Technical Report

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Lifespan Enhancement of Crane Rails, Runway Girders and Overhead Cranes Using Shape-memory Alloyed Fish-plates

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Abstract

In a full-scale steel plant, many overhead cranes are installed for conveyance of objects varying from raw materials to shipping products, and accompanying them are crane rails and crane runway girders (CRG) which cover a long distance. Fatigue crack initiation determines the lifespan of overhead cranes and CRG, while defects and dents on the rail joints are the main determinants for the lifespan of crane rails. The shaking and impact which occurs when the crane passes over a defected joint leads to crack initiation on the overhead crane and CRG. To tackle this problem Nippon Steel & Sumitomo Metal Corporation developed a rail joint using shape memory alloy which enables longer durability for rails. This report explains the characteristics and performance of the newly-developed rail joint.

1. Introduction

In an integrated steelworks, cranes are used in versatile fields such as unloading of raw materials at a raw-materials dock for subsequent transportation, transferring of molten pig iron and molten steel in iron making and steel making processes, transferring of semi-finished products and products in rolling and other processes, and in the final process of shipment at a products-shipping wharf. Furthermore, cranes are used widely in the maintenance work of the production equipment in each plant. In Nippon Steel & Sumitomo Metal Corporation, about 5 000 cranes are operating throughout the entire company steelworks wherein the indoor cranes represented by the general overhead crane share 90%, while the remaining 10% is shared by the open-air cranes like the wharf crane. Among them, as the open-air cranes are operated near sea-coastal areas in many cases, corrosion and fatigue are the lifespan-determining factors; in the indoor use cranes, the main lifespan-determining factor is fatigue.

These cranes are equipped with wheels installed under the main structure and designed to travel on the travelling rail (hereinafter referred to as “rail”) at a low speed. In the case of an overhead crane, the rail is laid on and fixed to the beam called a crane runway girder (CRG) built on either side of the building (**Photo 1**). In Nippon Steel & Sumitomo Metal, 520 km of CRG for overhead cranes is laid throughout the entire company steelworks. The lifespan-determining factor of CRG is also the fatigue caused by the repeated load of the travelling of the overhead crane.

A rail in the range from a light weight rail to an ordinary rail is used depending on the wheel load of the crane. However, in the case

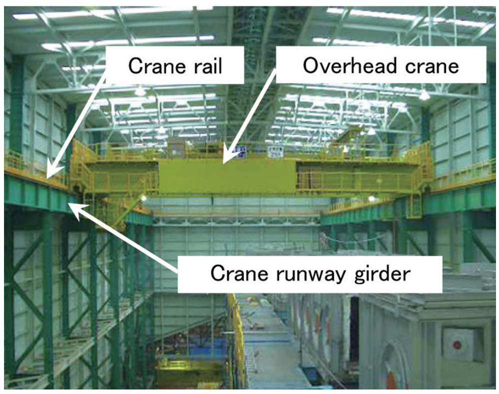

Photo 1 Overhead crane, crane runway girder and crane rail in a steel plant

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that the wheel load is very high such as that of a crane in steelworks, a crane rail with a special sectional shape of large head thickness, relatively low height and wide base (73 kg rail, 100 kg rail: weight per meter of the rail and larger in size than the rail of the Shinkansen of 60 kg) is used [1]. Conventionally, the rail for the overhead crane is cut into lengths of about 10 m and shipped due to the restriction in transportation and installation work and jointed on-site. In the rail structure, this joint section is the weakest and the deficit or the cavity at the rail end become the major cause of replacement of the rail; at the same time, the vibration and shock created when the overhead crane travels over the joint section cause fatigue-induced cracks of the overhead crane and CRG.

This article analyses the mechanism of the generation of vibration and shock when the overhead crane travels over the rail joint section and explains the features and the performance of the new type rail fish-plate that is able to suppress the vibration and shock, and can be installed within a short period of time even by unskilled workers.

2. Life-prolonging Effect of Vibration and Shock Suppressing Measures on Overhead Crane and CRG

As the increase in stress due to the vibration and shock caused by the travelling of the overhead crane is one of the factors which develops a fatigue crack that determines the lifespan of the overhead crane and CRG, they were measured in a plant to grasp the extent of the effect. The overhead crane used for the measurement was equipped with two wheels on either side and the rated hoisting capacity was 60 t (no loading at the time of measurement). The overhead crane was made to travel on the CRG at 60 m/min (**Fig. 1**). The rail joint section was located near the center of the CRG (length 15 m). The stress that developed on the overhead crane and the CRG was measured vs. the difference in level and the gap that were varied as parameters (**Photo 2**). The stress of the overhead crane was measured on the bottom face of the saddle which supports the wheels (**Photo 3**), and the stress of the CRG was measured on the outer face of the lower flange (**Photo 4**).

In **Figs. 2**, **3**, the stress that developed on the overhead crane and the CRG when the difference in level was 0mm and 2.9 mm (in the upward direction) is shown. The results of the measurement show that the stress of the overhead crane produced when it travels over the joint with a level height difference of 2.9 mm is 12% higher than

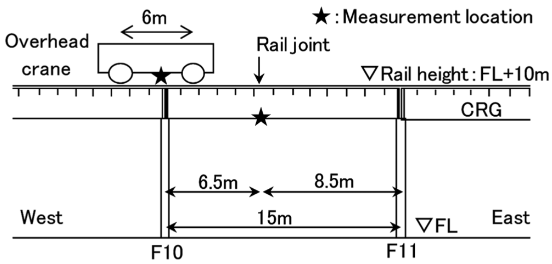


Fig. 1 Travelling range of overhead crane and measurement locations

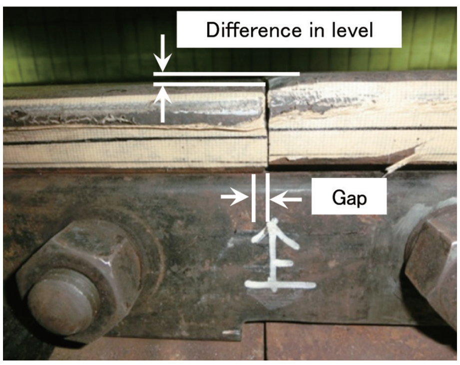


Photo 2 Condition of rail joint

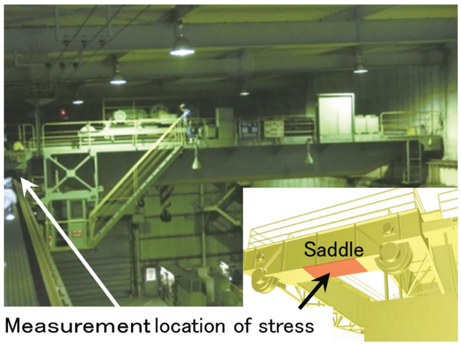


Photo 3 Measurement location of stress for overhead crane

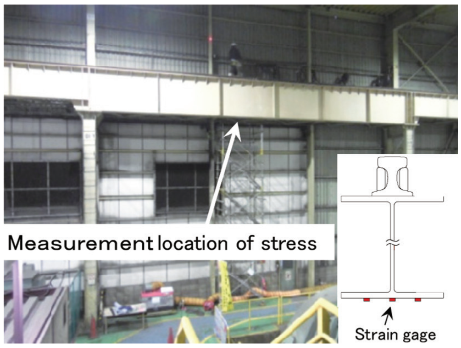


Photo 4 Measurement location of stress for crane runway girder

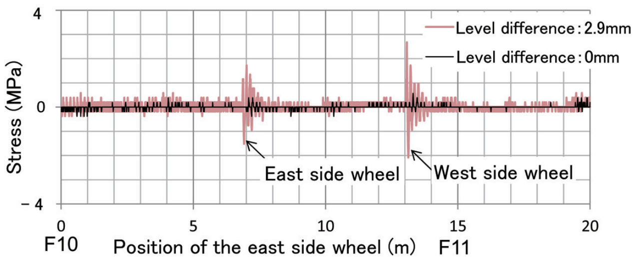


Fig. 2 Measurement results for overhead crane

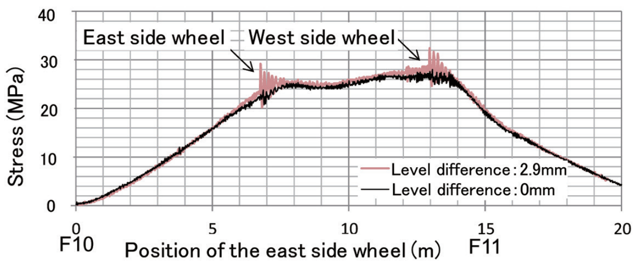


Fig. 3 Measurement results for crane runway girder

that produced when the level height difference is zero mm. The stress of the CRG is larger by 15%.

Similarly, the stress of the maximum values when the level height difference and the gap were varied is shown in **Table 1**. As for the gap, the stress scarcely increased even when the gap was 10.5 mm without the fall of the wheel to the gap, and it was confirmed that the effect of the level height difference is greater. The level height differences of 0.5 mm and the rail gap of 3 mm are specified as the maximum allowable limits in the guideline for the periodical self-inspection criteria and the explanation thereof[2], and within the ranges of the height difference and the gap, the increase in the stress was scarcely perceptible.

As the lifespan is inversely proportional to the cube of the fatigue, even with an increase of 15%, the lifespan is shortened by 66%, measures that prevent development of the height difference are important. As the height difference is caused by the deficit of the rail end due to an increase in the gap, the lives of the overhead crane and CRG are prolonged by rendering the measures to suppress the development of the gap.

3. Problem in Maintenance of Overhead Crane Rail and Method of Rail Jointing

In the rail structure, the rail joint section is the most fragile and most of the rail damage takes place at the rail end. The rail jointing section is subject to harsh conditions wherein, in addition to the large static stress, which acts upon the periphery of the rail jointing hole at the rail web and to the upper and lower necks, the large shock load caused by the passage of the overhead crane acts.

Table 1 Maximum stress for all cases measured

	Case					
Difference in level (mm)	0	0.5 Standard limit	2.4	2.9	0	0
Gap (mm)	0	0	0	0	3 Standard limit	10.5
Maximum stress of the saddle (MPa)	1.06σ	1.06σ	1.16σ	1.19σ	1.06σ	1.06σ
Maximum stress of the lower flange (MPa)	1.08σ	1.08σ	1.18σ	1.24σ	1.10σ	1.11σ

σ: Stress at the time of the overhead crane standstill

The standard rail jointing method used for the rail jointing section is the bolt method wherein bolt holes are opened at the rail end web and the rails are joined by tightening the bolts that run through the rail and the holes of the two plates each termed as fish-plate and installed on either side of the rail (**Table 2**). In the method, the bolt hole diameter is set larger than the bolt diameter by several millimeters so that an interaction is provided to absorb the rail processing errors and the tolerance of the bolt diameter. A rail joint gap is developed depending upon the amount of the interaction when a force that is caused by the acceleration or the deceleration of the crane acts to displace the rail (**Fig. 4**).

When the wheels of the overhead crane travel over the rail joint section, the wheel collides with the rail end and the shock force caused at the time develops the vibration of and the shock to the main body of the overhead crane. As the overhead crane travels repeatedly, deficiency or cavities are gradually developed (**Photo 5**), and the vibration and shock are encouraged to increase and become

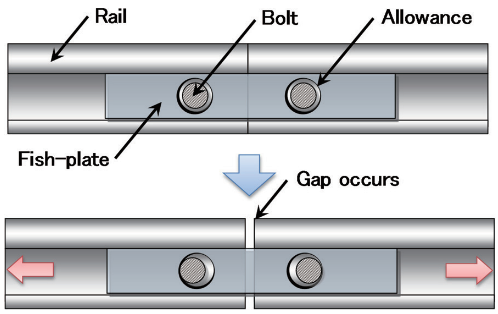


Fig. 4 Gap-generating mechanism

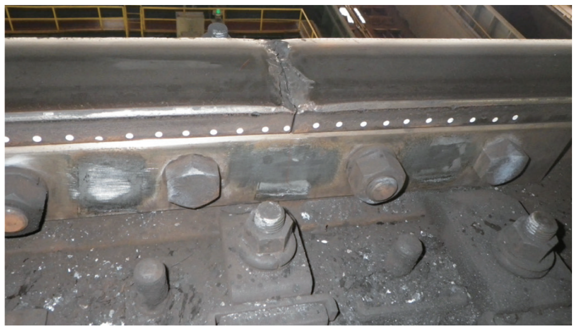


Photo 5 Damaged rail joint

Table 2 Issues of general rail joints and required performance for new rail joints

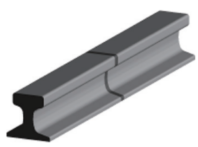
	Bolt rail joints	Enclosed welding rail joints	New rail joints
Outline			
Gap	× Gap occurs	○ No gap	○ No gap
Lifespan of rail joints	× Defects on the rail joints are determinant	○ Equal to the general part	○ Equal to the general part
Expert skill	○ Unnecessary	× Necessary	○ Unnecessary
Work time	○ Approx. 5 min	× Approx. 6–8 h	○ Approx. 10 min

Photo 6 Insertion of a cut rail

the cause of the problems of the main body of the overhead crane and the mechanical and electrical parts.

Accordingly, the rail needs to be replaced at an appropriate timing before the deficiency or the cavities become large. Because of the replacement cost and the restrictions in the replacement work, rather than the entire rail being replaced, the fish-plates are removed once and the damaged portion is cut away and a short rail of several meters is inserted, or a thin-cut rail piece is inserted (**Photo 6**). Thus temporary measures are taken.

The enclosed-welding method wherein the molten welding deposit metal is filled in the gap between the rails and the excess metal is ground off and finished is a method that does not create any rail joint gap (Table 2). However, as the time required for the on-site rail welding method is much longer than that of the bolt method and skilled workers are needed, the application of the method to crane rails in the steel plants is problematic because such steelworks are operated around the clock and therefore the working time is limited. Even in the bolt method, although the fish-plate with a small rail joint gap is available, the interaction between the bolt hole and the bolt diameter is required. Therefore, the complete zero rail joint gap is difficult to realize.

Accordingly, the idea of pulling both rails closer to each other to eliminate the interaction between the bolt hole and the bolt diameter after the fish-plates are fixed to the rail was conceived. At the beginning, tightening the two L-shaped fish-plates in the direction of pulling the two rails closer to each other was studied. However, it was proved that the state of zero rail joint gap failed to be maintained due to the insufficient tightening force and fatigue. Then, the development of the rail fish-plate made of a shape memory alloy that is designed to shrink by itself and realizes the state of zero rail joint gap was started [3, 4].

4. Outline of Zero Rail Joint Gap Fish-plate

4.1 Outline of features of fish-plate of ferrous shape memory alloy

Although among the shape memory alloys (SMA), the SMA of the Ni-Ti family is most widely and practically used, since it is costly and the application to practical use for large members is not realistic, the relatively low-cost SMA of the Fe-Mn-Si family [5] was used for study (**Table 3**). Since the discovery of the shape memory effect of the SMA of the Fe-Mn-Si family in the monocrystalline state in 1982, the materialistic research and development and the development of the production technology have been conducted in various places. Since the 1990s, the study on the application to practical use of Fe-28Mn-6Si-5Cr wherein Cr is added and the corrosion resistance have been taken into consideration [6]. To date, the usage appropriate for the features of SMA of the Fe-Mn-Si family such as the small parts like the coupling of the stainless steel pipe (**Photo 7**)

Table 3 Characteristics of Fe-Mn-Si and Ni-Ti series SMA

	Fe-Mn-Si series SMA	Ni-Ti series SMA
Cost	Low cost	High cost
Recovery temperature	250–300 °C	0–100 °C
Recovery strain	2.5–3.0 %	6–8 %
Properties	One time of shape recovery	Multi-cycle shape recovery

Photo 7 Joints for stainless steel pipes

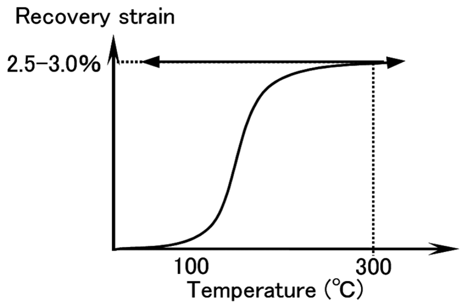


Fig. 5 Strain-temperature diagram for SMA

and the protection tube of the bottom-blowing converter nozzle (ceramic pipe) in steelworks, and the large parts like the coupling of the curved pipe in tunnel construction has been explored (hereinafter SMA means the shape memory alloy of the Fe-Mn-Si family collectively).

4.1.1 Fundamental characteristics

SMA is characterized by (unidirectional shape memorizing effect) being able to memorize its own shape when it is heated up to and retained at a constant temperature (950°C or above). Even if the SMA is forcibly deformed when it is returned to room temperature, it can restore the memorized shape when it is heated up to about 300°C and maintain the shape memorized after the heating even when the SMA is returned to room temperature. Accordingly, it possesses the characteristics advantageous for those of a jointing member.

4.1.2 Dynamic performance

In **Fig. 5**, the relationship between the strain of SMA after the restoration of shape and temperature is shown. The restoration of the shape starts around 100°C and the final maximum restored strain reached becomes about 2.5–3.0%. Furthermore, in **Fig. 6**, the relationship between the stress when the shape is restored and the temperature is shown. Along with heating, the stress emerges and

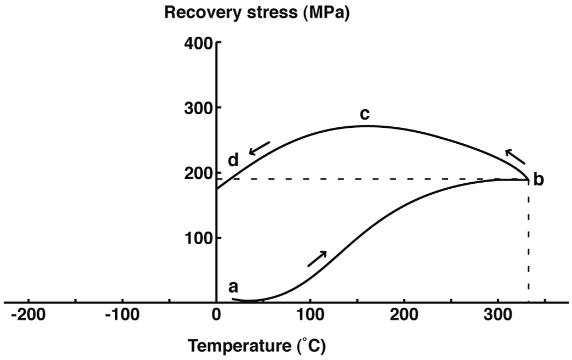


Fig. 6 Stress-temperature diagram for SMA

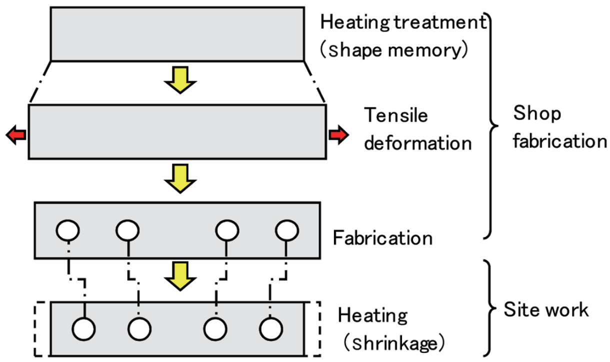


Fig. 7 Process of SMA fish-plate production

Table 4 Comparison of physical properties for SMA and steel

	SMA	Steel (S45C)
Tensile strength (MPa)	680–800	570–
Thermal expansion coefficient (°C^{-1})	16.5×10^{-6}	12×10^{-6}
Thermal conductivity (W/m·K)	8.37	45
Young modulus (GPa)	170	205

reaches its saturation point at about 300°C. Later on, although the stress increases temporarily during cooling, the stress decreases along with cooling and expresses the stress of 180 MPa when it returns to room temperature.

4.1.3 Physical properties

In **Table 4**, the physical properties of SMA are shown. As compared to the conventional carbon steel for machine structural use, for S45C steel, which is generally used for fish-plates, although SMA has the heat conductivity of one fifth of that of S45C, it is considered that as SMA has the high tensile strength of 680 MPa or higher, it reduces any inconveniences in terms of function and structure when it is applied to the fish-plate.

4.2 Mechanism of zeroing rail joint gap

The zero rail joint gap fish-plate using SMA (hereinafter referred to as the SMA fish-plate) is structured in the same manner as with that of the bolt method, except that SMA is used. After furnishing the fish-plate material with the shape memory by the heat treatment and with the tensional deformation at room temperature, the material is processed to the fish-plate by opening bolt holes. The fish-plate is deformed in the tensional direction from the memorized shape. Therefore, it has a shrinking nature by the restoration of shape when it is heated (**Fig. 7**).

When the SMA fish-plate is heated after installation to the rail, the shrinking of the fish-plate absorbs the interaction caused by the difference in diameters of the bolt hole and the bolt. It establishes the state of the contact of the bolt with the bolt hole and the shrinking of the SMA fish-plate is transferred to the rail; thus, zero rail joint gap fish-plate is realized (**Fig. 8**). Even after the rail joint gap is zeroed, the SMA fish-plate continues to exert a force that shrinks and a tightening force that presses one rail to another. By designing the tightening force larger than the tensile force of the rail which takes place when braking is applied to the overhead crane, the tensile force is cancelled and the regeneration of the rail joint gap is suppressed.

The cross-section of the SMA fish-plate is shaped so as to contact the rail at the head and the base likewise the cross-section of the conventional fish-plate in order to suppress the deformation of the head, except that only the form of chamfering of the corner is changed from the arch to a straight line for the ease of manufacturing (**Fig. 9**). The overall length of the fish-plate is the same as that of the general fish-plate and the desired tightening force is generated by changing the position of the bolt hole on the part of the fish-plate.

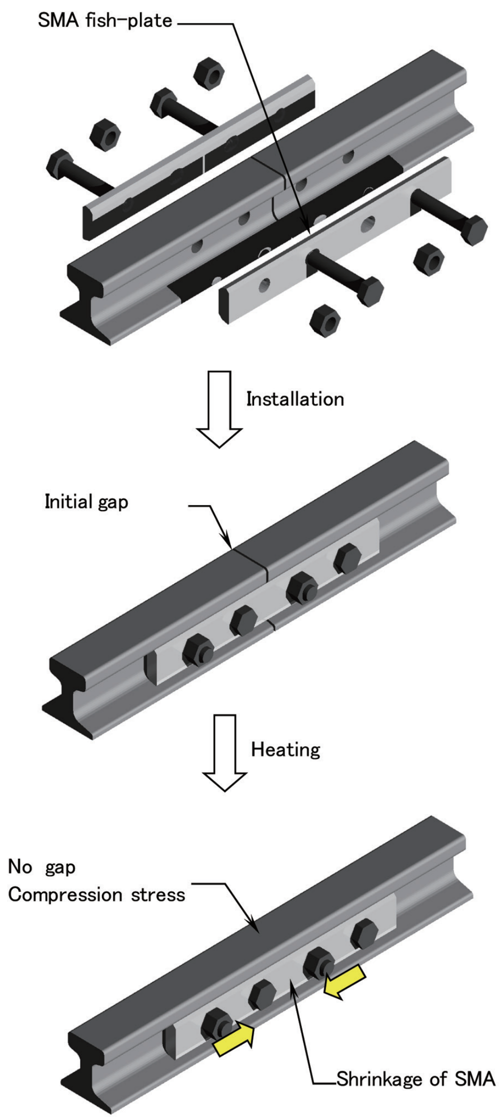


Fig. 8 General installation process of SMA fish-plate

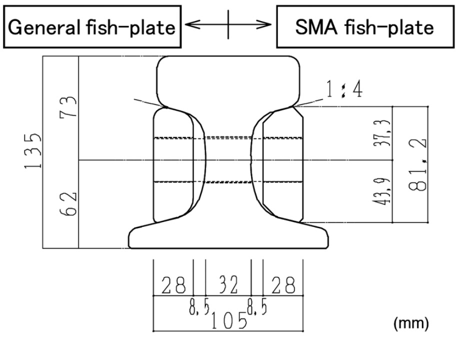


Fig. 9　Cross section of rail joint

5. Performance Confirmation Test

As the application of SMA to actual structural members is scarce, various tests were conducted to confirm the fundamental performance. The performance confirming tests were conducted based on a 73 kg rail that is used for the molten steel crane and the coil transferring crane, and the necessity of a zero crane rail joint gap is high. The methods of the tests and the results are explained in the following section.

5.1 Quantitative evaluation of crane load exerted on rail joint section

To apply a tightening force acting on the rail joint section and to prevent the occurrence of the rail joint gap, it is necessary to define the load developed by the overhead crane travelling as the premise of the study. According to the steel structure design standard, the braking force of an overhead crane is 15% of the wheel load of each wheel and acts on the upper face of the rail[7]. Tests to confirm the load that acts on the rail joint section were conducted.

The load that acts on the rail joint section was investigated by measuring the stress developed in the rail on which an overhead crane actually travels. Specifically, as the maximum stress in the rail takes place behind the wheel when sudden braking is applied, the overhead crane was made to travel at its highest speed and the sudden braking was applied immediately after the rear wheel cleared the stress-measuring point. The stress which acted on the rail was then measured (**Fig. 10**). The overhead crane used for the measurement was equipped with four wheels on either side with the wheel load of 228 kN (empty load, the hook placed aside the rail where the measurement was conducted).

In **Fig. 11**, results of the measurement are shown. Right before the application of the sudden braking of the overhead crane, four peak values appear which are captured by the strain gauge. These are considered to be the elongation of the rail caused by the Poisson ratio effect of the vertical load rendered by the wheel when the overhead crane traveled over the stress measuring point (**Fig. 12**). As the rail deforms in the elongating direction by the vertical load of the wheel, this is not considered to have any relation with the development of the rail joint gap. Accordingly, the load which acts on the rail joint section linked to the development of the rail joint gap is 25 kN that was produced right after the application of the sudden braking. This becomes 11% of the wheel load of each wheel. As the index specified in the steel structural design standard is 15% of the wheel load, the load of an overhead crane acting on the rail joint section is set at 15% of the wheel load as the index, taking into consideration the safety margin.

5.2 Tests on actual scale

The maximum crane wheel load of 73 kg rail is about 530 kN and the required tightening force was set at 80 kN, assuming that the braking force of the overhead crane is 15% of the wheel load.

A test of heating SMA fish-plates was conducted wherein two pieces of rail about one meter in length, each attached with a strain gauge to calculate stress, were tied and fixed by SMA fish-plates with bolts (**Photo 8**). Twelve test pieces were prepared wherein the bolt hole position and the hole diameter were varied as parameters in consideration of the influence of test-piece manufacturing errors.

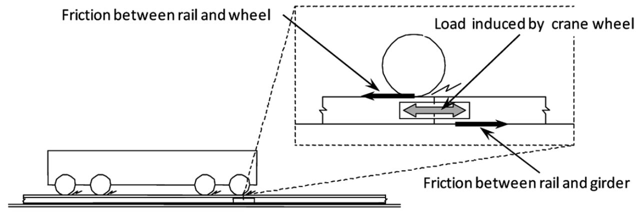


Fig. 10　Tensile stress at crane rail joint generated by travelling of crane wheel

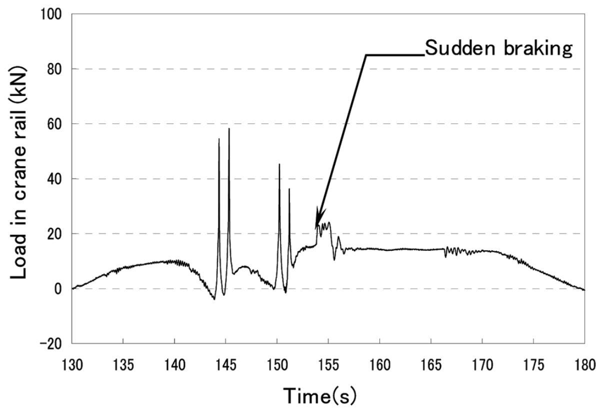


Fig. 11　Time history of load in crane rail

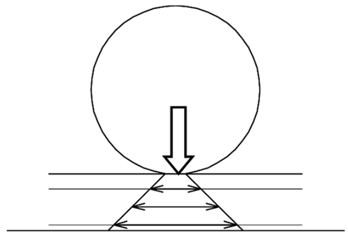


Fig. 12　Stress distribution in crane rail

Photo 8　Heating experiment of SMA fish-plate

About ten minutes after the start of heating with a gas burner, the rail joint gap started to narrow; after fifteen minutes, the gap disappeared and the rails contacted with each other; after twenty minutes, the SMA fish-plate temperature reached 300°C and the heating was finished. Moreover, the temperatures of the rails were below about 200°C and the amount of the thermal input was less than the level which affects the rail metallurgy.

The histogram of the force in the test piece taken on the horizontal axis is shown in **Fig. 13**. Although, influenced by the errors in manufacturing the test pieces, the dispersion of the generated force is observed, in all the test pieces provided for the tests, the required tightening force of 80 kN was satisfied, and the SMA rail joint is considered to possess sufficient tightening force.

5.3 Fatigue performance confirmation test

As the rail joint section is subject to the vibration and braking force caused by the travelling of the overhead crane for a long period of time, the fatigue performance confirmation test was conducted (**Fig. 14**). The axial direction of the rail was taken as the axis of loading wherein the variation of stress is large due to the rail tightening force and the braking force, and the test was conducted with three forces, including the required tightening force of the 80 kN fish-plate as previously mentioned. The number of the imposed frequency was 2.0×10^6 and 1.0×10^7 and the test piece which generated 120 kN force in the structural test was used as the subject test body.

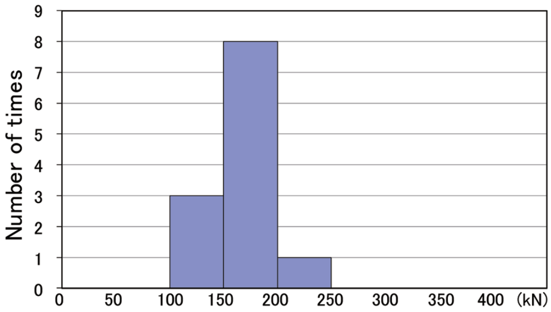


Fig. 13 Frequency distribution of generated loads

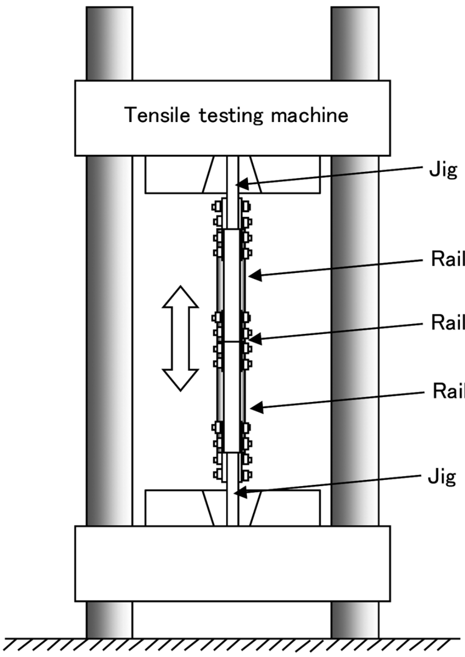


Fig. 14 General outline of fatigue testing

In **Table 5**, the results of the fatigue test are shown. The test was started with the tightening force of 30 kN and conducted incrementally, and no regeneration of the rail joint gap was confirmed in any cases. Based on the results, the SMA rail joint is considered to have sufficient fatigue-resistant performance with the required rail tightening force of 80 kN.

5.4 Exposure test

In the SMA rail joint, as the fish-plate and the steel rail remain in contact with each other and the corrosion developed by the contact of the heterogeneous metals is a concern, the test rail joint section used in the test was placed outdoors near a sea coast (Awaji Island, Hyogo Prefecture) and has been continually monitored for the state of corrosion since November 2004.

Photos 9, **10** show the state of the test piece as of November 2013. Ten years have passed since its installation and although conventional rust is observed on the rail and the fish-plate, no development of any particular rust is recognized at the contact section of the two, and therefore, no particular corrosion has developed at the con-

Table 5 Results of fatigue test

	CASE-1	CASE-2	CASE-3
Load (kN)	±30	±50	±80
Number of cycles	2.0×10^6		1.0×10^7
Frequency (Hz)	10		
Result	No space generated		


Photo 9 Exposure test of a steel fish-plate attached to a crane rail


Photo 10 Dismantlement of the exposure test specimen

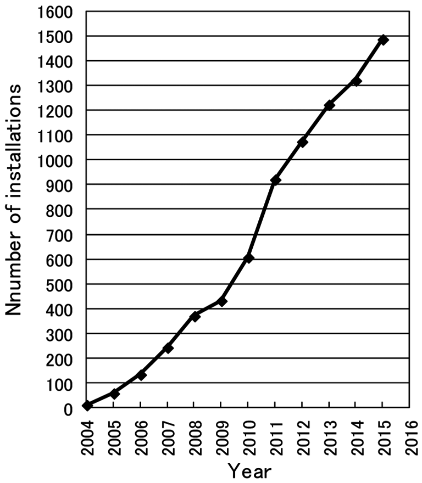


Fig. 15 Installation records

Photo 11 Installation of SMA fish-plates at the steel-making plant in Kimitsu Works

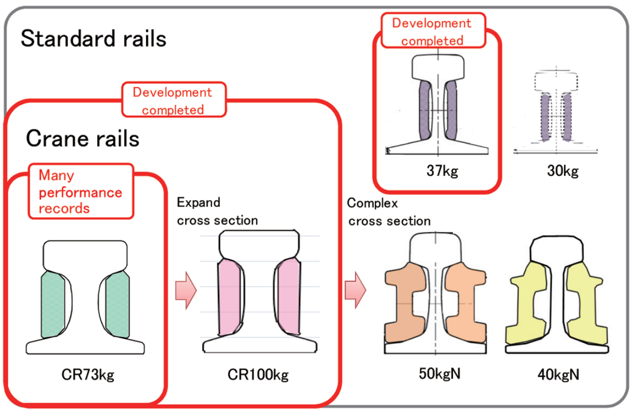


Fig. 16 Lineup expansion of SMA fish-plates

tact section of the SMA rail joint with a heterogeneous metal. Metallic gloss remains observable in part on the fish-plate.

6. Tackling Expansion of Application

Since its first application in October, 2004 in the Nagoya Works, the fish-plate has been applied mainly to the 1 500 joint sections for the entire crane rail length of 15 km in the iron and steel works of Nagoya, Kimitsu, Oita and Yawata (**Fig. 15**). Although in the earlier stage of the development, problems such as insufficient tightening force, loosened bolts, and broken bolts occurred, owing to the investigations on the causes and revisions of the design, currently there are no notable problems in the iron and steelworks (**Photo 11**). In the steel making plant in the Wakayama Works, the development of the rail joint gap and the bolt breakage frequently took place. We received a report that a zero rail joint gap was developed and the situation is proceeding well after the application of the SMA fish-plate.

In the early stage, the development was focused on the highly demanded cases of a 73 kg rail; presently development for the 100 kg and 37 kg rails has finished and the development of further expansion of application is under way (**Fig. 16**). The cost reduction is being tackled, and by improving the design, reduction of the fish-plate thickness, elimination of training treatment[6] and reduction of the alloy content (28% Mn to 15% Mn) have been realized.

7. Conclusion

SMA fish-plate is technology that can maintain the zero rail joint gap state for a long time wherein the vibration and shock caused by the travelling of the overhead crane decrease, while maintaining the advantageous features of the conventional bolt tightening method. We are determined to contribute to the lifespan enhancement and the stabilized equipment operation of rails, CRG and overhead cranes by expanding the area of application.

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