates, pivoting around the universal joints. In order to permit this rotational displacement, a rear gap has been provided between the end parts of the expansion joints and the bridge deck end. The amount of rear gap required in the Link-Type Expansion Joints for the Akashi Kaikyo Bridge is 30mm on the abutment side (expansion/contraction amount of +/−450mm) and on the side span side of the main towers (expansion/contraction amount of +/−600mm), and 61mm on the center span side of the main towers (expansion/contraction amount of +/−1 450mm). Among these, the rear gap amount of 61mm required for the expansion joints on the center span side of the main towers is large and is likely to hinder the vehicle travel characteristics. Hence, short teeth are provided, as shown in **Fig. 6**, on the back side of the holding plate at the two ends of the expansion joint and on the end plate of the deck, so that a projecting finger structure is realized and the gap amount between the tips of the teeth when they are in the neutral position is 30mm. Thus, the above structure of the expansion joint achieves superior vehicle travel charactristics and a rotational displacement of 61mm in the horizontal plane.

### 3.2.3 Design of the Fingers

(1) Finger hinge structure

In conventional Link-Type Expansion Joints, each finger is prepared individually from steel plates, then



(Unit : mm)

Fig. 6 Detail of finger section of expansion joint on center span side of tower

several fingers are bundled together and placed between the projections on the end beam, and fixed to the projections on the end beam by passing a pin through the holes in the ends of the fingers and the end beam projections. However, since there is a gap between the holes in the finger ends and the pin, shock noise was being generated when a heavy vehicle passed over the expansion joints.

In order to achieve low noise in the Link-Type Expansion Joints for the Akashi Kaikyo Bridge, an improved type of structure was developed in which all the fingers are formed as an integral structure by casting, and this integral unit is fixed to the end beam using a holding plate with damper rubber pieces placed between the finger unit and the holding plate and between the finger unit and the end beam. Further, the cross-sectional shape of the damper rubber pieces was made in an inverted V-shape to suppress any displacement due to horizontal forces such as the braking forces of vehicles. Thus a finger hinge structure without any gap is realized. **Fig. 7** compares the structures of the conventional type and the low noise type. In addition, **Fig. 8** shows the finger unit of the low noise type Link-Type Expansion Joint and **Fig. 9** shows the details of the damper rubber pieces.

(2) Selection of finger material

In selecting the material for the integrated type fingers, we carried out a comparative study in terms of low cost, ease of manufacturing, and dimensional accuracy. The results of this study are shown in **Table 3**.

When manufacturing a tooth shape from steel plates, in the case of the longest fingers for the expansion/contraction amount of +/−1450mm, the height is 200mm at the finger part, and 240mm at the attaching part. These are very large, thereby giving difficulties in manufacturing and in dimensional accuracy if we use the cutting or the welding method. We therefore selected the casting method for the fingers.

The materials available for casting are cast steel (SC, SCW) and cast iron (FC, FCD). Since cast iron basically has the features of-(1) good dimensional accuracy, (2) lesser occurrences of internal defects, (3) good vibration damping performance, and (4) good

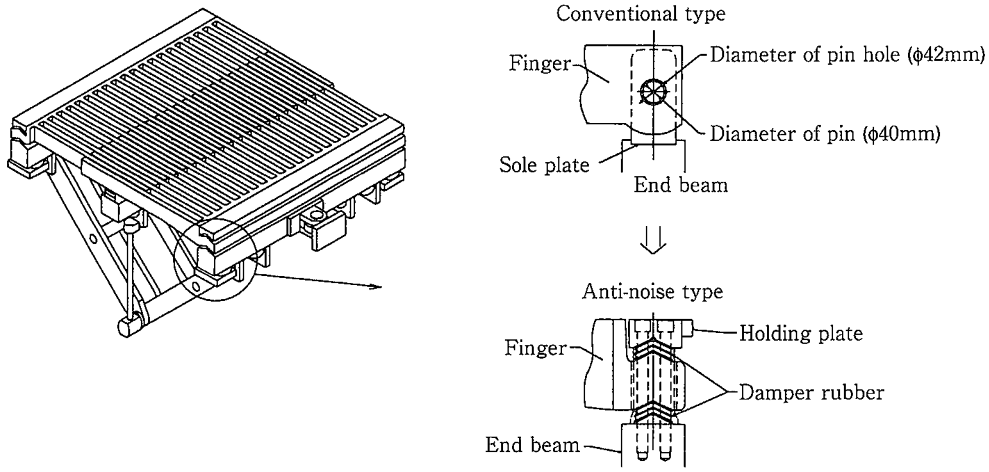


Fig. 7 Structures of finger hinge section

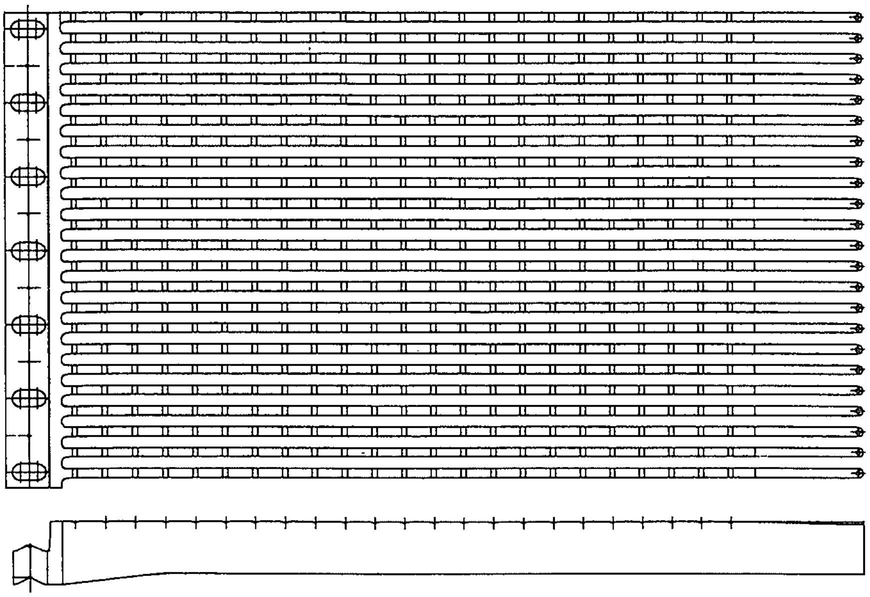


Fig. 8 Detail of finger

wear resistance, we selected spheroidal graphite iron casting (FCD400), which has a fatigue strength higher than or equal to steel plates (SM400B). Further, FCD400 has good machinability, has relatively good toughness, and is very frequently used in expansion joints.

(3) Design of damper rubber

**Figure 10** shows the conceptual diagram of the damper rubber structure of the finger hinge part. The spring supporting part consists of gripping the finger unit from above and below with damper rub-

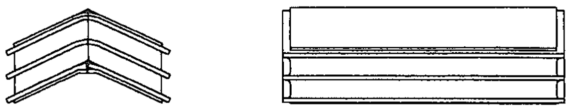


Fig. 9 Detail of damper rubber

Table 3 Comparison of materials and manufacturing processes of finger units

| Material | Method of manufacturing | Evaluation | | | Total |
|---|---|---|---|---|---|
| | | Cost | Producibility | Dimensional accuracy | |
| Steel plate | Machine cutting from steel plates | × | △ | ◎ | × |
| | Gas cutting from steel plates | △ | × | × | × |
| | Welding at the roots of fingers | △ | × | × | × |
| Casting | Cast steel | ○ | × | △ | × |
| | Cast iron | ○ | ○ | ○ | ○ |

ber pieces, the holding plate is fastened with bolts on the stay at the top surface of the end beam, thereby providing pre-compression on the damper rubber.

When the wheel load (Q) of vehicles is operating on the joint, the following relationship exists between the spring constant (K) of the damper rubber and the displacement (δ) of the finger unit.

$$Q = 2K.\delta$$

The following points were considered in setting the spring constant of the damper rubber.

(1) The displacement due to wheel load is to be suppressed to a maximum of 1mm considering the generation of steps in the road surface.

(2) The drooping angle due to the weight of the finger unit should be more than the designed angular rotation in the vertical plane.

### 3.2.4 Materials

**Table 4** lists the materials of the major components of the Link-Type Expansion Joints for the Akashi Kaikyo Bridge.

Table 4 Material grades of major parts

| Parts | Material grades (JIS) |
|---|---|
| Finger | FCD400 |
| Holding plate | SM570 |
| Damper rubber | Sulfurized rubber |
| End beam | SM490 |
| Middle beem | SM490 |
| Middle beam rubber pad | Urethane rubber |
| Main link | SM490 |
| Auxiliary link | SM400 |
| Pin | SUS304 |
| Bushing | HBsC4+Graphite |
| Universal joint housing | SC450 |
| Vertical shoe | SCM440 |

### 3.2.5 Design calculations

(1) Evaluation of stress of parts

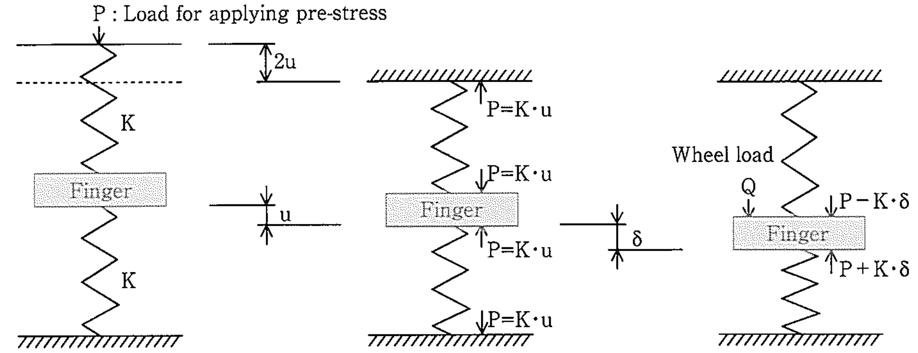
The evaluation of the stress of parts was done according to the procedure[1] given in **Table 5**.

(2) FEM Analysis of finger section

Since the construction is made so that all the fingers for one unit are formed as an integral structure and are fixed via damper rubbers, the stressed condition of the fixing part becomes complex. Therefore, we carried out FEM analysis in addition to evaluation of the permissible stress described above. An example of the results of such FEM analysis is shown in **Fig. 11**.

(3) Fatigue evaluation

Since expansion joints directly bear the wheel loads, the welded parts are considered to be suscepti-



(1) Before applying pre-stress to damper rubber
(2) After applying pre-stress to damper rubber
(3) Applying wheel load

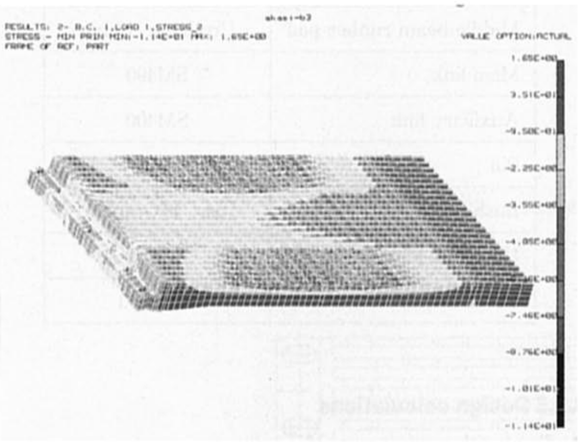
Fig. 10 Conceptual diagram of damper rubber section

Table 5 Evaluating procedures for the stress of parts

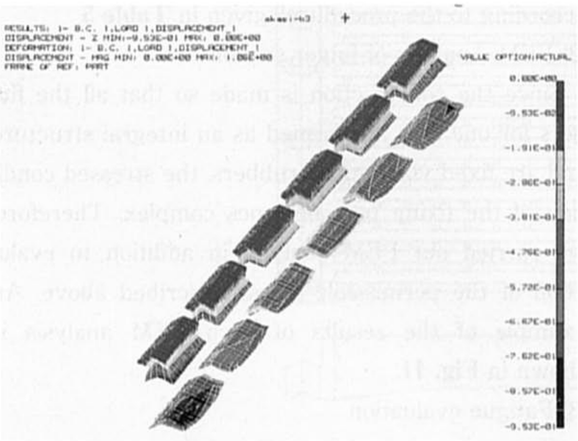
Calculation of maximum nominal stress that can be generated in each of the parts according to the design dimensions.

↓

Passed if the maximum nominal stress of material < the permissible stress of the materials.



a. Stress of finger



b. Deformation of damper rubber

Fig. 11 Results of FEM analysis on finger section

Table 6 Evaluating procedure for the fatigue of welded parts

Calculation of the maximum nominal stress that can be generated in the welded parts.

↓

Determination of the strength grades of welded parts.

↓

Obtaining the permissible stress range limit for the strength grades of welded parts.

↓

Passed when the maximum nominal stress that can be generated in the part < the permissible stress range limit for the strength grade of the welded part.

ble to fatigue damages. Hence, such parts were subjected to fatigue evaluation according to the procedure[2)] given in **Table 6**. The applicable parts are the connecting points of main links, the link bracket attaching parts on the bottom surface of the end beams, and the stay attaching parts on the top surface of the end beams.

### 3.3 Performance Verification Tests

Before embarking on full scale production of the Link-Type Expansion Joints for the Akashi Kaikyo Bridge, we first prepared prototypes of one special joint for the center part which has the maximum number of new developments and one general joint on the center span side of the main towers (expansion/contraction amount of +/−1450mm), and carried out performance verification tests at our company's Hazaki Research Center of the Central Research Laboratories (**Photos 1 to 4**). The outline of the test results is given in **Table 7** which verified that the newly developed expansion joints have fully satisfactory performance.

### 3.4 Installation

The installation of the expansion joints was done according to the procedure given in **Table 8**, and it was possible to complete the installation in a short time with good accuracy.

**Photo 5** shows the installation condition of the expansion joints on the center span side of the main tower (expansion/contraction amount of +/−1450mm) and **Photo 6** shows the condition after completion of installation.

Table 7 Summary of results of performance verification tests

<table>
<tr><th>Test item</th><th>Outline of test</th><th>Test result</th></tr>
<tr><td>Finger section static load test</td><td>Prototypes of only the finger part were prepared, vertical and horizontal loads due to wheel load were applied, and the resulting stress and strain were measured. (a total of 11 cases)</td><td>The maximum stress value in the parts was 1183(kgf/cm$^2$) in the finger, which was less than the permissible stress of 1400(kgf/cm$^2$) for the material FCD400.<br>Further, the maximum stress generated in the welded parts was 81(kgf/cm$^2$) in the stay attaching part on the top surface of the end beam, and was less than the permissible stress range limit of 235(kgf/cm$^2$).</td></tr>
<tr><td>Finger section fatigue test</td><td>Repetitive loads were applied using servo actuators for the finger seciton prototypes prepared as above and the durability of each part was verified. (a total of 2 cases) The testing condition is shown in <b>Photo 1</b>.</td><td>There were no problems pevealed by the results of the magnetic particle tests of the fingers and end beams. There were also no problems in the damper rubber pieces and the connecting plates (urethane rubber).</td></tr>
<tr><td>Static load test of the fully assembled central special unit</td><td>The stresses and strains generated in each of the parts were measured when vertical load and horizontal load due to wheel loads were applied to the fully assembled special unit (a total of 12 cases). The testing condition is shown in <b>Photo 2</b>.</td><td>The maximum stress value of parts was 1038(kgf/cm$^2$) in the link, which was less than the permissible stress of 1900(kgf/cm$^2$) of the material SM490.<br>In addition, the maximum stress in the welded part of the links was 432(kgf/cm$^2$), which was less than the permissible stress range limit of 469(kgf/cm$^2$).</td></tr>
<tr><td>Displacement following test of the fully assembled central special unit</td><td>Forced displacement corresponding to the bridge girder displacement was applied to the attaching base using hydraulic jacks for the fully assembled central special unit, and the operting load at that time and the resulting stresses and strains in each of the expansion joint were measured. (a total of 7cases).</td><td>The resistance of the expansion joints was small for displacement in each of the directions, thereby confirming that the ability to follow displacement was good.<br>In addition, there were no problems in the stresses generated at this time.</td></tr>
<tr><td>Static load test of the fully assembled general unit</td><td>The stresses and strains generated in each of the parts were measured when vertical load and horizontal load due to wheel loads were applied to the fully assembled general unit. (a tatal 12 cases) The testing condition is shown in <b>Photo 3</b>.</td><td>The maximum stress value of parts was 1304(kgf/cm$^2$) in the link, which was less than the permissible stress of 1900(kgf/cm$^2$) of the material SM490.<br>In addition, the maximum stress in the welded part of the links was 422(kgf/cm$^2$), which was less than the permissible stress of 469(kgf/cm$^2$).</td></tr>
<tr><td>Actual vehicle travel test</td><td>The finger sections were embedded in the road on the premises of the research center and the stresses generated in the finger parts. Vibration, displacement, and noise were measured when a 20-ton truck was driven on the road.<br>In addition, in order to compare the noise levels, we carried out measurements by running the vehicle on the expansion joints and on a normal asphalt road surface. The testing condition is shown in <b>Photo 4</b>.</td><td>There were no problems in the stress generated, vibration, and displacement. Regarding noise, there was almost no difference in the acoustic pressure levels generated on normal asphalt road surface and on the expansion joints, as shown in the following table.
<table>
<tr><th>Speed / Item</th><th>60km/h</th><th>70km/h</th><th>80km/h</th></tr>
<tr><td>Acoustic pressure level on normal asphalt road surface (dB (A))</td><td>84.0</td><td>87.1</td><td>88.4</td></tr>
<tr><td>Acoustic pressure level on expansion joint (dB (A))</td><td>84.5</td><td>86.9</td><td>89.4</td></tr>
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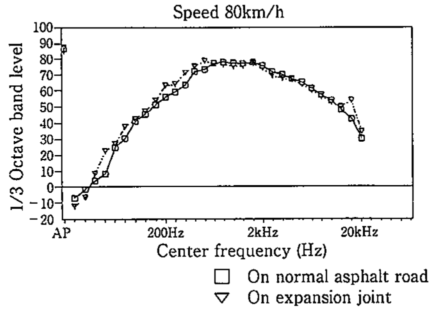
In addition, as shown in the following fingure, there was almost no difference in the noise generated on a normal asphalt road and on the expansion joints as observed from the results of 1/3 octave band frequency analysis.

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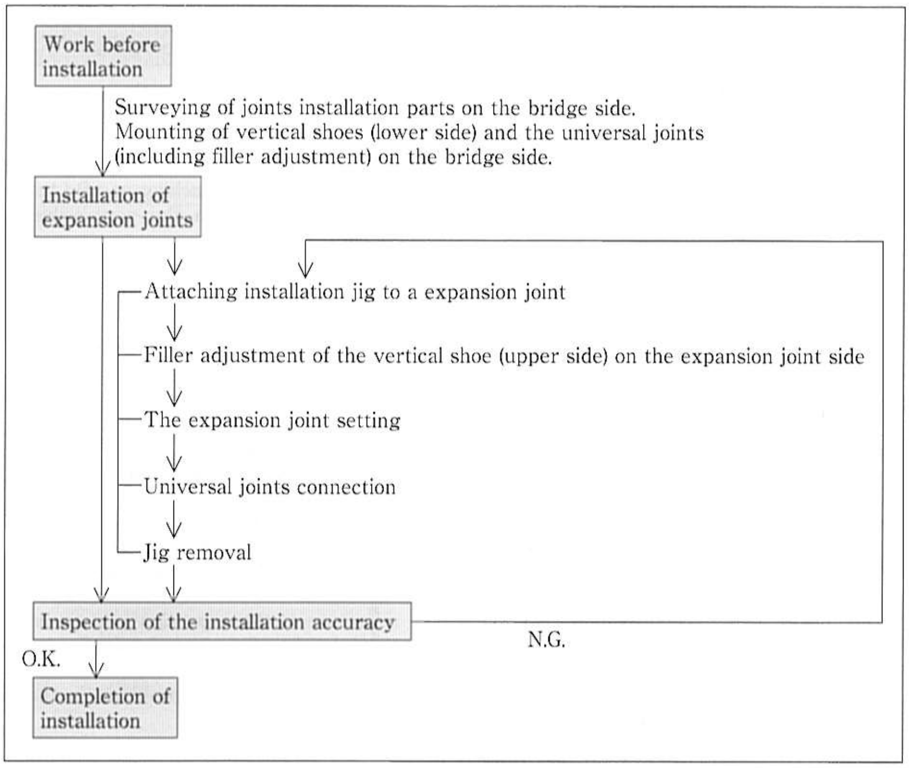
</table>

Table 8 Installation procedure for Link-Type Expansion Joints


Work before installation

Surveying of joints installation parts on the bridge side.
Mounting of vertical shoes (lower side) and the universal joints (including filler adjustment) on the bridge side.

Installation of expansion joints

Attaching installation jig to a expansion joint

Filler adjustment of the vertical shoe (upper side) on the expansion joint side

The expansion joint setting

Universal joints connection

Jig removal

Inspection of the installation accuracy

N.G.

O.K.

Completion of installation

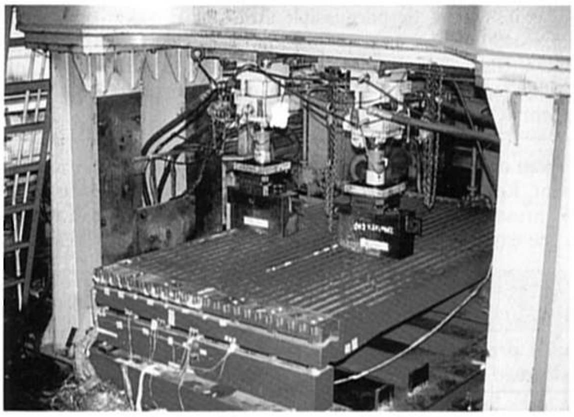


Photo 1 Fatigue test on finger section

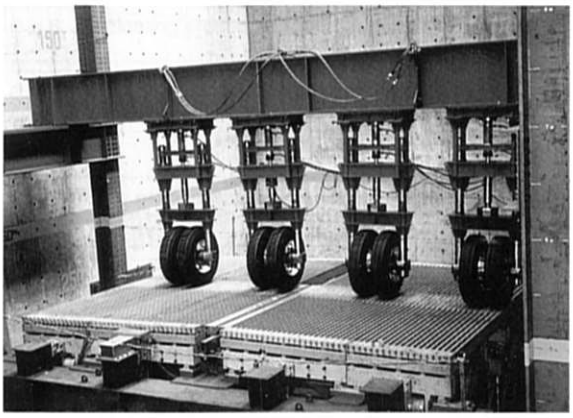


Photo 2 Static load test on special unit

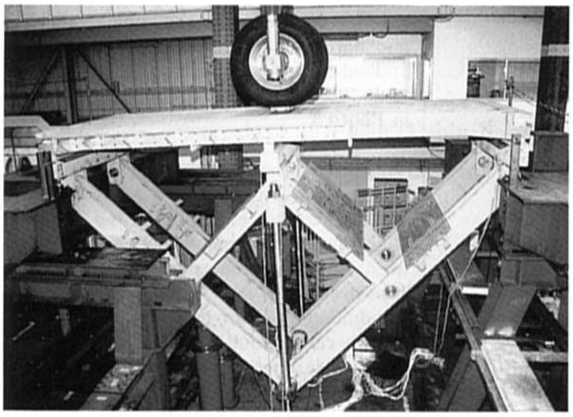


Photo 3 Static load test on general unit


Photo 4 Truck running test

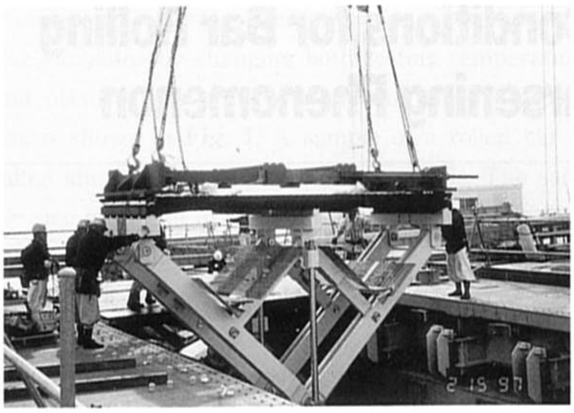


Photo 5 Installation scene (Center span side of tower)

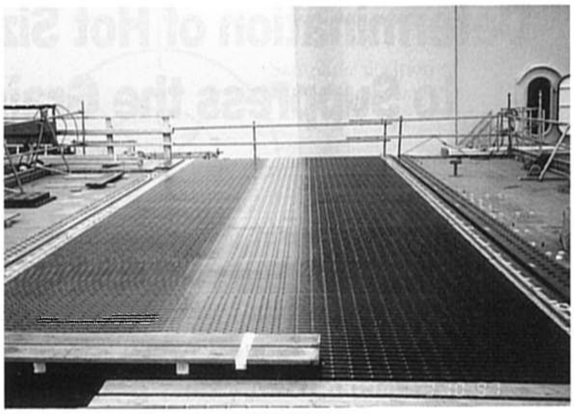


Photo 6 Completion of installation (Center span side of tower)

## 4. Conclusion

The design of the Link-Type Expansion Joints for the Akashi Kaikyo Bridge was started in November 1993, performance verification tests on prototypes were completed and full scale production was started in August 1995 ; all installation work was successfully completed by September 1996.

In the future, we are planning to fully utilize the design and production know-how obtained from the Link-Type Expansion Joints for the Akashi Kaikyo Bridge, which has the largest amount of expansion and contraction in the world, in other large scale projects such as the Kitan Kaikyo Bridge, etc..

Finally, the authors wish to express their deep gratitude to the First Construction Office of the Honshu-Shikoku Bridges Authority and Akashi Kaikyo Bridge Stiffening Girder Construction Works Joint Venture for their guidance during this development work.

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### References

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2) Japan Society of Steel Construction, Specifications of Fatigue Design for Steel Structures in 1993