RA2022-2-I

RAILWAY ACCIDENT
INVESTIGATION REPORT

Railway accident with train derailment in the premises of Aoto station,
Main Line, Katsushika City, Tokyo Metropolitan,
Keisei Electric Railway Co., Ltd.

March 24, 2022

JTSB Japan Transport Safety Board

The objective of the investigation conducted by the Japan Transport Safety Board in accordance with the Act for Establishment of the Japan Transport Safety Board is to determine the causes of an accident and damage incidental to such an accident, thereby preventing future accidents and reducing damage. It is not the purpose of the investigation to apportion blame or liability.

TAKEDA Nobuo
Chairperson
Japan Transport Safety Board

Note:

This report is a translation of the Japanese original investigation report. The text in Japanese shall prevail in the interpretation of the report.

《Reference》

The terms used to describe the results of the analysis in "3. ANALYSIS" of this report are as follows.

i) In case of being able to determine, the term "certain" or "certainly" is used.
ii) In case of being unable to determine but being almost certain, the term "highly probable" or "most likely" is used.
iii) In case of higher possibility, the term "probable" or "more likely" is used.
iv) In a case that there is a possibility, the term "likely" or "possible" is used.

Railway Accident Investigation Report

Railway operator	Keisei Electric Railway Co., Ltd.
Accident type	Train derailment
Date and time	About 10:16, June 12, 2020
Location	In the premises of Aoto station, Main Line, Katsushika City, Tokyo Metropolitan

February 24, 2022

Adopted by the Japan Transport Safety Board

Chairperson	TAKEDA Nobuo
Member	OKUMURA Fuminao
Member	ISHIDA Hiroaki
Member	KAKISHIMA Yoshiko
Member	SUZUKI Mio
Member	NIITSUMA Mihoko

SYNOPSIS

<SUMMARY>

On June 12, 2020, the inbound 1022N train, composed of eight vehicles started from Keisei Takasago station bound for Haneda Airport No.1 and No.2 Terminal station, of Keisei Electric Railway Co., Ltd., departed from Keisei Takasago station about one minute behind the scheduled time 10:13. While the train was entering the platform of Aoto station at the velocity of about 30 km/h, the emergency brake was applied and the train stopped about 44 m before the stop sign. The emergency brake had been applied by the conductor because the conductor felt the abnormal vibration of the train and pulled the conductor's valve.

After the train had stopped, the conductor checked the side surface of the train, and found that the seventh vehicle had been tilted to right and derailed. After that, the staffs of the railway company checked the derailed status and found that there was the crack in the side beam in front right of the rear bogie.

About 100 passengers, the driver and the conductor were boarded on the train, but no one was injured.

<PROBABLE CAUSES>

The JTSB concludes that the probable cause of this accident is as follows :

It is probable that the right wheel climbed up rail and derailed at around the end edge, in the direction to Aoto station, of the guard angle, where derailment could not become to be protected, because the unbalance of wheel loads in the front axle of the bogie became large, while the vehicle ran in the status that the crack was generated from lower surface to upper part of the side surface of the side beam of the bogie and expanded, and the lateral force increased while the vehicle passed the curved track in the status that the wheel load of right wheel had been decreased, in this accident.

It is probable that the unbalance of the wheel loads in the front axle of the bogie became large, because the shared vertical load could not be supported by the decreased strength of the side beam due to the crack.

Furthermore, it is likely that the crack had generated in the side beam because the large stress was generated locally by the stress concentration in the inside of the side beam where the reinforcing plate was welded, and became to the origin of the crack and the crack had expanded due to the fatigue fracture.

It is likely that the railway operator could not find the crack expansion in the periodic inspection, because there was the possibility that the crack had not been opened when the latest general inspection before the occurrence of this accident was conducted, even though there was the possibility that the crack had already been reached to the surface of lower surface of the side beam at that time, and the place to be inspected by the magnetic particle test for the side beam had not been prescribed precisely.

CONTENTS

ATTACHED MATERIALS

1. PROCESS AND PROGRESS OF THE RAILWAY ACCIDENT INVESTIGATION

1.1. Summary of the Railway Accident

On Friday, June 12, 2020, the inbound 1022N train, composed of eight vehicles started from Keisei Takasago station bound for Haneda Airport No.1 and No.2 Terminal station, of Keisei Electric Railway Co., Ltd., departed from Keisei Takasago station about one minute behind the scheduled time 10:13. While the train was entering the platform of Aoto station at the velocity of about 30 km/h, the emergency brake was applied and the train stopped about 44 m before the stop sign. The emergency brake had been applied by the conductor because the conductor felt the abnormal vibration of the train and pulled the conductor's valve.

After the train had stopped, the conductor checked the side surface of the train and found that the seventh vehicle had been tilted to right and derailed. *Hereinafter, the words "left", "right", "front" and "rear" was defined base in the traveling direction of the train and the vehicles are counted from the front.* After that, the staffs of the railway company checked the derailed status and found that there was the crack in the side beam in front right of the rear bogie.

About 100 passengers, the driver and the conductor were boarded on the train, but no one was injured.

1.2. Summary of the Railway Accident Investigation

1.2.1. Organization of the Investigation

On June 12, 2020, the Japan Transport Safety Board, *hereinafter referred to as "the JTSB"*, designated the investigator-in-charge and the other two railway accident investigators to engage in the investigation of this accident.

The Kanto District Transport Bureau dispatched its staffs to the accident site to support the investigation of this accident.

1.2.2. Implementation of the Investigation

June 12 and 13, 2020	Site investigation, vehicle inspection and hearing statements
June 25, 2020	Bogie investigation
August 6, 2020	Flaw detection test investigation of the bogie

1.2.3. Comments from the Parties Relevant to the Causes

Comments were invited from the parties relevant to the causes of this accident.

2. FACTUAL INFORMATION

2.1 Process of the Train Operation

2.1.1. Statements of the Train Crews, etc.

According to the statements of the driver and the conductor of the inbound 1022N train, composed of eight vehicles started from Keisei Takasago station bound for Haneda Airport No.1 and No.2 Terminal station, of Keisei Electric Railway Co., Ltd., *hereinafter referred to as "the Driver", "the Conductor", "the Train", and "the Company", respectively*, and the driver who operated the 723N train *hereinafter referred to as "the 723N Train Driver", "the 723N Train", respectively*, composed of the same trainset as the Train, *hereinafter referred to as "the Trainset"*, and departed from Haneda Airport No.1 and No.2 Terminal station bound for Keisei Takasago station, from Oshiage station before the occurrence of this accident, and the limited driver[*1] in car inspection depot who was charged in the entering and departing operation of the Trainset in the depot, the summary of the process to the Accident was as follows.

(1) The Driver

The Driver started his duty on the operation of the Train from Keisei Takasago station, located at 12,660 m from Keisei Ueno station, *hereinafter "from Keisei Ueno station" is omitted*.

The Train departed from Keisei Takasago station about one minute behind the scheduled time 10:13. After departed, the Driver accelerated the Train by the Notch 2, after accelerated by the Notch 5 till to about 50 km/h, the Driver operated the notch off. The Driver applied the service brake at a little before the protection area of the No.2 home signal, at 11,827 m, because there was the speed limit of 45 km/h at the No.3 home signal, at 11,690 m, of Aoto station, at 11,510 m, where was the next stop station, and entered the protection area of the No.3 home signal at the velocity of about 40 km/h. After entered, the Driver operated the Train in the coasting operation and applied the service brake again to decelerate to about 30 km/h in order to pass the turnout, and passed the turnout. When the front head of the Train entered the platform of Aoto station at that velocity, the Driver felt as dragged from backward, and one to two seconds later, noticed that the emergency brake by the conductor's valve had applied by the warning sound and the monitor display, and the Train stopped about 44 m before the stop sign. At this time, the Driver received a notification from the Conductor that the Train seemed to be derailed.

The Driver reported to the transport dispatcher that "the Train seemed to derail, then going to check the site from now", and detrained and checked the site, and found that the seventh vehicle, *hereinafter referred to as "the Vehicle"*, had been tilted, the pantograph had come off from the Vehicle and hung from the overhead trolley, and confirmed that the Vehicle had been derailed. Then, the Driver returned to the driver's cab, and reported to the transport dispatcher that the Train had been derailed. After that, the Driver let the passengers in the cabins detrained, in cooperation with the rushed company staffs, and closed the doors after completed to detrain passengers, and operated the measures for the parking.

The Driver felt no particular abnormality in the vehicles of the Train, from the start of the duty for the Train till to the occurrence of this accident.

(2) The Conductor

The Train departed from Keisei Takasago station about one minute behind the scheduled time 10:13.

When the Train had departed, the Conductor closed the door in the conductor's cabin, and watching the train while holding the conductor's valve by left hand and the outside bar, *i.e.*, hand rail, by right hand. After that, the Conductor felt something strange *i.e.*, the occurrence of the inexplicable vertical vibration different from as usual, at around the up line No.3 home signal of Aoto station, and felt the impact soon after that. The Conductor, while opened right window, heard the impact sound as "squawk", and confirmed by putting his head out of the window that something like white smoke was raised up, and felt that it was something serious, therefore, the Conductor operated the conductor's valve. The Conductor remembered that the place where operated the conductor's valve was in around the crossed part in the scissors crossing[*2], *hereinafter referred to as "the Turnout"*. The Conductor felt that the velocity when the Conductor operated the conductor's valve was not faster than as usual. The Train had been operated as usual and there was no uncomfortable feeling until to feel something strange.

When the Conductor looked backward of the Train after the Train had stopped, it was found that something like pantograph had been hung down, therefore, the Conductor thought that the overhead trolley had been sagging, and operated the alarm signal switch of the train radio. The Conductor looked side surface of the train and confirmed that the Vehicle had been tilted compared to the other vehicles. Furthermore, the Conductor looked the cabin, and felt abnormality because there was the height difference, *i.e.*, vertical difference, between the Vehicle and the eighth vehicle, then reported to the Driver that the Train had been derailed, and asked the Driver to report it to the transport dispatcher. In addition, the Conductor announced the passengers that the train had been derailed, and informed to evacuate to the forward, in the direction to Oshiage station, vehicles of the train. After that, the Conductor received the instruction, from the assistant station master rushed to the driver's cab, to operate the door cock and to let evacuation of passengers, therefore, opened the front and the rear doors in three doors in right side of each vehicle in turns from the sixth vehicle, the fifth vehicle, the fourth vehicle and the third vehicle, to let the passengers detrain.

According to the report from the company staff of Keisei Takasago station when completed to detrain passengers, about 100 passengers were guided and confirmed that there was no injured person.

*1 *"Limited driver" in this context is the driver who received the driver's license, which limited the area of the operation and added by the required conditions, to implement the shunting operation and the entrance or departure operation in the car inspection depot or the factory.*

*2 *"Scissors crossing" is to cross two set of the crossovers, and composed of 4 set of the turnout and one set of the diamond crossing.*

(3) The 723N Train Driver

The 723 train had arrived at Oshiage station on schedule at 08:53, from Asakusa Line of the Tokyo Municipal Subway. The 723N Train Driver received the report as "On schedule, no abnormality" from the preceding driver and was handed over the operation of the 723N Train. After that the 723N Train Driver operated the train from Oshiage station till to Keisei Takasago station, but did not feel any abnormality in the vehicles, and operated as usual. There was no particularly uncomfortable feeling when compared to the same type vehicles as the Train that the 723N Train Driver had operated on the accident day.

The 723N Train Driver reported as "no abnormality" and handed over the operation to the limited driver in the car inspection depot, because the 723N Train was scheduled to enter the depot after arrived at Keisei Takasago station.

Furthermore, the 723N Train Driver had operated the other train in the same section as the Train before the occurrence of this accident in the accident day, but the 723N Train Driver felt that there was no abnormality in the status of the track, etc., and felt as usual.

(4) The limited driver in car inspection depot

When the limited driver dealt with the entrance of the 723N Train to the depot, the limited driver was taken over the duty after received the report as "no abnormality" from the 723N Train Driver at Keisei Takasago station at 09:06. There was no uncomfortable feeling at all in the operation while the 723N Train was entering the platform.

When the limited driver drove the 723N Train to enter the depot, the eighth vehicle near to the derailed seventh vehicle of the Train was the most front vehicle, and the limited driver opened the window in the driver's cab and drove the train, in the status that the sound could be heard well, there was no difference from usual operation while entering the depot, and there was no particular uncomfortable feeling for the acceleration and deceleration, the vibration and the abnormal sound, and did not feel any abnormality.

Furthermore, the limited driver drove the 723N Train to depart from the depot toward Keisei Takasago station at 10:10, while opening the window of the driver's cab in the first vehicle, which was the most front vehicle, there was no particularly abnormal sound and no uncomfortable feeling. The 723N Train arrived at Keisei Takasago station at about 10:12, and reported as "no abnormality" and took over the duty to the Driver.

The confirmation of the bogies had not been implemented at this time, because it was the subject out of the inspection in the inspection at the entrance and the departure from depot.

2.1.2. Records of the Operating Status

The operated status of the Train, *i.e.*, the information such as the time, the velocity, the limited speed, the running distance, etc., had been recorded in the automatic train stop device, *hereinafter referred to as "the C-ATS device"*.

The major records in the C-ATS device on the Train, from the departure from Keisei Takasago station till to the occurrence of this accident, were as shown in Table 1.

The drive recorder had not been equipped in the Train.

Table 1. Records of operating status in the C-ATS device, extracted only major records.

Time [hh:mm:ss]	Velocity [km/h]	Limited speed [km/h]	Running distance [m]	Remarks
10:14:38	0	45.00	0	Depart from Keisei Takasago station
:	:	:	:	
10:16:07	36.30	45.00	937.2	The Bogie passed around 11,750 m

:	:	:	:	
10:16:15	32.27	45.00	1,019.0	The Bogie passed around 11,670 m
:	:	:	:	
10:16:22	29.28	45.00	1,078.8	Just before the deceleration
10:16:23	28.13	45.00	1,086.8	Start of sudden velocity decrease
10:16:24	25.05	45.00	1,094.2	Sudden velocity decrease
10:16:25	20.69	43.30	1,100.4	Same as the above
10:16:28	8.02	39.95	1,112.1	Same as the above
10:16:30	0	9.50	1,114.5	The Train stopped

* *Time data was revised based on the actual time.*

* *Running distance indicates the accumulated running distance from the departure from Keisei Takasago station.*

* *There is a possibility to include errors in the velocity and the running distance.*

* *The limit speed is the check speed in the C-ATS device.*

[Refer to Attached Figures 1 to 3]

2.2. Death, Missing and Injury of Persons

2.2.1. Information on the Injured Person

According to the Company, about 100 passengers and two train crews, *i.e.*, the Driver and the Conductor, were boarded on the Train, but no one was injured.

2.3. Information on the Railway Facilities, etc.

2.3.1. Information on the Accident Site, etc.

2.3.1.1. Status of Aoto station and surroundings

Aoto station is the station connecting the Main Line and the Oshiage Line of the Company, and the double layers structure with two platforms and four tracks, *i.e.*, the second floor was the platform of the up line, and the third floor was the platform of the down line. Furthermore, Keisei Takasago station was the station connecting the Main Line and the Kanamachi Line of the Company and the Hokuso Line of the Hokuso-Railway Co., Ltd., *hereinafter referred to as "the Hokuso Railway"*.

2.3.1.2. Status of the derailment

The front head of the Train had been halted at around 11,450 m. The rear end of the eighth vehicle had been halted at around 11,590 m. The rear bogie of the Vehicle, *hereinafter referred to as "the Bogie"*, had been halted at around 11,570 m, and left wheel of the first axle and left wheel of the second axle of the Bogie had been derailed from left rail to right side by about 14 cm and about 10 cm, respectively. Furthermore, right wheels had also been derailed to right side of right rail.

There were the traces considered as caused by the Train on the sleepers, the rails, the rail fastening devices, etc., in the range from around the end of the guard angle in the direction to Aoto station, at around 11,670 m, to the place where the Bogie of the Vehicle had been halted, at around 11,570 m. Furthermore, there were the traces considered as caused by being contacted with the wheels on the guard angle, and the traces considered as caused by the running wheel flanges on the top surface of right rail, from around 11,750 m to around 11,670 m.

[Refer to Attached Figures 3, 4]

2.3.2. Information on the Railway Facilities

2.3.2.1. Outline of the route

The Main Line of the Company was the route of the railway business mile 69.3 km from Keisei Ueno station to Narita Airport station, composed of the quadruple track section between Aoto station and Keisei Takasago station, the double track sections between Keisei Ueno station and Aoto station and between Keisei Takasago station and Airport No.2 Building station, and the single track section between Airport No.2 Building station and Narita Airport station, and electrified by DC 1,500 V, with the gauge of 1,435 mm.

[Refer to Attached Figure 1]

2.3.2.2. Outline of the railway track

Information on the railway track and the facilities in around the accident site was as follows.

The track structure in around the accident site in the direction to Keisei Takasago station was the ballast track, and the 50 kgN rails were used. The PC sleepers and the synthetic sleepers were used for the sleepers.

(1) The distance between Aoto station, at 11,510 m, and Keisei Takasago station, at 12,660 m, was about 1.1 km. The above kilometerage indicates the kilometerage of the center of the station.

(2) The track shape from 11,859 m to 11,670 m was the 270 m radius left curve including the transition curves, *hereinafter referred to as "the Curve"*, with the 80 mm cant[*3], and the 0 mm slack[*4]. The Turnout has been installed in Aoto station side of the Curve. The limited speed for the curved track, that the radius is 250 m or above and less than 275 m, is stipulated as 65 km/h or slower in the implementing standard of handling operation decided by the Company. Furthermore, the gradient was 15.3 ‰ down grade from 11,820 m to 11,680 m, and 1.02 ‰ down grade from 11,680 m to around 11,390 m.

(3) The guard angle was installed in inside of left rail in the Curve, for the entire length of the Curve except for the place of the insulated joint at 11,827 m. The designed spacing between the guard angle and left rail was 85 mm.

The installation of the guard angle was stipulated in the implementing standard of railway track and structure, which is one of the implementing standards reported by the Company to the Director General of the Kanto District Transport Bureau based on the Ministerial Ordinance Providing for the Technological Standards for Railways, Ministerial Ordinance No.151, prescribed by the Ministry of Land, Infrastructure, Transport and Tourism, 2001, *hereinafter referred to as "the Reported Implementing* *standard*", as follows.

[Railway Track Structure]

Article 26. Railway track shall conform to each item in the followings.

(1) The railway track shall conform to the vehicle structures and shall be able to guide the vehicles to the specified direction.

(2) The railway track shall withstand the anticipated loads.

(3) The railway track shall not be in danger to deform to the extent to hinder the safe operation of the vehicles.

(4) The railway track shall not be in danger to hinder the maintenance.

2. Equipment to prevent derailment or to reduce the damages by the derailment shall be installed depending on the status of the facilities and the structure of the vehicles, etc., in the curved track of small radius in the main line, in the other place where there was in danger of derailment, and in the place where there were in danger of serious damages when derailment was happened.

(1) The guard angle shall be installed in the curved section of the radius of less than 250 m in the main track, and the radius of 160 m or less in the side track. Furthermore, the guard rail or the guard angle shall be installed in the curved section where the safety factor of flange climbing estimated by the following equation is less than 1.2, and the other places where in danger to derail.

Safety factor of flange climbing

= Estimated derailment coefficient / Critical derailment coefficient

(2) to (5) [Omitted]

(4) The Turnout to branch the inbound trains into two lines, *i.e.*, toward Ueno station and toward Oshiage station, was installed between the Curve and Aoto station, and the 22B turnout was installed in the direction to Keisei Takasago station, and the 23A turnout was installed in the direction to Aoto station, for the trains toward the direction to Oshiage station.

(5) In Aoto station, the inbound No.1 home signal, the inbound No.2 home signal, and the inbound No.3 home signal were installed at 12,025 m, 11,827 m, and 11,690 m, respectively.

*3 *"Cant" is the height difference between the outer rail and the inner rail in the curved track section.*

*4 *"Slack" is the enlarged amount of the gauge in the curved track section.*

[Refer to Attached Figures 3, 4]

2.3.2.3. Information on the maintenance of the railway track

The maintenance of the railway track has been prescribed in the implementing standards of railway track and structures, which was one of the Reported Implementing Standards. The track irregularities, *i.e.*, the irregularity of gauge, the irregularity of cross level, the irregularity of twist, the longitudinal level irregularity and the irregularity of alignment, have been prescribed to be inspected once or more a year, and the maintenance management values of the static track irregularities and the irregularity of twist are as shown in Table 2.

Table 2. Maintenance management values of the railway track

Items for each track	*Main track*	*Side track*
Gauge	*140 m to 600 m radius : +19 mm, -4 mm* *The other section : +14 mm, -4 mm*	*Same as left*
Cross level	*Maintain based on the irregularity of twist*	*Same as left*
Twist in 2.5 m extent	*14 mm*	*Same as left*
Longitudinal level within 10 m extent	*17 mm*	*22 mm*
Alignment within 10 m extent	*17 mm*	*22 mm*

#1. Numbers indicate the static values measured by the track inspection car.

#2. The slack, the cant and the versine including the vertical curve, in the curved track were not included.

#3. When exceeded the above maintenance management values, implement the repair works promptly, as the principle.

#4. 「+」 is the upper limit of gauge widening, 「-」 is the lower limit of the gauge narrowing.

In addition, the material inspection for the track components is prescribed to conduct once or more a year, on damages, abrasion, corrosion, etc., of the track components, such as rails, ballast or roadbed, sleepers, etc.

2.3.2.4. Information on the track irregularities

The latest inspection of the track irregularities before the occurrence of this accident for the section from 11,859 m to 11,670 m, where the guard angle is installed, had been conducted on May 20, 2020, using the track inspection car, and the results of the inspection were within the maintenance management values shown in Table 2.

In addition, the measurement of the track irregularities for the section from 11,760 m to 11,655 m was conducted after the occurrence of this accident by the manual inspection, and the results were within the maintenance management values shown in Table 2.

2.3.2.5. Information on the track components

The latest periodic inspection of the major track components before the occurrence of this accident was conducted on February 4, 2020, and there was no abnormal record in the records of the inspection and the inspected results in each inspection. There was no abnormality in the track components in around the accident site after the occurrence of this accident.

2.3.2.6. Information on the situation of the Train when arrived at Aoto station

According to the records kept in the ground devices, the situation of the Train arriving at the No.1 track of Aoto station was that, the Train entered the protection area of the No.1 home signal, about 10 seconds after that, the Train entered the protection area of the No.2 home signal, about 10 seconds after that, the Train entered the protection area of the No.3 home signal, and about 10 seconds after that, the Train entered the platform of the No.1 track.

2.3.2.7. The image records in Aoto station

The monitor cameras had been equipped in Aoto station, and status of the platforms was recorded in the image data.

The situations of the Train entering and stopping before the stop sign in the track No.1 of Aoto station were recorded in the records of the monitor cameras at the time of the occurrence of this accident.

2.4. Information on Vehicles

2.4.1. Outline of Vehicles

The vehicles of the Train have been leased from the Company to Hokuso Railway, and have been belonged to Hokuso Railway.

Vehicle category	The 7800 type DC electric railcar, DC 1,500 V
Number of vehicles in the trainset	8 vehicles
Capacity of the trainset	1,068 persons
Distance between bogie centers	12,000 mm
Distance between coupler heads	18,000 mm
Tare of the Vehicle	34 t[*5]
Completion of the Vehicle	February, 1995
Type of the Bogie	FS547 type
Vehicle body suspension device	Direct mounted type, vehicle body directly connected with air springs
Axle box suspension device	Leaf spring type[*6]
Wheel base	2,100 mm
Wheel tread profile	Conical profile
Wheel flange angle[*7]	69.3°
Manufactured date of the Bogie	December, 1990

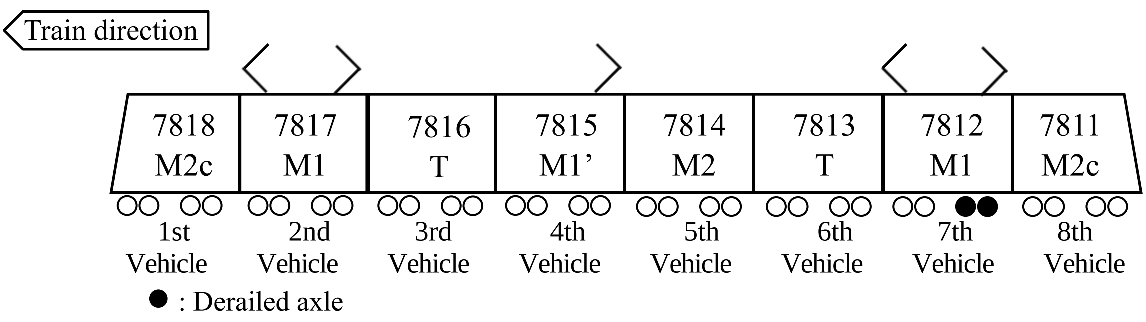


Figure 1. Composition of the Train

*5 *[Unit conversion] 1 t = 1,000 kg-weight, 1 kg-weight = 1 kg-force, 1 kg-force = 9.8 N*

*6 *"Leaf spring type" is the type to connect the bogie frame and the axle box via the rubber isolator by installed the leaf spring only in the bogie center side of the axle box.*

*7 *"Wheel flange angle" is the maximum angle between the wheel flange surface and the center axis of wheel axle. Generally, the larger the flange angle, the harder to derail.*

2.4.2. Information on the Maintenance of Vehicles

The inspection of the Vehicle has been prescribed in the implementing standards of vehicle maintenance which is one of the Reported Implementing Standards of the Hokuso Railway. There were the train inspection[*8], the general inspection[*9], the critical parts inspection[*10], the monthly inspection[*11], etc., in the inspections of vehicles and the inspection has been conducted based on the period, *i.e.*, inspection cycle, or the running distance of the vehicles, prescribed for each inspection, as indicated in the following regulations. The train inspection and the monthly inspection of the Train have been conducted by the Hokuso Railway, and the general inspection and the critical parts inspection of the Train were conducted by the Company entrusted from the Hokuso Railway.

[Inspection of the train]

Article 10. Inspection shall be conducted in on-condition status on the consumables and the functions of the critical parts, in the extent not exceeded 10 days, responding to the used status of the vehicles.

[Category of the periodic inspection]

Article 11. Category of the periodic inspection of the vehicles shall be as listed in the followings

(1) Inspection on the status and the functions, hereinafter referred to as "the monthly inspection".

(2) Critical parts inspection

(3) General inspection

[Monthly inspection]

Article 12. Periodic inspection shall be conducted in on-condition status on the status and the functions of the electric railcars, in every period not exceeded three months, responding to the used status of the vehicles.

[Critical parts inspection]

Article 13. Periodic inspection shall be conducted for the critical parts such as the power generation device, the running gear, the brake gear, etc., in every shorter period of four years or the period that the running distance of the vehicle did not exceed 600,000 km, responding to the used status of the vehicles.

[General inspection]

Article 14. Periodic inspection shall be conducted for the entire electric railcars, such as the power generation device, the running gear, the brake gear, the vehicle body, the other devices equipped with the vehicle, etc., in every period not exceeded eight years, responding to the used status of the vehicles.

It is prescribed to conduct the inspection on the sizes of the wheel diameter, height of wheel flange, thickness of wheel flange and check gauge for the wheel axles, in addition to the visual inspection in the monthly inspection, for the bogies. The limit values and the standard values for each inspection item were as shown in Table 3.

Table 3 Limit values and standard values on the wheel axle

Inspection item	Limit value or standard value
Thickness of tire	Solid rolled wheel, 25 mm or above
Difference of wheel diameters	Wheels in the same wheel axle : 1 mm (1 mm) Wheels in the same bogie : 6 mm (10 mm) Wheels in the same vehicle : 11 mm (20 mm) Numbers in ( ) are for the trailing bogie
Flange thickness	Standard value : 31 mm. Limit value : 26 mm
Flange height	Standard value : 27 mm. Limit value : 30 mm
Flange angle	Standard value : 69.3°. Limit value : 73°
Check gauge	Standard value : 1,360 mm. Limit value : 1,359 to 1,361 mm

Concerning to the bogie frames, it is prescribed to conduct the visual inspection for the portions indicated by the circled number, and to conduct the magnetic particle inspection[*12] for the portions indicated by the squared number, shown in Figure 2, after removed from the bogie in the critical parts inspection and the general inspection. The area surrounded by the dotted line in Figure 2, was the place where added to conduct magnetic particle inspection for the entire side beam in addition to the portions indicated by the squared number, referring the past incidents of crack generation in the other company[*13]. Furthermore, the conducted status of magnetic particle test was checked after the occurrence of this accident, and found that it had been conducted for the circumference of the entire side beam.

*8 *"Train inspection" is prescribed as to conduct inspection in on-condition status for the major parts of the vehicle in every period not exceed 10 days, in the Company and the Hokuso Railway.*

*9 *"General inspection" is prescribed as to conduct periodic inspection for the entire vehicle, in every period not exceed eight years, in the Company and the Hokuso Railway.*

*10 *"Critical parts inspection" is prescribed as to conduct periodic inspection for the major parts, such as power generating device, running gear, brake gear, etc., in every shorter period of four years or the period not exceed 600,000 km of the running distance of the vehicle, in the Company and the Hokuso Railway.*

*11 *"Monthly inspection" is prescribed as to conduct periodic inspection in on-condition status, on the status and function of the vehicle, in every period not exceed three months.*

*12 *"Magnetic particle inspection" is the nondestructive test to detect flaws in the surface and in the neighborhood of surface by visualizing flaws by the leakage magnetic field. The proper test materials including magnetic powders were used.*

*13 *"Past incidents of crack generation in the other company" is the train derailment accident in the premises of Naka-Itabashi station, Tojo Main Line of Tobu Railway Company, occurred on May 18, 2016.*

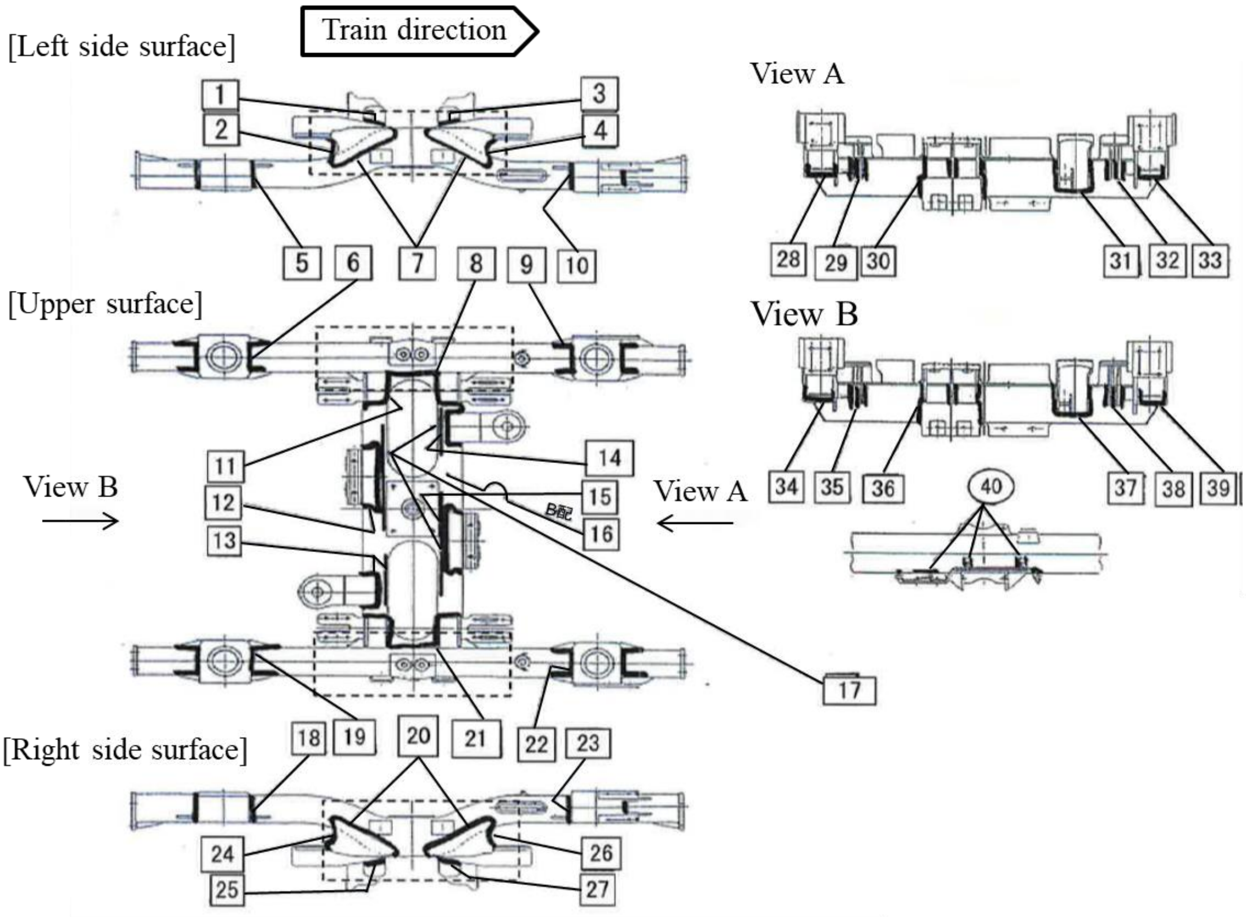


Figure 2. Places for the flaw detecting inspection in the bogie frame

Concerning to the static wheel load of left and right wheels, it is prescribed to manage as that the ratio of wheel load unbalance*14 is within 10% by conducted the measurement in the critical parts inspection and the general inspection.

*14 *"Ratio of wheel load unbalance" is the value that the wheel load, i.e., the static wheel load, of one side wheel is divided by the average wheel load of the wheel axle for an axle. The managing value is expressed by the absolute value, in the unit of %, of the difference with 100 %.*

2.4.3. Information on the Vehicle

2.4.3.1. Information on the inspection, etc., of the vehicle

The status of the inspection, etc., of the Vehicle conducted just before the occurrence of this accident were as shown in Table 4, and no abnormality was found in the records of these inspections. The running distance from the general inspection in December 1, 2016, to the occurrence of this accident was about 490,000 km.

Table 4. Inspection records, etc., of the Train

General inspection	December 1, 2016
Critical parts inspection	February 26, 2014
Monthly inspection	April 7, 2020
Train inspection	June 8, 2020

2.4.3.2. Status of the wheel axle

The wheel turning of the wheel axles in the Vehicle had been implemented on November 7, 2019. The results of the inspection for the wheel axles in the monthly inspection were as shown in Table 5, and tire thickness, flange height, flange thickness and check gauge were all within the limit values or the standard values shown in Table 3, and there was no abnormality.

Table 5. Inspected results of wheel axles of the Vehicle in the latest monthly inspection conducted before the occurrence of this accident [Unit : mm]

	Front bogie				Rear bogie, *i.e.*, the Bogie			
Wheel axle	Front axle		Rear axle		Front axle		Rear axle	
Axle position	Right	Left	Right	Left	Right	Left	Right	Left
Tire thickness	29.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0
Flange thickness	31.0	31.0	31.0	31.0	31.0	31.0	31.0	31.0
Flange height	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0
Check gauge	1359.0		1359.0		1359.1		1359.0	

Furthermore, the wheel tread profiles of the Vehicle were checked after this accident, but there was no large difference with the designed profile.

2.4.3.3. Status of the ratio of wheel load unbalance

The ratio of wheel load unbalance estimated from the measured values of the static wheel load of the Vehicle in the latest general inspection implemented before the occurrence of this accident, were within 10 %, as shown in Table 6, and there was no problem in these results.

Table 6. Ratio of wheel load unbalance at the time of the general inspection

Bogie	Wheel axle	Ratio of wheel load unbalance
Front bogie	Front axle	3 %
	Rear axle	5 %
Rear bogie, *i.e.*, the Bogie	Front axle	6 %
	Rear axle	1 %

2.4.3.4. Status of the vehicle body and the bogie

According to the measured results in the latest general inspection conducted just before the occurrence of this accident, the sizes of the assembled bogie of the Vehicle were within the managing values and there was no abnormality in the results of the monthly inspection.

In addition, the Bogie was checked after this accident, and found that there was the crack in around the through hole for the brake lever in right side beam of the bogie frame, *hereinafter referred to as "the Crack", and "the Side Beam", respectively.* In addition, the leaf spring in lower part of the Side Beam had been broken, *hereinafter referred to as "the Leaf Spring Breakage"*, other than the Crack but there was no abnormality in the other vehicle body suspension device such as the axle box suspension device, the air spring height control device, etc. *[Attached Figures 5, 6]*

2.4.3.5. Information on the side beam of the Bogie

The bogie frame in the bogie is composed of two side beams, *i.e.*, left and right side beams, which maintain the span of the front and the rear wheels and suspend the vehicle weight mainly, and the cross beams connecting these side beams.

The side beam is made by faced, welded and assembled in the square shape beam, the outer side of the bogie frame, named as "the outer beam", and the inner side beam of the bogie frame, named as "the inner beam", which are made of the steel material, *i.e.*, SM400B of the nominal plate thickness 12 mm, and press formed into U-shape. The cross section of the side beam in the direction of sleepers at the place of the Crack, are 170 mm high in vertical direction and 180 mm wide in the direction of sleepers. It was said that, although the allowance of thickness of the plate after press formed in the manufacturing process was unknown, the thinner limit value for the steel plate after press formed, at present, was 9.6 mm or above, considering the local decrease of plate thickness which is able to occur due to the local extension in the press forming process.

The reinforcing plate, *hereinafter referred to as "the cross rib"*, had been welded in the direction to sleepers in inside of the side beams in order to keep strength and suppress deformation of the side beam. The material of the cross rib was the steel plate SM400B of 6 mm thick.

Total 14 cross ribs had been welded, *i.e.*, seven cross ribs were welded to inner and outer side beams each in the same positions, respectively. The cross ribs were positioned by the jigs and welded mechanically by the machine, *i.e.*, the robot, in the straight portions and welded manually in the edge portions and the curved portions.

The major managing standard of the weld bead[*15] and weld end edge part[*16] of the cross rib welded to the side beam in the company who manufactured the Bogie, *hereinafter referred to as "the Bogie Maker"*, at the time when the Bogie was manufactured and at present were as follows, respectively.

(1) When the Bogie was manufactured

(i) Standard of judgement

Both undercut[*17] and overlap[*18] were prescribed as 0.5 mm or smaller, and the standards has been prescribed on the items for the appearance test of the welded part.

(ii) Inspection method

The welding workers shall inspect visually, and measure discretionary using scales and gap gauge, etc., and write the pointed out comments directly on the actual product using the chalk, etc.

(2) At present

(i) Standard of judgement

Undercut and overlap were prescribed as 0.3 mm or less, and 0.5 mm or less, respectively, and the standards were prescribed on the items of the appearance test of the welded part.

(ii) Inspection method

The person exclusively charged in the inspection shall implement the visual inspection, and measure discretionary using scales and gap gauge, etc., the magnetic particle test, the ultrasonic testing[*19], and the sample of the limit was used as the standard for the place, where it was difficult to evaluate quantitatively, to improve the accuracy of the visual inspection. Furthermore, inspection is implemented using the portable fluorescent light to improve the visibility and the convenience in the inspection works.

[Refer to Attached Figure 6]

*15 *"Weld bead" is the swelled parts created on the surface jointed by welding.*

*16 *"Weld end edge part" is the place where the surfaces of the mother material and the weld bead are crossing.*

*17 *"Undercut" is the groove in the end edge created by the welding work on the mother material or on the already welded part.*

*18 *"Overlap" is the part where the melted material overlapped on the mother material at the end edge without fused together.*

*19 *" "Ultrasonic testing" is the nondestructive test to investigate the inner flaws or the materials of the test piece, utilizing the acoustic characteristics of the test piece when the ultrasonic waves was transmitted in the test piece.*

2.4.3.6. Information on the Crack

The positions in the side beam of the Bogie were defined as that, front right is the Pos. 5, front left is the Pos. 6, rear right is the Pos. 7 and rear left is the Pos. 8, as shown in Figure 3.

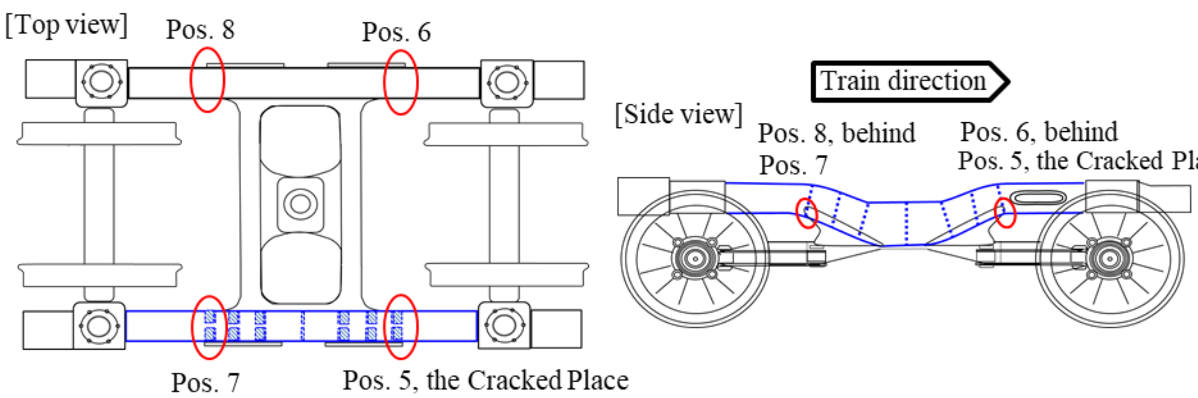


Figure 3. Definition of the positions in the side beam of the Bogie

(1) Information on the place where the Crack had generated

The place where the Crack had generated was in around the place where 2 cross ribs, *hereinafter the cross ribs in the outer and the inner side beams are referred to as "the Outer Rib", and "the Inner Rib", respectively*, were welded, *hereinafter referred to as "the*

Cracked Place", near the through hole for the brake lever in the Side Beam. The size of the Outer Rib and the Inner Rib are 146 mm high in vertical direction and 58 mm wide in the direction of sleepers.

The magnetic particle test was conducted for the places corresponded to the Cracked Place in the Pos. 6, the Pos. 7 and the Pos. 8 of the side beam of the Bogie, but no crack was found.

In addition, after the accident, the Company implemented the magnetic particle test and the visual check for all 1,244 owned bogies, including 128 same type bogies, and the Hokuso Railway conducted the same tests for all 192 bogies, including 128 same type bogies, but no crack was found in the side beams.

The Cracked Place was the place where is the target of the flaw detection described in 2.4.2.

(2) Information on the status of the Crack

The status of the Crack was checked in Sogo Vehicle Depot of the Company after the accident, and it was found that the Crack had been generated in the lower surface and the side surface of the Inner Beam and the Outer Beam.

The both cracks in the bottom of the outer beam and the inner beam had been broken at around the welded part in the front side of the Outer Rib and the Inner Rib, and continued to upper part, about 170 mm, of side surface of the side beam. The size of the opening part of the crack was about 28 mm in the maximum at the opening part in the lower surface of the side beam.

[Refer to Attached Figures 5 to 7]

2.4.3.7. Investigation of the broken surface and the welded part of the Crack

The results of the investigation on the broken surface of the Crack conducted by the Company and the Hokuso Railway, and the strength evaluation for the welded part conducted by entrusted to the Bogie Maker were as follows.

(1) Investigation of the broken surface of the Crack

(i) Based on the results of the macro-observation of the broken surface of the Crack, the beach mark*20, which is considered as the feature of the fatigue crack, was found from the lower surface of the side beam to the height of about 135 mm, and the whole length of the trace of the fatigue crack was about 450 mm, except for the forcibly opened part cut for the investigation and the part of crashed broken surface. The uneven pattern had become larger from lower part to upper part, and broken surface had been crashed from around the curved part from side surface to upper surface of the side beam. Generally, size of unevenness in broken surface was affected by the expanding speed of the crack, and when the expanding speed is high the unevenness becomes large.

Furthermore, the ratchet mark*21 was found in around the weld end edge part in the Outer Rib, and the beach mark had been expanded from around the ratchet mark toward the lower surface of the side beam, and the crack had expanded further toward side surface of the side beam.

(ii) Based on the results of the microscopic observation of the broken surface of the Crack, the elongated dimple pattern, which is the feature of the ductile fracture, was found in a part of upper surface side of the side beam. There was no characteristic pattern in other places.

*20 *"Beach mark" is the trace that the fatigue crack had expanded.*

*21 *"Ratchet mark" is the bump generated in the neighborhood of start point of the fatigue crack.*

(2) Strength evaluation for the welded part of the Cracked Place

(i) In order to implement the strength evaluation of the welded part where the Crack had generated, *hereinafter referred to as "the Welded Part"*, the static loading test was conducted using the FS513 type bogie, which the structure of side beam is the same as the Bogie, *i.e.*, the FS547 type.

In this static loading test, the direct measurement of the stress in the weld end edge corresponded to the Welded Part and surroundings was tried in the Pos. 5 of side beam of the FS513 type bogie, but the machining to measure the accurate stress could not be implemented because there was the through hole for the brake lever near the measuring place. Therefore, the Pos. 8 of side beam without the through hole for the brake lever was set as the measuring place where corresponded to the Welded Part, *hereinafter referred to as "the welded part stress measuring place"*, and measured the stress directly at the weld end edge and surroundings using the 5 mm long strain gauge. As described later in 2.8.1.2, it had been confirmed by the finite element method analysis, *hereinafter referred to as "the FEM analysis*[*22]*"*, that the maximum stresses in the Welded Part and the welded part stress measuring place were in the same level. The test load was applied up to the load corresponded to the designed full load in the Company, *i.e.*, 234.2 kN when loaded with 250% of the capacity, in the vertical direction which affect at most to the strength of the Welded Part.

The stress at the lower part of the side beam in the weld end edge part and surroundings, *i.e.*, the representing point, in the conditions in the designed empty loaded, loaded by 150% of the capacity, loaded by 250% of the capacity, were shown in Table 7. Furthermore, the critical stress chart was shown in Figure 4, by assumed the value measured at the weld end edge part as the average stress, and assumed the 0.3 times of the average stress as the fluctuating stress.

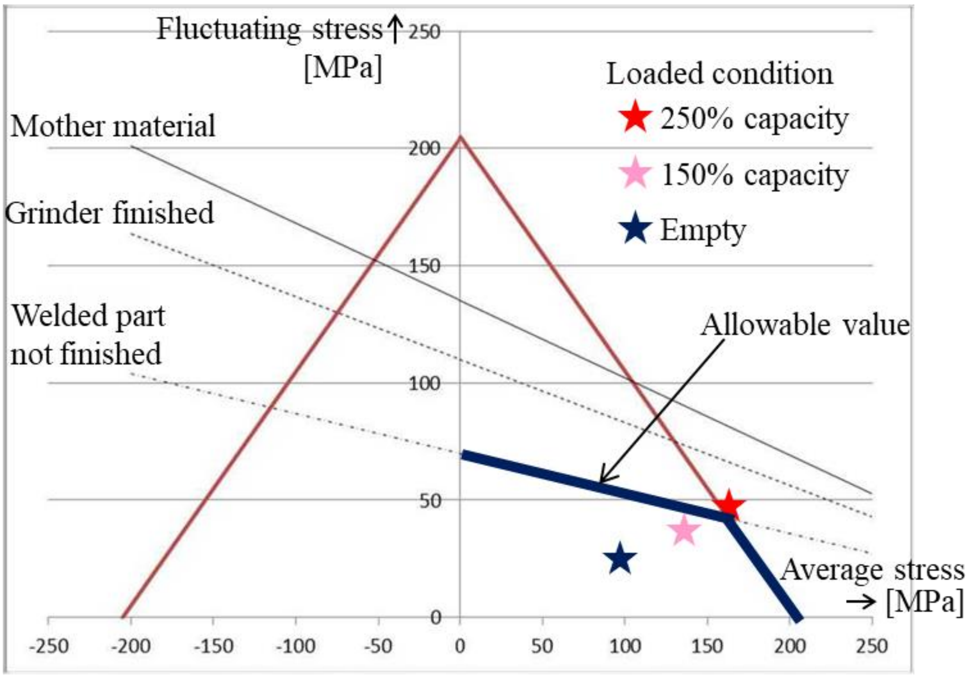
The result of the static load test in the 250% capacity loaded condition showed that the stress exceeded the allowable value in the critical stress chart. Furthermore, the stress measured at the weld end edge part in the welded part stress measuring place was about 2.4 times of the stress measured in the lower part of the side beam in the vicinity of the welded part stress measuring place, regardless of the loaded conditions.

*22 *"FEM" is the abbreviation of the Finite Element Method, which is the numerical analysis* *method to divide the structure body, etc., into the simple shape small elements, and analyze the equations for each element and estimate the strain and the stress, etc., generated in the place of each element.*

Table 7. Results of the static load test of the FS513 type bogie

Measured place, representative point, etc.	Measured stress, etc.		
	Tare (142.5 kN)	150% capacity (197.6 kN)	250% capacity (234.2 kN)
Weld end edge part	95.8 [MPa]	136.9 [MPa]	165.2 [MPa]
Lower surface of side beam	40.8 [MPa]	57.9 [MPa]	70.1 [MPa]
Ratio of stress	2.3	2.4	2.4

Ratio of stress was the number estimated as the stress at weld end edge part divided by the stress in the lower surface of side beam.



"Mother material" in this context is the part without welded.

"Grinder finished" is the status of the welded part implemented surface finishing.

"Welded part not finished" is the status as being welded without surface finishing.

Figure 4. Critical stress chart for the vertically loaded condition in the welded part stress measuring place in the FS513 type bogie

(ii) To evaluate the life of the Welded Part, the running test in the main line using the train of the same type as the Train was conducted. The running test was conducted by a round trip started from Sogosando, to Narita Airport, Oshiage, Narita Airport, and back to Sogosando. This test was conducted by loading the water tanks to simulate the loaded status by about 100% capacity load, in the 7th vehicle same as in the Vehicle, and measured the stress by attached the strain gauges to the mother material in the lower part of the side beam in the neighborhood of the place corresponded to the Cracked Place.

The estimated life of the Welded Part, obtained by calculated the stress frequency in every 0 MPa to 4 MPa by the Rainflow algorithm[*23] using the stresses obtained from the running test, and compared the result with the judging curve of the critical fatigue diagram, was the running distance of 22,000,000 km or above.

*23 *"Rainflow algorithm" is one of the calculating methods for the stress frequency or the strain frequency in order to predict the fatigue life in the machines or the structures that suffered from irregularly repeated fluctuating loads.*

(3) Investigation on the welded status in the Welded Part, etc.

(i) Welded status of the Welded Part

The investigation on the cross section of the Welded Part was implemented picking the test piece by cut precisely the welded parts of the side beam and the inner reinforcing plate in lower surface side of the side beam in the neighborhood of the supposed start point of the crack, after faced each other the broken surfaces of the Crack of the Outer Rib, as shown in Figure 5.

The microscopic dents considered as already been existed from the time when implemented the welding works on the welded surface, were found in the weld end edge part of the Welded Part, but the incompletely welded part[*24] such as the overlap, etc., was not found in the weld end edge part. In addition, the incompletely welded part such as the porosity[*25], etc., was found in the Welded Part, but no trace of crack was not found in all incompletely welded parts.

Furthermore, as shown in Figure 6, the shape of the weld bead in the weld end edge part of the Welded Part was convex compared to the shape of the weld bead in the same part of the Pos. 6, the Pos. 7 and the Pos. 8, and the angle of excess welding was in the stratus as large.

*24 *"Incompletely welded part" is the deviation from the ideally welded part.*

*25 *"Porosity" is the hollow generated by involving gases.*

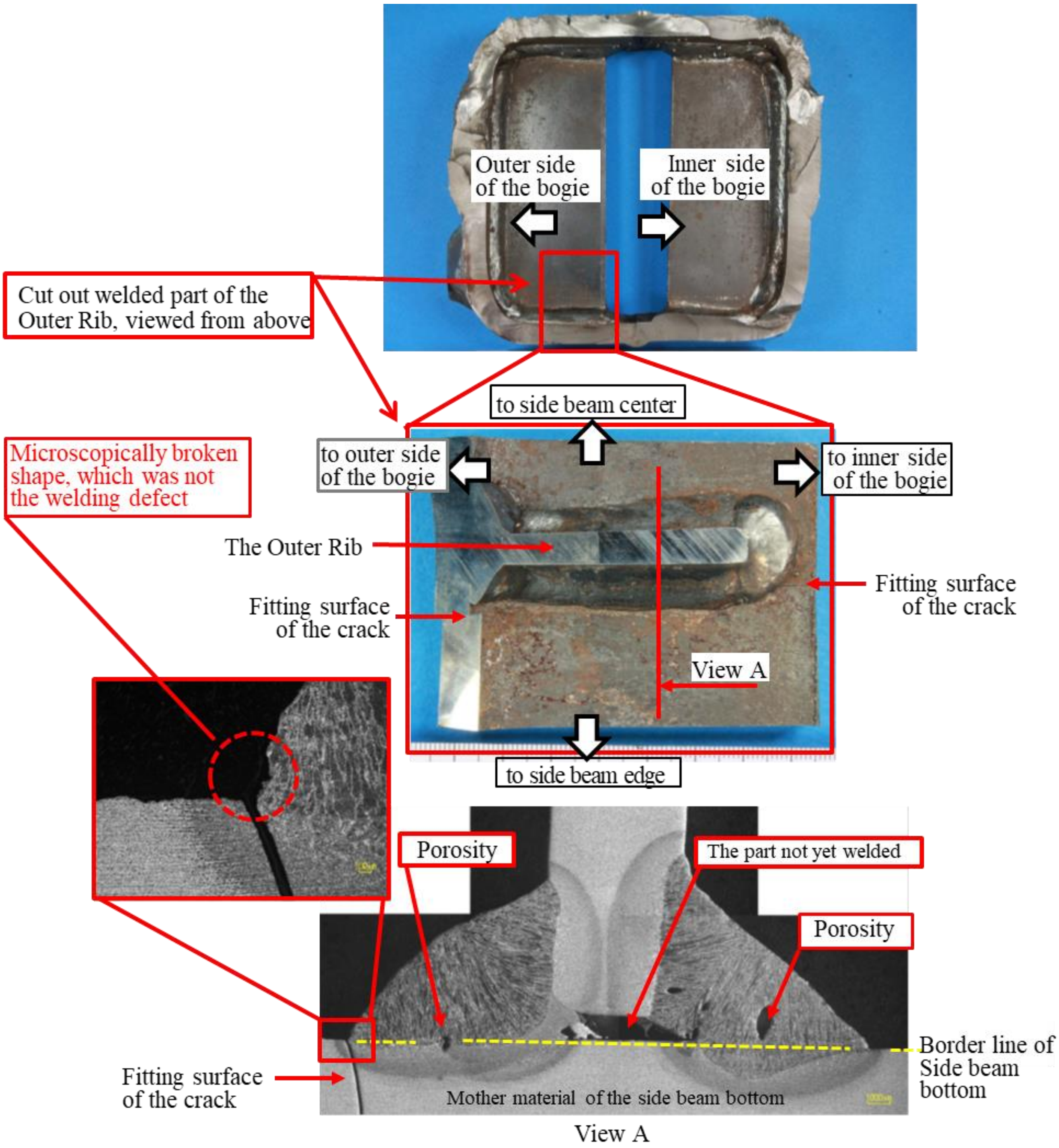


Figure 5. Observed results of cross section of the Welded Part

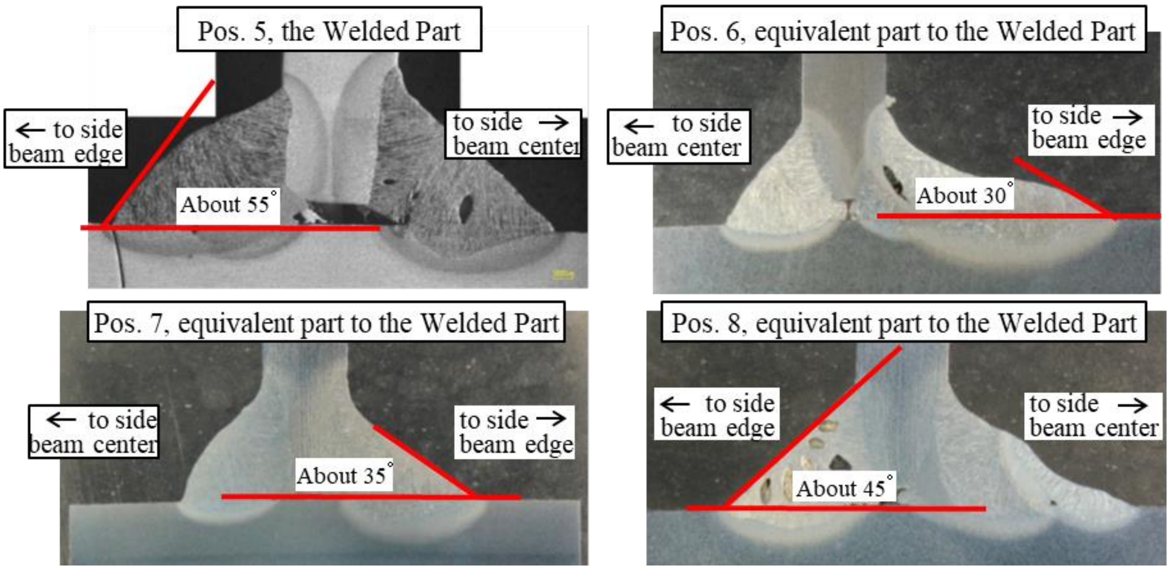


Figure 6. Comparison of welded shape of the started part of the Crack and the other equivalent parts.

(ii) Welded status of the Bogie

The flaw echo[*26] was found in the Pos. 6 of the Bogie in the results of the previous ultrasonic testing conducted for the place corresponded to the Cracked Place in the Pos. 6, Pos. 7 and Pos. 8 of the side beam of the Bogie. Therefore, the investigation was implemented on the welded status at the place considered as the reflecting source of the flaw echo in the Pos. 6, and on the equivalent places confirmed in the Welded Part for the Pos. 7 and the Pos. 8.

The spatter[*27] were found here and there in the Pos. 6 in the appearance test of the welded part of the side beam and the cross rib in the Pos. 6, the Pos. 7 and the Pos. 8 of the Bogie. Furthermore, it was confirmed that there was the place that the weld bead existed in over double layers or more in the Pos. 6 and the Pos. 8.

Plural incompletely welded parts were found in the investigation of cross section of the place corresponded to the Cracked Place in the Pos. 6, Pos. 7 and Pos. 8 of the side beam of the Bogie. Furthermore, it was found that there was the part not yet welded where considered as the reflecting source of the flaw echo in the inner side beam of the Pos. 6.

Although the incompletely welded parts such as the overlap, the blowhole[*28], etc., were found in each welded part, the cracked trace was not found in these incompletely welded parts.

[Refer to Attached Figure 7]

*26 *"Flaw echo" is the echo from the disconnected part or the flaw.*

*27 *"Spatter" is the metal particles scattered and adhered during welding works, in the arc welding, the gas welding, the brazing, etc.*

*28 *"Blowhole" is the spherical hollow generated in the welding metal.*

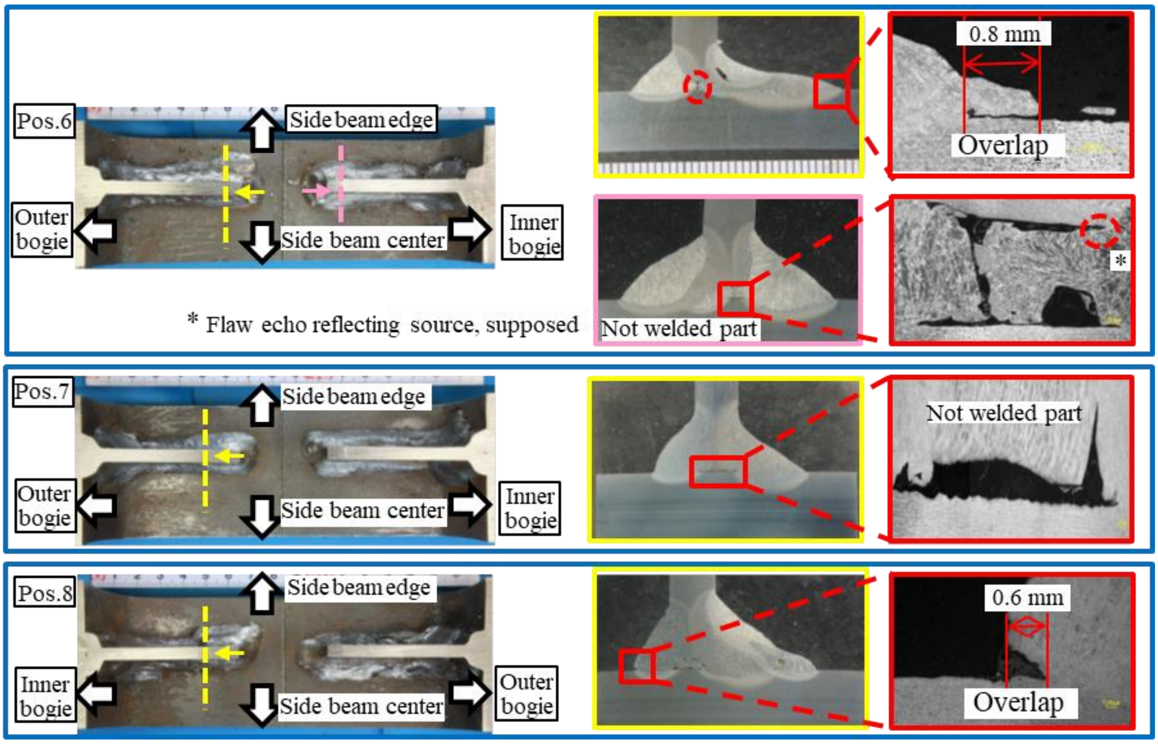


Figure 7. Representative figures of the investigated cross section of the welded parts in the Pos. 6 to the Pos. 8 of the Bogie.

(4) Investigation on the other items related to the crack

(i) The EDX analysis*29 of the broken surface of the Crack was implemented, as the result, there was no element considered as particular problem. Furthermore, the measurement of the hardness of the mother material in the neighborhood of the Crack was implemented, but the lack of the hardness was not found.

(ii) The plate thickness of the lower part of the side beam was checked in the neighborhood of the Crack and the places corresponded to the Cracked Place in the Pos. 6, the Pos. 7 and the Pos. 8 in the side beam of the Bogie, and it was found that the average thickness was 11.29 mm in the neighborhood of the Crack and from 11.11 mm to 11.24 mm in the Pos. 6 to the Pos. 8, against the nominal plate thickness 12 mm.

(iii) As shown in Figure 8, which shows the status of broken surface of the Leaf Spring Breakage, the radial pattern was found from the broken surface in upper part of leaf spring was observed by the macro-observation, and only the dimple like pattern, which is the feature of the ductile fracture, was found by the micro-observation

[Refer to Attached Figures 5, 7]

*29 *"EDX analysis" is the abbreviation of the Energy Dispersive X-ray spectrometry, used to detect the alien substance and identify the composing elements in the surface of materials.*

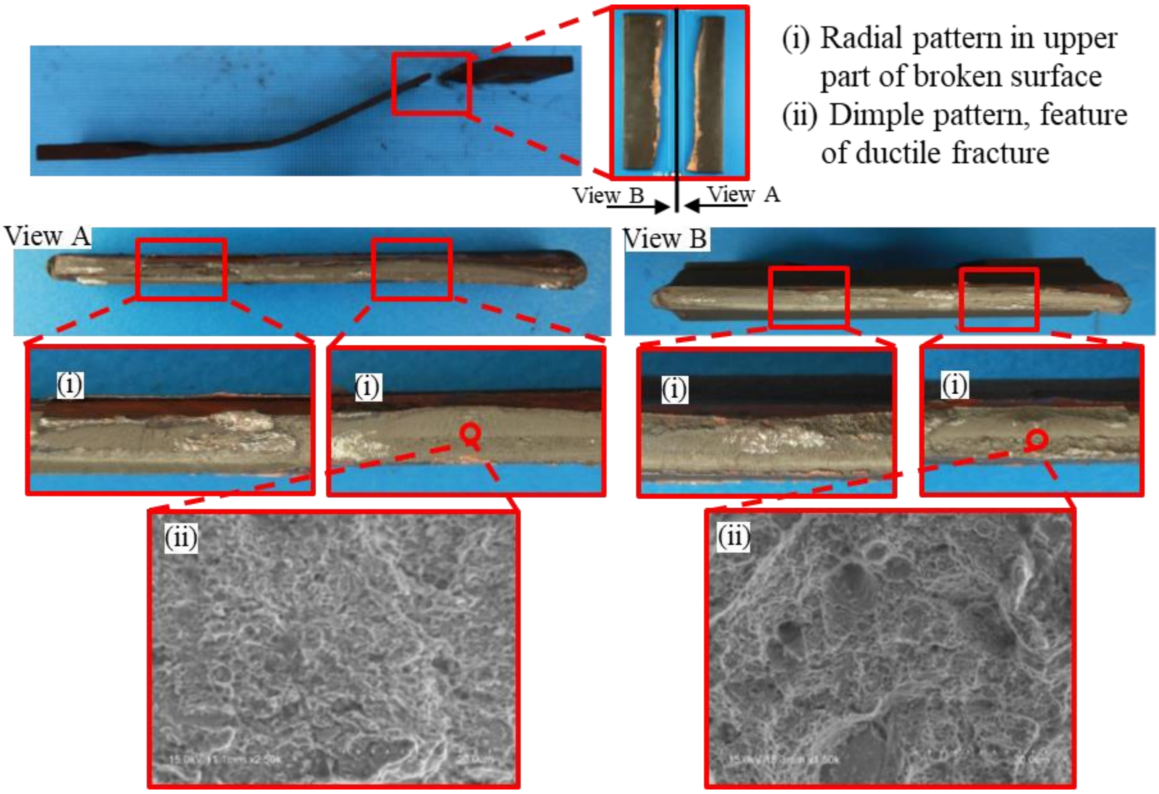


Figure 8. Status of the broken surface of the Leaf Spring Breakage

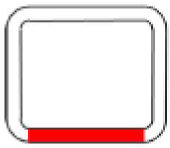
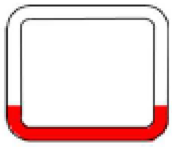
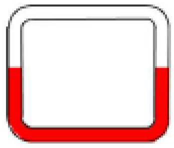
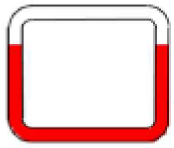
2.4.3.8. Relation between the crack in the side beam and the wheel load, etc.

In order to investigate the relation between the crack in the side beam and the wheel load, the Company and the Bogie Maker conducted the test, *hereinafter referred to as "the stationary test"*, to apply the loads from no load to the passenger capacity load for the bogie, which has the side beam of the same structure as the Bogie and processed the simulated crack, as shown in Table 8, in the same place as the Crack in the Pos. 5 of side beam of the bogie, *hereinafter referred to as "the test bogie"*.

Based on the test results for the maximum simulated crack, 180 mm wide and 134 mm high, in the stationary test 4, the estimated results of the reduced ratio of wheel load[*30] was as shown in Figure 9, and the wheel load at the Pos. 5 and the Pos. 8 were decreased. The ratio of wheel load unbalance in the front axle of the bogie in the empty loaded condition was in the level of 50 %.

*30 *"Reduced ratio of wheel load" is the value estimated as the static wheel load subtracted by the measured wheel load and divided by the static wheel load. The absolute value of the reduced ratio of wheel load obtained by the above stationary test corresponds to the managing value of the ratio of wheel load unbalance.*

Table 8. Condition of the simulated crack in the stationary test

	Stationary test 1	Stationary test 2	Stationary test 3	Stationary test 4
Rough drawing of the simulated crack				
Width of the simulated crack	About 150 mm	180 mm	180 mm	180 mm
Height of the simulated crack from the side beam bottom	0 mm	35 m	100 mm	134 mm

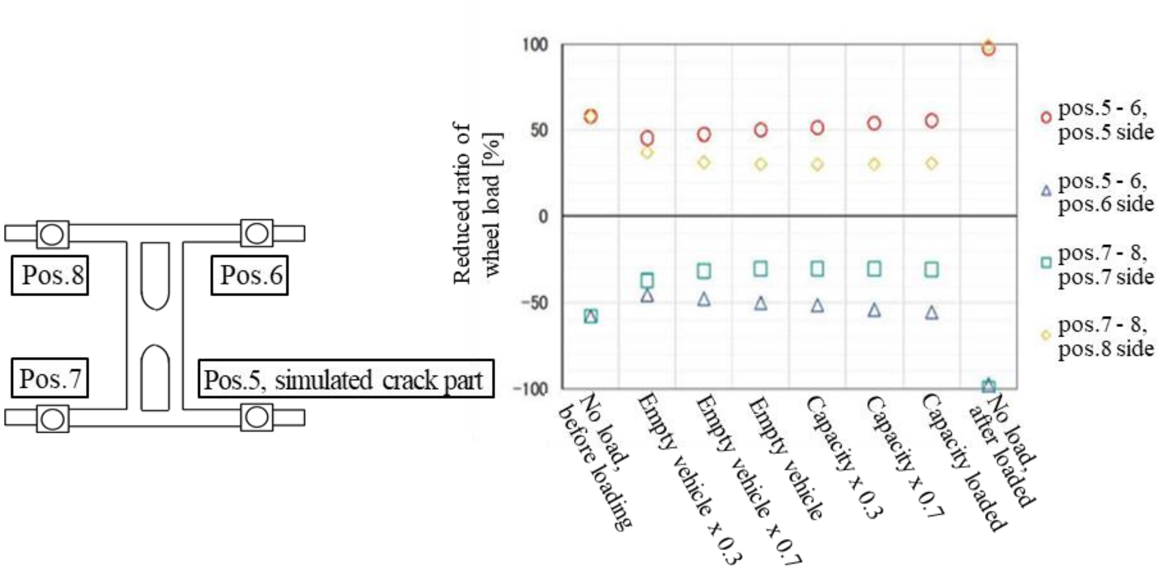


Figure 9. Measured results of ratio of wheel load unbalance for the maximum crack length of the test bogie

The opening width of the simulated crack in the lower surface of side beam for each stationary test in the empty loaded condition was that the opening width did not change when the width and the height of the simulated crack was about 150 mm and 0 mm, respectively, and became wider as the height of the simulated crack became higher, and the opening width was 6.85 mm in the stationary test 4, as shown in Table 9.

Table 9. Opening width of the simulated crack against the simulated crack length in the empty loaded condition

Test No.	Opening width of simulated crack	Remarks
Stationary test 1	0.08 mm	No change in opening width
Stationary test 2	0.32 mm	
Stationary test 3	3.53 mm	
Stationary test 4	6.85 mm	

2.4.3.9. Safety factor of flange climbing

The safety factor of flange climbing[*31] of the Vehicle in the Curve was calculated for the ratio of wheel load unbalance 10% which is the usual managing standard, and 50% which was calculated from the stationary test for the maximum simulated crack of 180 mm wide and 134 mm high, described in 2.4.3.8, the results were as follows.

The safety factor of flange climbing for the ratio of wheel load unbalance 50% was lower than 1.0, which meant no margin against the flange climbing.

(i) When the ratio of wheel load unbalance is 10%, safety factor of flange climbing was 2.45.

(ii) When the ratio of wheel load unbalance is 50%, safety factor of flange climbing was 0.81.

*31 *"Safety factor of flange climbing" is the evaluating index on the margin against the flange climb derailment while running in the steep curve in the slow speed. When it is 1.0 or above, it is considered that a certain level margin against derailment has been secured.*

2.4.3.10. Information on the used history, etc., of the Bogie

According to the Company, the used history of the Bogie was as shown in Table 10, and the total running distance was about 5,103,665 km.

It was said that the passenger load factor could not be estimated because the data for each trainset had not been recorded, but the maximum congestion factor in the commercial line of the Company has been changing almost between 150 % and 160 %, in the past 10 years.

It was said that the history of remodeling of the Bogie was that the remodeling works of the reinforcing rib to improve strength was conducted, because the crack had been found in the reinforcing rib in the axle spring support in the same type bogie as the Bogie in August 2005. However, the place of the above remodeling work was different from the place of the Crack.

Table 10. List of used history of the Bogie

Period	User	Vehicle number	Commercial line section	Commercial maximum velocity	Running distance [km]	Remarks
March, 1991 - June 2008	Keisei Electric Railway Co., Ltd.	3712	Keisei Main Line, Oshiage Line, Higashi Narita Line, Hokuso Line, Asakusa Line, Keikyu Line, Shibayama Railway Line[#1]	110 km/h	3,124,592.4	
August, 2008 - July, 2010		3742			385,840.6 [#2]	Replaced bogies accompanied to repair bogie frame
July, 2010 - March 2015			Keisei Main Line, Narita Airport Line, Oshiage Line, Higashi Narita Line, Hokuso Line, Asakusa Line, Keikyu Line, Shibayama Railway Line	120 km/h	848,333.0 [#2]	Accompanied to open business of Narita Airport Line, on July 17, 2010

March, 2015 - June, 2020	Hokuso Railway Co., Ltd.	7812	Hokuso Line, Oshiage Line, Asakusa Line, Keikyu Line	110 km/h	744,889.5	Started to lease vehicles to Hokuso Railway Co. Ltd.

#1 Shibayama Railway Line started commercial operation in October 2002

#2 Running distance was estimated from end of July, 2010, based on the specification of the vehicle management system.

2.5. Information on the Damaged Status, etc., of the Railway Facilities and the Vehicles

2.5.1. Status of the Damages and Traces of the Railway Facilities

The major damages of the railway facilities were as follows.

2.5.1.1. Railway tracks related

The status of the major damages and traces related to the railway track, from the end edge toward Keisei Takasago station of the Curve to the place where the Bogie had stopped, were as follows.

(1) There were the traces considered as caused by being contacted with the wheels on the side surface of the guard angle in the Curve, from around 11,750 m to around 11,670 m.

(2) There were the traces considered as caused by the running of wheel flanges on the top surface of right rail in the same section in the Curve described in the previous paragraph (1). There was the single trace in around 11,750 m, and there was the second trace as moved in the direction to Aoto station, these two traces joined into single trace as moved further in the direction to Aoto station, and the trace had been continued till to around 11,670 m.

(3) There were the traces considered as caused by the running wheel flanges, on the left rail and on the PC sleepers and the synthetic sleepers in right side of the right rail, from the end edge in the direction to Aoto station of the guard angle in the Curve to the place where the Bogie had stopped.

(4) There were the damages considered as caused by the running wheel flanges in the front rod[*32], etc., in the 22B turnout in the Turnout.

(5) There were the damages considered as caused by the running wheel flanges in the tongue rail[*33], the stock rail, etc., in the 23A turnout in the Turnout.

*32 *"Front rod" is the device attached so as to connect left and right tongue rails in order to transmit the status of the tip of tongue rails to the pointing machine in the turnout.*

*33 *" Tongue rail" is the switching rail with the sharp tip, used in the point part.*

2.5.1.2. Electric power facilities related

There were the damages considered as the effects by the came off and the hung pantograph of the Vehicle, in the overhead contact line, the contact line supporting metals, the insulated droppers, the jumper lines, etc., in the overhead contact line installed in above of the Turnout.

2.5.2. Status of Damages and Traces of the Vehicles

The status of the major damages, etc., of the Vehicle were as follows.

(1) The Bogie related

(i) There was the Crack in right side beam.

(ii) There was the damage in the front right leaf spring.

(iii) There were many hit traces in the wheel treads and the tip of flanges, and the scratched traces in the back side surface of the rims, in all wheels.

(iv) The inspection window of the gear box of the front axle had been damaged.

(v) There was the scratched trace in lower part of side surface of the gear box of the rear axle.

(2) Vehicle body related

(i) There were damages of outer board of air conditioning device, damage of the roof board, wound and damage of the gangway footplate, wound and damage of the shank guide of the coupler, scratched trace in the coupler, etc., in the 8th vehicle of the Train.

(ii) There were the breakage and damage of the pantograph attachment and peripherals, the dent of the bogie frame edge and outer end plate, wound and damage of the gangway footplate, wound and damage of the shank guide, damage of the lid of the jumper cable, damage of the piping in the end part, damage of cross beam of the bogie frame, breakage of welded part of the pipe support, etc., in the Vehicle.

[Refer to Attached Figures 3, 4, 5, 8]

2.6. Information on the Train Crews, etc.

The Driver was 51 years old, having the driver's license of the Class A electric railcar issued on June 6, 1996.

The Conductor was 46 years old.

The 723N Train Driver was 31 years old, having the driver's license of the Class A electric railcar issued on April 25, 2018.

The limited driver in car inspection depot was 42 years old, having the driver's license of the Class A electric railcar issued on March 26, 2015.

2.7. Information on the Weather Condition

The weather in around the accident site when this accident had occurred was fine.

2.8. Information on the Design and the Verification after the Accident

2.8.1. Information on the Design

2.8.1.1. Design contents of the Bogie

According to the Company, the information on the design context of the side beam of the Bogie when manufactured, obtained from the Bogie Maker, were as follows.

(1) At the time of 1990, there were two types of press molds for the side beam, and one of them was selected when designed.

(2) Because the strength of the side beam is affected dominantly by the vertical load to the generation of stress compared to the longitudinal and the lateral loads, the necessity to

implement the strength evaluation had been judged by the size of the vertical load, *i.e.*, whether the vertical load is the same level or not compared with the past bogie types using the press mold to be adopted, as shown in Figure 10.

(3) The adopted side beam press mold was the type used in the bogie type for the other company which had started operation in 1967. The strength estimation was implemented as to calculate the stress for the designed maximum vertical load based on the cross section coefficient for the major cross sections (a) to (h) in the side beam as shown in Figure 11, and obtained the result that the maximum stress was 106.3 MPa in the cross section (d). Then it is judged as no problem considering the total amplitude of fatigue limit 108 MPa for the yield stress 216 MPa of the SS41, which was the material used when designed, as the allowable value. The cross section corresponded to the Crack was the cross section (e), and its calculated results of the stress was 82.4 MPa.

Furthermore, the static load test was conducted to evaluate the strength against the stress estimation for the major cross section, and the result was no problem.

The strength design and the evaluation considering the stress concentration for the weld end edge, etc., was not implemented.

(4) This side beam press mold had been u+sed in the other private railways including the Company at the time of 1990, it has been used in the FS513 type bogie for the 3600 type commuter train, which started operation in 1982, of the Company.

(5) The designed maximum vertical load required to the Bogie is the same level as the FS513 type bogie for the other company, and strength of the used materials, SS41 and SM400B, are in the same level, therefore, it was judged that the strength was sufficient.

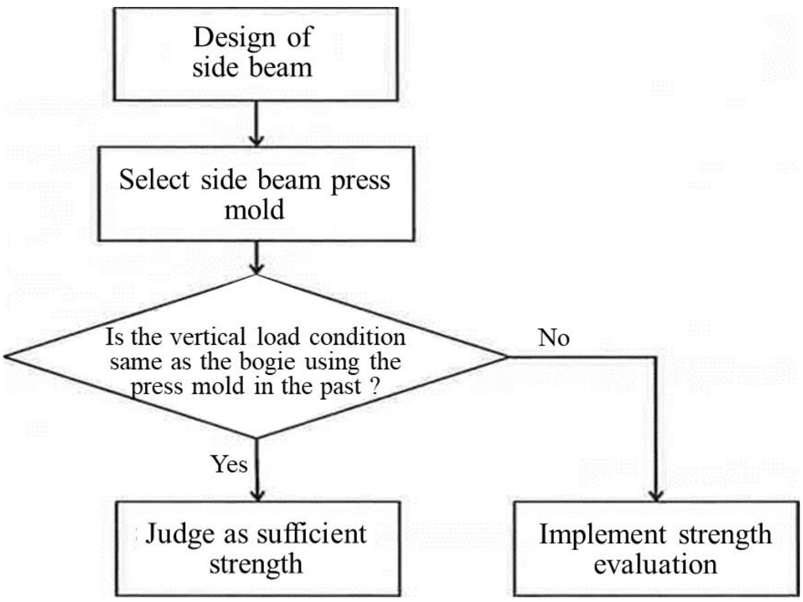


Figure 10. Flow to judge the implementation of strength evaluation of the side beam

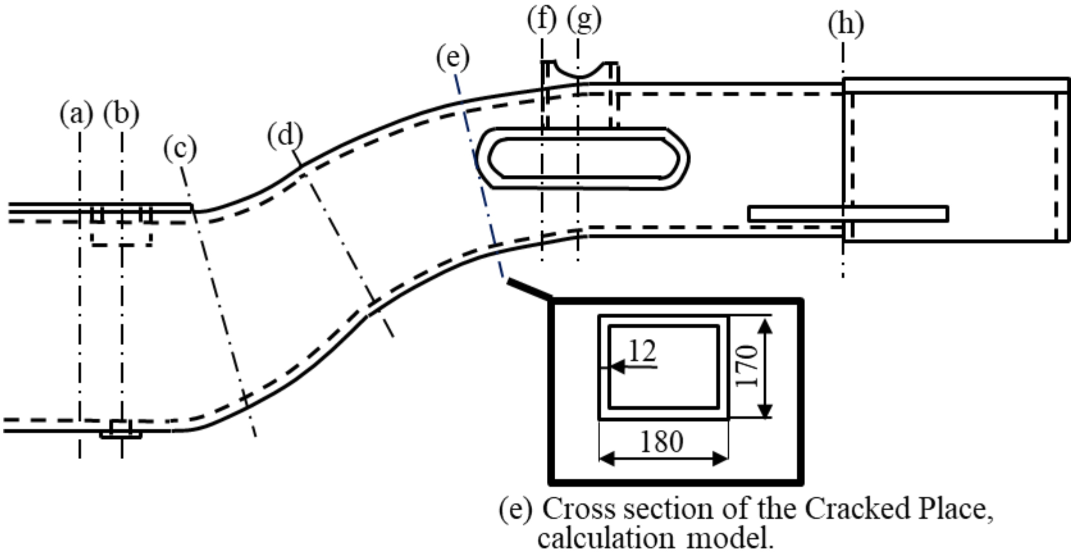


Figure 11. Rough figure of the side beam for the strength calculation, used when designed the Side Beam.

2.8.1.2. Evaluation of the strength design after the occurrence of the accident

In order to implement evaluation of the strength design of the Cracked Place, the FEM analysis was implemented. The side beam model for the FEM analysis was made as to set the excess welding angle as 45°, to divide the welded part of the cross rib by the elements of the isosceles triangles of 13.6 mm side and two 8.3 mm sides each, and to divide the other place by the elements of the equilateral triangle of 16 mm sides each.

As shown in Figure 12, the maximum stresses generated in the Welded Part when the designed maximum vertical load was loaded were 124.7 MPa at the weld end edge, 131.0 MPa at the weld end edge in the welded part stress measuring place in the Pos. 8 in the side beam. Therefore, the stresses considering the vertical vibration against the vertical load were all within the allowable value at the welded part without finishing work in the critical stress chart for the Welded Part and the welded part stress measuring place, and the maximum stresses at the Welded Part and the welded part stress measuring place were in the same level.

Furthermore, the FEM analysis was implemented for the side beam model, which the elements in the weld end edge part is the equilateral triangle of 1 mm sides, in order to confirm precisely the stress distribution generated in the weld end edge part at the Welded Part. As shown in Figure 13, the stress generated in the weld end edge part at the Welded Part was 230 MPa or above, which was the analyzed result as to become to 329 MPa in the extremely local point. The average stress at 5 mm in vertical direction, considered the weld end edge part as the center, was about 160 MPa in the place where the stress became to 329 MPa in extremely local.

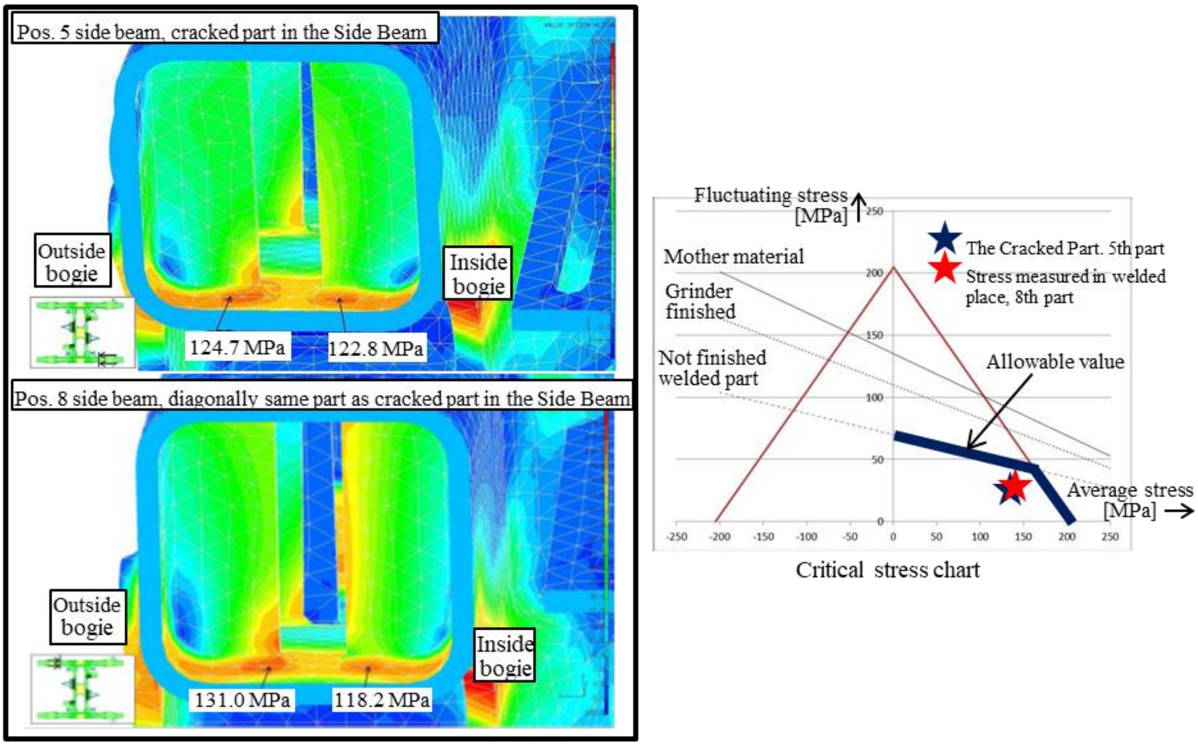


Figure 12. Results of the FEM analysis for the side beam, Pos. 5 and Pos. 8, of the Bogie.

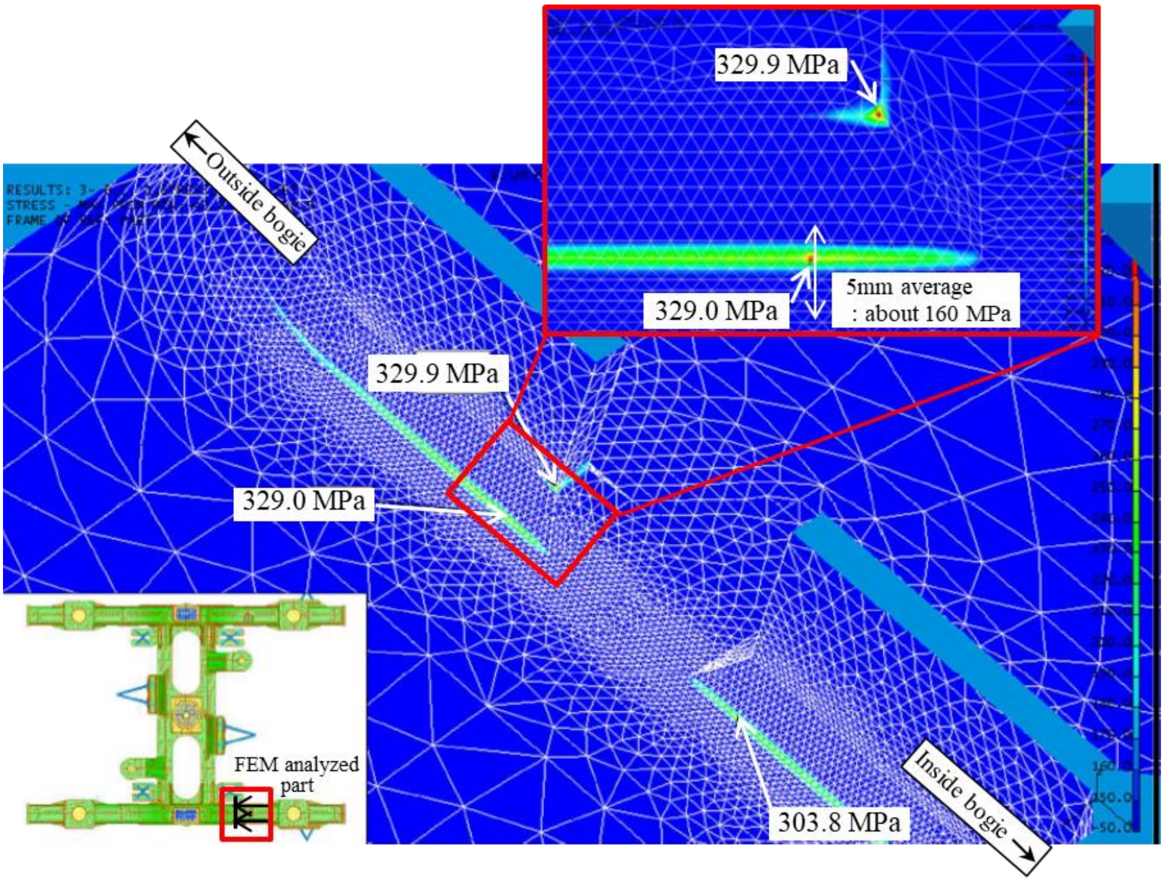


Figure 13. Precise stress distribution in the weld end edge, Pos. 5, of the Welded Part, results of the FEM analysis.

2.8.1.3. Trends of the stress concentration

In order to confirm the trend of the stress concentration in the weld end edge part of the Welded Part, the stress concentration factors[*34] were calculated, referring the equation of the stress concentration factor for the filet welded T joint which suffering the bending load, which was reported in the home page of the Japan Welding Engineering Society. The conditions for the calculation of the shapes of the weld end edge part were set as follows.

(1) The cases that the excess welding angle at the weld end edge part was changed as 45°, 50°, 55°, 60°, and 70°.

(2) The cases that the radius of curvature at the weld end edge part was changed as 0.5 mm, 1.0 mm, 2.0 mm, and 3.0 mm.

The calculated results of the stress concentration factor for the calculating conditions (1) and (2) were shown in Table 11. The calculated results showed that the larger excess welding angle at the weld end edge part, and the smaller radius of curvature cause the trend to increase the stress concentration factor.

*34 *"Stress concentration factor" is the ratio of the maximum stress generated locally and the averaged stress in the cross section.*

Table 11. Stress concentration factor of the filet welded T joint suffering the bending load

		Excess welding angle at weld end edge part				
		45°	50°	55°	60°	70°
Radius of curvature at weld end edge part	0.5 mm	2.86	2.97	3.06	3.15	3.30
	1 mm	2.38	2.46	2.53	2.60	2.70
	2 mm	2.02	2.08	2.14	2.18	2.26
	3 mm	1.86	1.91	1.95	1.99	2.06

2.8.2. Measured Results of the Residual Stress

In order to evaluate the residual stress in the weld end edge part in the Welded Part, the measurement of the residual stress was implemented by making 5 test pieces of the weld joint structure, *i.e.*, the T joint, of the Outer Rib. The measured places and the typical measured results were shown in Figure 14.

The measurement of the residual stress was implemented perpendicular to the weld end edge part, and the measuring points were set for the places in the center and the positions about 25 mm apart each other from the center against the welding length, *i.e.*, Pos. 1A, Pos. 2A and Pos. 3A, and measured every 0.5 mm, from 0.5 mm to 2.0 mm from the weld end edge part, *i.e.*, measuring point a : 0.5 mm, b: 1.0 mm, c : 1.5 mm, and d : 2.0 mm, each.

There was unevenness in the measured results of the residual stress for each test piece, but there was the trend that the tensile residual stress, *i.e.*, the positive stress, became small, at the measuring point a, *i.e.*, close to the weld end edge part, as shown in the typical sample of the measurement shown in Figure 14.

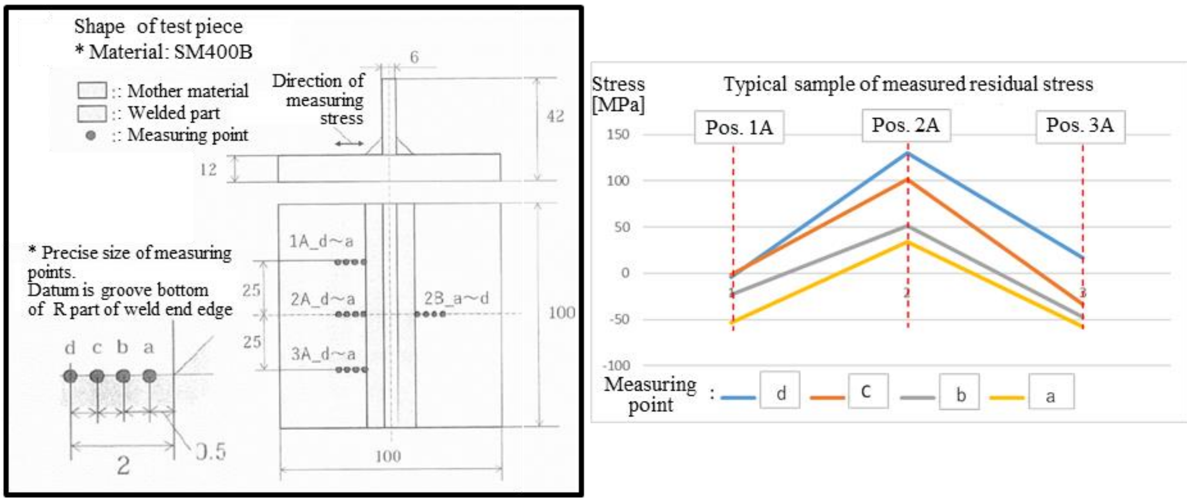


Figure 14. Test piece to measure the residual stress and the typical sample of measured results

3. ANALYSIS

3.1. Analysis on the Derailment

The JTSB concludes the followings.

3.1.1. Operation of the Train

It is probable that the handling operation by the Driver did not affect to the derailment in this accident, because the velocity of the Train at the occurrence of the accident was less than the limit speed, the checked speed, of the C-ATS device, based on the operation records of the C-ATS device, as described in Table 1 in the paragraph 2.1.2.

3.1.2. Track

It is probable that there was no abnormality in the track in around this accident site, because the track irregularities were within the maintenance management values prescribed by the Company in the latest track irregularity inspection conducted before the occurrence of this accident and the measurement conducted after this accident as described in 2.3.2.4, in addition, there was no abnormality in the status of the track materials in the latest periodic inspection and the status after this accident as described in 2.3.2.5. It is probable that the damages described in 2.5.1.1, was caused when the derailed wheel, etc., had contacted.

3.1.3. The Place where the Train Derailed

It is probable that the derailment of the Train started from around the end edge of the guard angle, *i.e.*, around the end of the Curve in the direction to Aoto station, at around 11,670 m, although the derailment had been protected by the guard angle in the Curve, based on the followings.

(1) There were the traces considered as caused by the Train on the sleepers, the rails, the rail fastening devices, etc., in the range from around the end edge in the direction to Aoto

station of the guard angle, around 11,670 m, to the place where the Bogie of the Vehicle had been halted, around 11,570 m, as described in 2.3.1.2.

(2) There were the traces considered as the contacted trace with the wheels on the guard angle in the Curve from around 11,750 m to around 11,670 m, as described in 2.5.1.1 (1), and there were the traces considered as caused by the running wheel flange on the top surface of the rail in the same section, as described in 2.5.1.1 (2).

It is probable that the time when the Train started to derail was about 10:16, and the velocity at that time was about 32 km/h, based on the records of the operating status in the C-ATS device described in Table 1 in 2.1.2.

3.1.4. Status of Climbing Up of the Wheels in the Bogie

It is probable that right wheels in the Bogie had been running as being climbed up right rail as shown in Figure 15, in the section between around 11,750 m and around 11,670 m in the Curve, because derailment has been protected by the guard angle in the Curve, as described in 3.1.3, and the status at this time was that the spacing between the guard angle and left rail was 85 mm, as described in 2.3.2.2 (3).

Additionally, it is likely that right wheel of the front axle climbed up right rail, after that, right wheel of the rear axle climbed up, because single trace was found in around 11,750 m, and the second trace was found as to move in the direction to Aoto station, as described in 2.5.1.1 (2).

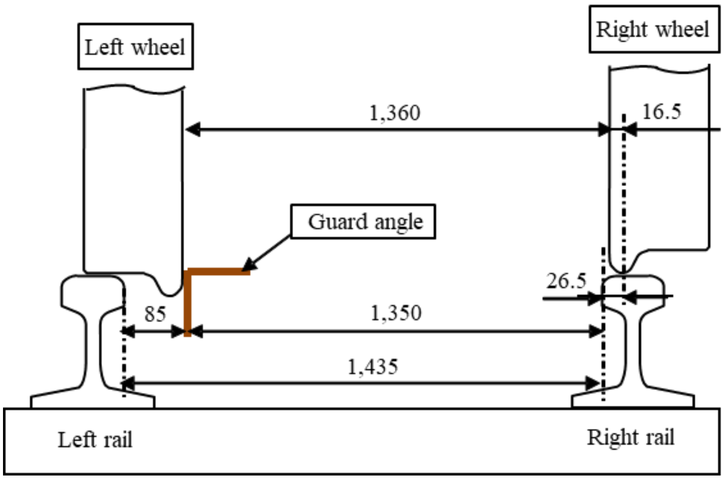


Figure 15. Positional relations between rail and wheel, from around 11,750 m to around 11,670 m.

3.1.5. Factor of Derailment of the Train

As described in 2.4.3.7 (1) (i), there was the beach mark, which is the typical feature of the fatigue crack, till to the height about 135 mm from the lower surface of the side beam, therefore, it is probable that crack due to the fatigue fracture had been expanded up to this height at least by the running just before the derailment, and it is probable that the ratio of wheel load unbalance of the front axle of the Bogie at this time was in the level of 50%, as described later in 3.2.2. When vehicle passed through the Curve in the status as generating unbalance in the wheel loads, the lateral force increased in the status that the wheel load of right wheel in the front axle of the Bogie has been decreased significantly, as indicated by the calculated results for the safety factor of flange climbing with no margin against the flange climb derailment as described in 2.4.3.9. Thus, it is probable that right wheel of the Bogie climbed up rail at around 11,750 m in the Curve, as described in 3.1.4.

Furthermore, it is probable that the derailment started from around the end edge in the direction to Aoto station of the guard angle, at around 11,670 m, as the derailment had been protected by the guide angle while running in the Curve, as described in 3.1.3.

It is probable that the wheel climbed up rail and derailed as the result of the enlarged unbalance of wheel loads caused by the crack generation in the bogie in this accident, therefore, it is expected to prevent occurrence of the accident by finding the abnormality of the bogies in early stage by monitoring the wheel load unbalance. The investigation report on the past railway serious incident[*35] had been proposed to study on the system to notify the abnormality of the bogie to the train crews, etc., by the effective use of the data such as the air spring pressure, etc., as one of the measures to prevent recurrence, therefore, it is expected to implement the similar studies.

*35 *"Past railway serious incident" is the "Vehicle damage, in the premises of Nagoya station of Tokaido Shinkansen, West Japan Railway Company, December 11, 2017".*

3.2. Analysis on the Vehicle

3.2.1. Vehicle body and Bogie of the Vehicle

There was no abnormality in each part of the Vehicle, because the assembled sizes of the vehicle body and the bogie, and the sizes of the wheel axles were within the managing values prescribed in the company's regulation of the Company, in the result of the latest periodic inspection conducted before the occurrence of this accident, as described in 2.4.3.1 to 2.4.3.4.

On the other hand, the Vehicle was checked after this accident, and the Crack and the Leaf Spring Breakage were found in the Bogie, *i.e.*, the rear bogie, as described in 2.4.3.4 and 2.4.3.6.

It is probable that the damages described in 2.5.2, except for the Crack and the Leaf Spring Breakage, were caused when the Vehicle contacted with the rail, etc., after derailed.

3.2.2. The Crack and Ratio of Wheel Load Unbalance of the Bogie

It is probable that the ratio of wheel load unbalance in the status that the crack due to the fatigue fracture had expanded in the Bogie, was in the level of 50%, based on the relations between the Crack and the ratio of wheel load unbalance of the Bogie described in the followings.

(1) It was confirmed that the ratio of wheel load unbalance becomes larger due to the crack in the side beam, as the ratio of wheel load unbalance in the empty loading condition for the maximum simulated crack length of 180 mm wide and 134 mm high, was in the level of 50% which remarkably exceeded the managing value in the Company, 10%, based on the results of the stationary test conducted by processed the simulated crack in the side beam

of the test bogie, as described in 2.4.3.8.

(2) The maximum height of the trace of the fatigue crack, from the lower surface of the side beam of the Bogie, was about 135 mm, as described in 2.4.3.7 (1).

(3) It is probable that the load per one vehicle was close to the empty load weight, because the passengers boarded on the Train when derailed was about 100 passengers, as described in 2.2.1.

It is probable that the ratio of wheel load unbalance became large by the Crack because the strength of the side beam decreased due to the crack, and the side beam in front right wheel side of the Bogie displaced in the direction that the axle spring getting longer, and became unable to support the vertical load.

3.2.3. Analysis on the Generation and Expansion of the Crack

(1) It is probable that the Crack had generated at the weld end edge part between the Outer Rib and the lower surface of the side beam as the start point, after spread in the lower surface of the side beam, expanded in the side surface of the side beam from the bottom to upward, based on the followings, as described in 2.4.3.7 (1).

(i) The ratchet mark was found in around the weld end edge part of the Outer Rib, and the beach mark had expanded from around there toward lower surface of the side beam, after that, expanded toward the side surface of the side beam.

(ii) The beach mark, which was considered as the feature of the fatigue fracture, was found from the lower surface of the side beam to a height of about 135 mm, and the trace of the fatigue fracture was about 450 mm long in total.

(2) On the strength of the Welded Part, it is likely that the stress concentration was generated in the weld end edge part of the Welded Part, and the stress, which exceeded the allowable limit in the critical stress chart, was generated, based on the followings.

(i) As described in 2.4.3.7 (2), the stress measured for the 250% capacity loaded condition, in the welded part stress measuring place of the bogie, which was the same side beam structure as the Bogie, had exceeded the allowable value indicated in the critical stress chart.

(ii) As described in 2.4.3.7 (2) (i), the measured stress in the weld end edge at the welded part stress measuring place was about 2.4 times of the measured stress in the lower part of the side beam in the neighborhood of the welded part stress measuring place, regardless of the loading condition.

(iii) As described in 2.8.1.2, the maximum stresses in the Welded Part and the welded part stress measuring place were almost in the same level, based on the result of the FEM analysis.

However as described in 2.4.3.10, the maximum congested factor in the commercial line of the Company had been changed between about 150% and 160% in the past 10 years, therefore, it is probable that the generated stress in the weld end edge part of the Welded Part in the actual loading condition has not always exceeded the allowable limit in the critical stress chart.

Furthermore, as described in 2.4.3.7 (2) (ii), the supposed life of the Welded Part, estimated from the stress obtained by the running test in about 100% capacity loaded condition, was over 22,000,000 km running distance, therefore, it is probable that the crack had been expanded in the long term in the actual loading condition which was not always in the 250% capacity loaded condition.

(3) It is likely that the welded status of the Welded Part had been in the status as the large stress had been generated due to the stress concentration in the weld end edge part of the Welded Part, based on the followings, as described in 2.4.3.7 (3).

(i) The microscopic dents were found in the welded surface in the weld end edge part of the Welded Part, even though they were not the incompletely welded parts

(ii) The shape of the weld bead in the weld end edge part of the Welded Part was in the convex shaped status compared to the shape of the weld bead in the same places in the Pos. 6, Pos. 7 and Pos. 8, and in the status of large excess welding angle.

(iii) As described in 2.8.1.3, based on the result of the calculation of stress concentration for the different shaped weld end edges, the stress concentration factor is in the trend to increase as the excess welding angle in the weld end edge becomes larger and the radius of curvature becomes smaller.

Additionally, although the part not yet welded was found in a part of the Welded Part, it is probable that this situation did not affect to the generation of the stress in the weld end edge part, because the periphery had been welded in good status.

(4) It is likely that the large stress had been generated due to the stress concentration in the weld end edge of the Welded Part, and caused the generation of the Crack, as described in the above (2) and (3). Therefore, it is likely that the stress became large locally due to the stress concentration originated by the microscopic dents and the excess welding angle in the weld end edge part, and became the origin of the crack generation, and the crack due to the fatigue fracture had been expanded, although the average stress had been within the strength design value, as the factors to cause the Crack.

3.2.4. Relationship between the Crack and the Periodic Inspection

There was the description "*it was cleared that the crack did not expand rapidly because the running distance level of 1,200,000 km to 1,500,000 km is required for the crack in the level of 40 mm reached to the plastic deformation, on the size of the crack generated in the bogie frame*" and indicated the "*sample of simulation on the crack expansion in the side beam of bogie frame*" in the inspection manual of bogie frame, indicated in the notification of the "Approved Model Specifications on the Ministerial Ordinance Providing for the Technological Standard for Railway, Director General, Railway Bureau, Ministry of Land, Infrastructure, Transport and Tourism, March, 2002".

The trace of the fatigue fracture was about 450 mm long in the extent as described in 2.4.3.7 (1), and the vehicle running distance from the latest general inspection for the Vehicle on December 1, 2016, conducted before the occurrence of this accident, was about 490,000 km, as described in 2.4.3.1. Therefore, it is likely that the crack generated from around the welded part of the Outer Rib had already been reached to the lower surface of the side beam at the time of the general inspection.

On the other hand, the entire side beam had been added to the flaw detecting place as to be inspected by the magnetic particle test in the critical parts inspection and the general inspection, as described in 2.4.2, but the opening width had not been changed when the simulated crack was about 150 mm wide and 0 mm high in the test conducted in the empty loaded condition, as described in 2.4.3.8. Therefore, it is likely that the crack had not been opened at the time of the latest general inspection implemented before the occurrence of this accident, in which the magnetic particle test for the bogie frame had been implemented in the empty loaded status. Furthermore, it is likely that the crack in the lower surface of the side beam could not be found because the place to be inspected by the magnetic particle test for the side beam was not designated precisely and the magnetic particle test had been implemented for the circumference of the entire side beam.

Therefore, it is considered as necessary to make clear the places where large stress is generated based on the design information by the FEM analysis, etc., and to make clear the places to implement the magnetic particle test against the generation of crack, when implement the magnetic particle test for the side beam. Furthermore, it is considered as necessary to inspect the lower surface of side beam in high priority in the visual inspection for the side beams in the train inspection and the monthly inspection, because large stress was generated in the lower surface of the side beam by the large stress generated in the side beam by the vertical load due to its structure. In addition, it is desirable to study to conduct together with the inspecting method such as the ultrasonic flaw detection which enables to detect crack expansion in early stage, in the case that the crack expands from inside to outside of lower surface such as the Crack.

Furthermore, it is desirable to study on the introduction of the design emphasized the improvement of the maintainability, such as the structure to delay the expansion of crack or the structure to make easy to find cracks, and to develop new inspection methods which enable to find in early stage in cooperation with the visual inspection or the nondestructive inspection, by predicting the generation or the expansion of the crack by the effective use of the technologies of the analysis, etc.

3.2.5. Analysis on the Quality at the Time of Manufacturing Bogies

As described in 2.4.3.7 (3), the incompletely welded parts such as the overlap, the blowhole, etc., were found in the welded status at the Welded Part and the other 3 places corresponded to the Welded Part in the Bogie, however, the incompletely welded part was not found in the weld end edge of the Welded Part, where considered as the start point of the crack. Therefore, it is probable that the possibility that the incompletely welded part became to the factor of the crack generation was low, in this accident. However, it is important to find out the incompletely welded part in the inspection in the welding works, because the incompletely welded part such as the overlap, etc., causes the phenomena such as to cause the stress concentration and to cause the lack of strength of the welded part, etc.

The welding worker had implemented the inspection visually as the inspection method when the Bogie was manufactured, as described in 2.4.3.5 (1), however, at present, the staff exclusively charged in the inspection implemented the visual inspection, the magnetic particle test, and the ultrasonic test and implemented the measures to apply the standard utilizing the sample of the limit for the place difficult to implement the quantitative evaluation, etc., as described in 2.4.3.5 (2). Therefore, it is probable that the accuracy to find the incompletely welded part has been improved, because the inspection system and the improvement of quality of the welding works has been established at present compared to the time when the Bogie was manufactured.

It is required to consider the stress concentration in the design stage, as described in the latter paragraph 3.2.6, because there is the possibility to generate the stress concentration due to the microscopic dents and the excess welding angle in the weld end edge part as described in 3.2.3 (4), although it is probable that the shape, which the weld bead was not identified as the incompletely welded part, was judged as normal in the inspection. Furthermore, it is desirable to study the measures such as to instruct the radius of curvature and the excess welding angle in the weld end edge part in the design stage, and to confirm by the inspection, when there is a concern that the stress concentration at the weld end edge part affects to the strength.

3.2.6. Analysis on the Design of the Side Beam

The strength calculation of the Side Beam was implemented for the bogie type targeted to the other company started the operation in 1967, as described in 2.8.1.1 (3). This strength calculation was implemented as to calculate the stress in the designed maximum vertical load based on the cross section coefficient against the major cross section of the side beam, and the calculated result was 106.3 MPa in the maximum stress, in contrast that the stress in the cross section corresponded to the Crack was 82.4 MPa, which was within the allowable value of the total amplitude fatigue limit 108 MPa for the yield stress 216 MPa of the material SS41 which was used at the time of designing. Based on these situations, it is probable that the strength design implemented at that time was valid.

On the other hand, the results of the FEM analysis implemented after the occurrence of this accident were as follows. The stresses shown in Figure 12 were within the allowable value for the welded part without finishing in the critical stress chart in the Welded Part and the welded part stress measuring places, as described in 2.8.1.2. However, as shown in Figure 13, the stress obtained by the FEM analysis in the side beam model, which the elements for the weld end edge part are the equilateral triangle of 1 mm sides, was 230 MPa or above at the weld end edge of the Welded Part. Furthermore, in the static load test using the FS513 type bogie, the stress at the weld end edge part of the welded part stress measuring place was about 2.4 times of the stress measured in the lower surface of the side beam in around the welded part stress measuring place, as described in 2.4.3.7 (2) (i).

Therefore, it is considered as necessary to design to enlarge the radius of curvature of the weld end edge part by the grinder finishing, etc., in order to relax the stress concentration, because it is probable that the large stress due to the stress concentration is generated in the weld end edge part in the structure which the reinforcing plate is welded to inside of the side beam same as in the Side Beam. Additionally, it is desirable to implement the structure design as to set the allowable stress in the lower surface of the side beam in around the welded part, considering the stress concentration factor which is considered as the maximum for the used materials, when the design to enlarge the radius of curvature of the weld end edge part could not be implemented due to the reasons in the structure, etc.

In addition, it is considered as necessary to pay attention to increase the accuracy of the analysis such as to comprehend the precise distribution of the generated stress by making the area of the elements as small as possible, etc., when implement the study by the FEM analysis for the local stress such as the stress concentration, etc., in the design stage.

3.2.7. Analysis on the Leaf Spring Breakage

It is probable that the Leaf Spring Breakage was caused by rapid generation of the stress exceeding the yield point of the material, not by the fatigue fracture, because only the dimple pattern which is the feature of the ductile fracture was found in the broken surface as described in 2.4.3.7 (4) (iii). It is likely that the reason, why the stress exceeding the yield point of the material had been generated rapidly, was affected by the rapid fluctuation of the vertical load due to the derailment.

4. CONCLUSION

4.1. Summary of the Analysis

(1) The place where the Train started the derailment was in around 11,670 m, *i.e.*, around the end edge in the direction to Aoto station of the guard angle. *[Refer to 3.1.3]*

(2) The status to climb up rail of the wheels in the Bogie was as follows. The right wheel of the Bogie was running in the status as being climbed up right rail in the section between around 11,750 m and around 11,670 m in the Curve. *[Refer to 3.1.4]*

(3) The cause of the derailment of the Train was as follows. The wheel climbed up rail and resulted to derail as the result of the enlarged unbalance of the wheel loads caused by the generation of the crack in the bogie. *[Refer to 3.1.5]*

(4) The ratio of wheel load unbalance became larger due to the Crack, because the right wheel side of the side beam in the front axle of the Bogie displaced in the direction to expand the axle spring because the strength of the side beam decreased due to the crack, and became unable to support vertical load. *[Refer to 3.2.2]*

(5) The Crack had generated from the weld end edge part between the Outer Rib and the lower surface of the side beam, as the start point, and expanded in the lower surface of the side beam, after that, expanded in the side surface of the side beam from lower part to upward. *[Refer to*

3.2.3 (1)]

(6) It is likely that the stress concentration had been generated in the weld end edge part and the stress exceeding the allowable limit in the critical stress chart had been generated in the Welded Part. *[Refer to 3.2.3 (2)]*

(7) The welded status of the Welded Part was that there were the microscopic dents in the welded surface in the weld end edge part although it was not the incompletely welded part, and the excess welding angle was in the status as large compared to the shape of the weld bead in the same places in the Pos. 6, the Pos. 7 and the Pos. 8. Based on these situations, it is likely that large stress due to the stress concentration had been generated in the weld end edge part of the Welded Part. *[Refer to 3.2.3 (3)]*

(8) It is likely that the factor to cause the Crack was that, the stress had increased locally due to the stress concentration caused by the microscopic dents and the excess welding angle in the weld end edge part, even though the average stress was within the strength design value, and became the start point of the crack, and the crack had expanded due to the fatigue fracture. *[Refer to 3.2.3 (4)]*

(9) It is likely that the crack had been reached to the surface of the lower surface of the side beam but had not been opened at the time of the latest periodic inspection of the Bogie, conducted before the occurrence of this accident. And the implementing standard of vehicle maintenance had been added to inspect the entire side beam for the flaw detecting place in the bogie frame in order to conduct the magnetic particle test, but the places to be inspected had not been prescribed precisely. Therefore, it is likely that the crack in the lower surface of the side beam could not be found. *[Refer to 3.2.4]*

(10) It is desirable to study on the measures such as to instruct the radius of curvature and the excess welding angle in the weld end edge part in the design stage and check by the inspection, when there is a concern that the stress concentration in the weld end edge part strongly affected to the strength. *[Refer to 3.2.5]*

(11) It is necessary to consider the design against the stress concentration in the design stage because it is probable that large stress due to the stress concentration would be generated at the weld end edge part in the structures which the reinforcing plates are welded to inside of the side beam such as the Side Beam. *[Refer to 3.2.6]*

4.2. Probable Causes

The JTSB concludes that the probable causes of this accident are as follows :

It is probable that the right wheel climbed up rail and derailed at around the end edge, in the direction to Aoto station, of the guard angle, where derailment could not become to be protected, because the unbalance of wheel loads in the front axle of the bogie became large, while the vehicle ran in the status that the crack was generated from lower surface to upper part of the side surface of the side beam of the bogie and expanded, and the lateral force increased while the vehicle passed the curved track in the status that the wheel load of right wheel had been decreased, in this accident.

It is probable that the unbalance of the wheel loads in the front axle of the bogie became large, because the shared vertical load could not be supported by the decreased strength of the side beam due to the crack.

Furthermore, it is likely that the crack had generated in the side beam because the large stress was generated locally by the stress concentration in the inside of the side beam where the reinforcing plate was welded, and became to the origin of the crack and the crack had expanded due to the fatigue fracture.

It is likely that the railway operator could not find the crack expansion in the periodic inspection, because there was the possibility that the crack had not been opened when the latest general inspection before the occurrence of this accident was conducted, even though there was the possibility that the crack had already been reached to the surface of lower surface of the side beam at that time, and the place to be inspected by the magnetic particle test for the side beam had not been prescribed precisely.

5. SAFETY ACTIONS

5.1. Measures to Prevent Recurrence Considered as Necessary

It is considered as necessary to conduct flaw detection test after designated precisely the place, where large stress had been generated due to the welding of the inner reinforcing plate, as the target of the inspection, based on the design information, etc., in the flaw detection test for the side beam in the periodic inspection which has already been conducted, in the bogies which the reinforcing plates were welded to inside of side beam. Furthermore, it is desirable to study on the parallel use of the inspection method such as the ultrasonic test, etc., in order to find out the crack expansion from inside in early stage. In addition, it is considered as necessary to inspect the lower surface of the side beam in high priority, particularly in the visual inspection in the monthly inspection, because the large stress is generated in the lower surface of the side beam as stress generated by the vertical load is large due to the structure of the side beam.

It is considered as necessary, in the future design, for the structure that the reinforcing plate was welded to inside side beam, to design so as to enlarge radius of curvature of the weld end edge part in order to relax stress concentration to the weld end edge part, or to implement the structure design as to set the allowable stress in the lower surface of the side beam in around the welded part, considering the stress concentration factor which was considered as maximum in the variety of the used materials, when the design to enlarge radius of curvature of the weld end edge part could not be implemented by the reasons due to the structure, etc.

5.2. Measures Taken by the Company after the Accident

The Company took the following measures after this accident.

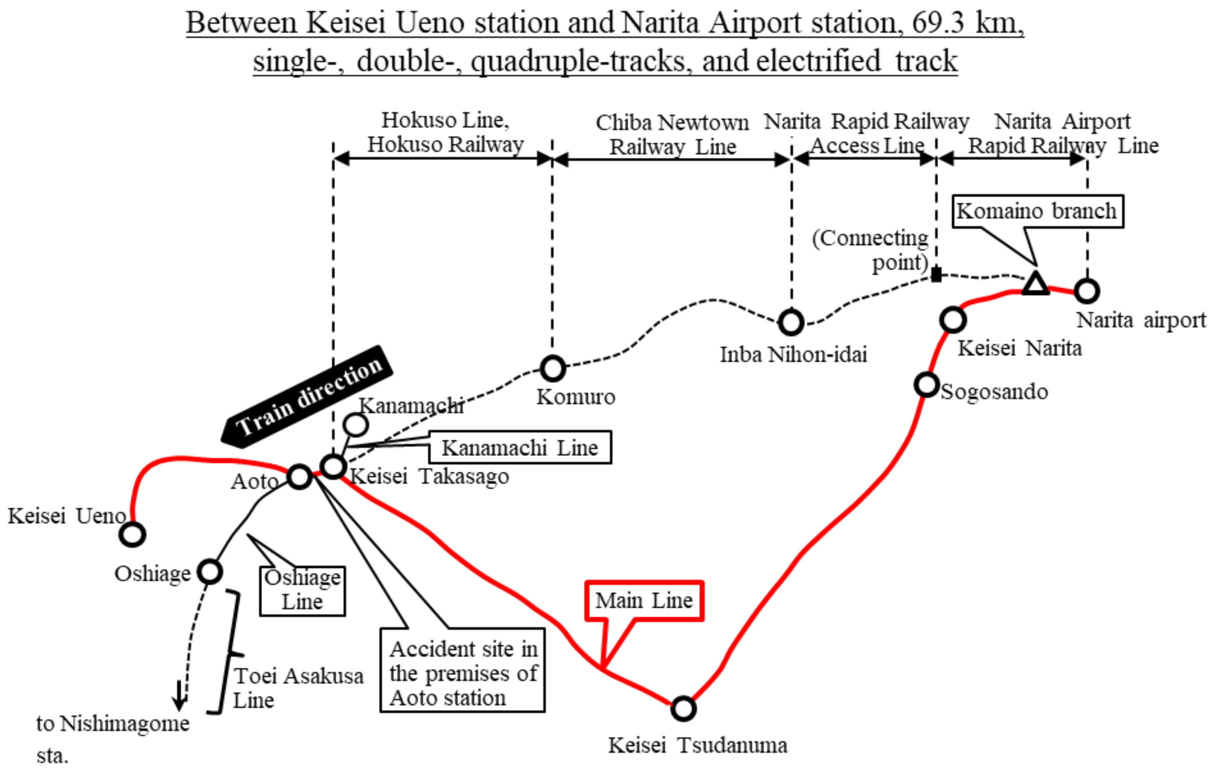
The Company added the implementation of the visual inspection and the hammering test after picked up samples in the similar place as the place where the Crack had generated in the train inspection and the monthly inspection, targeted all bogies owned by the Company and the Hokuso Railway.

Additionally, the Company implemented the measures to indicate clearly the important inspecting place on actual thing using the chalk, to make thoroughly the removal of paints on the lower surface of the side beam, and to add the double check system by two inspectors, for the place where the Crack had generated and the similar places, in the magnetic particle tests in the critical part inspection and the general inspection, targeted the same type bogies as the Bogie. Furthermore, the Company prescribed to conduct education on the magnetic particle test once a year, and to conduct the magnetic particle test every 2 years until the causes of this accident were identified.

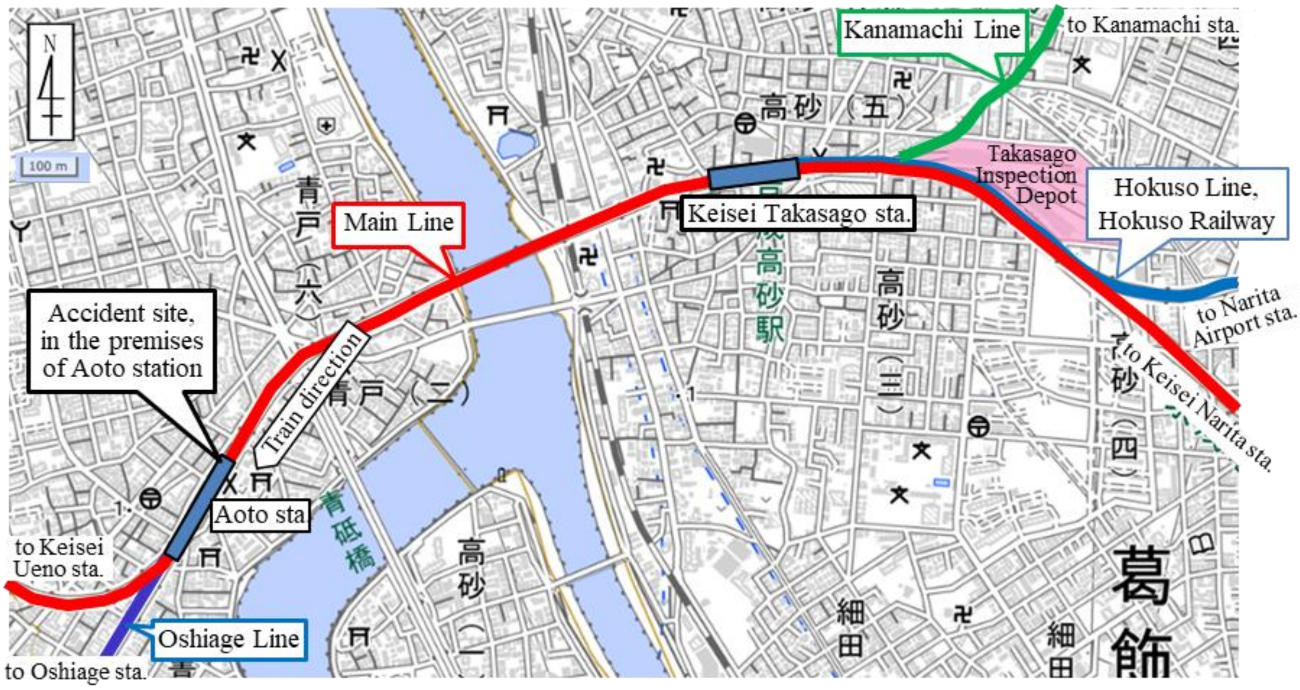
5.3. Measures Taken by the Ministry of Land, Infrastructure, Transport and Tourism after the Accident

On June 12, 2020, the Ministry of Land Infrastructure, Transport and Tourism instructed the railway and tramway operators who own the bogies of the similar structure, to conduct the urgent inspection by the visual check, etc. It was reported that there was no abnormality in the targeted bogies, about 9,900 bogies including the Company, as the result of the inspection.

Attached Figure 1. Route Map of Main Line, Keisei Railway Co., Ltd.

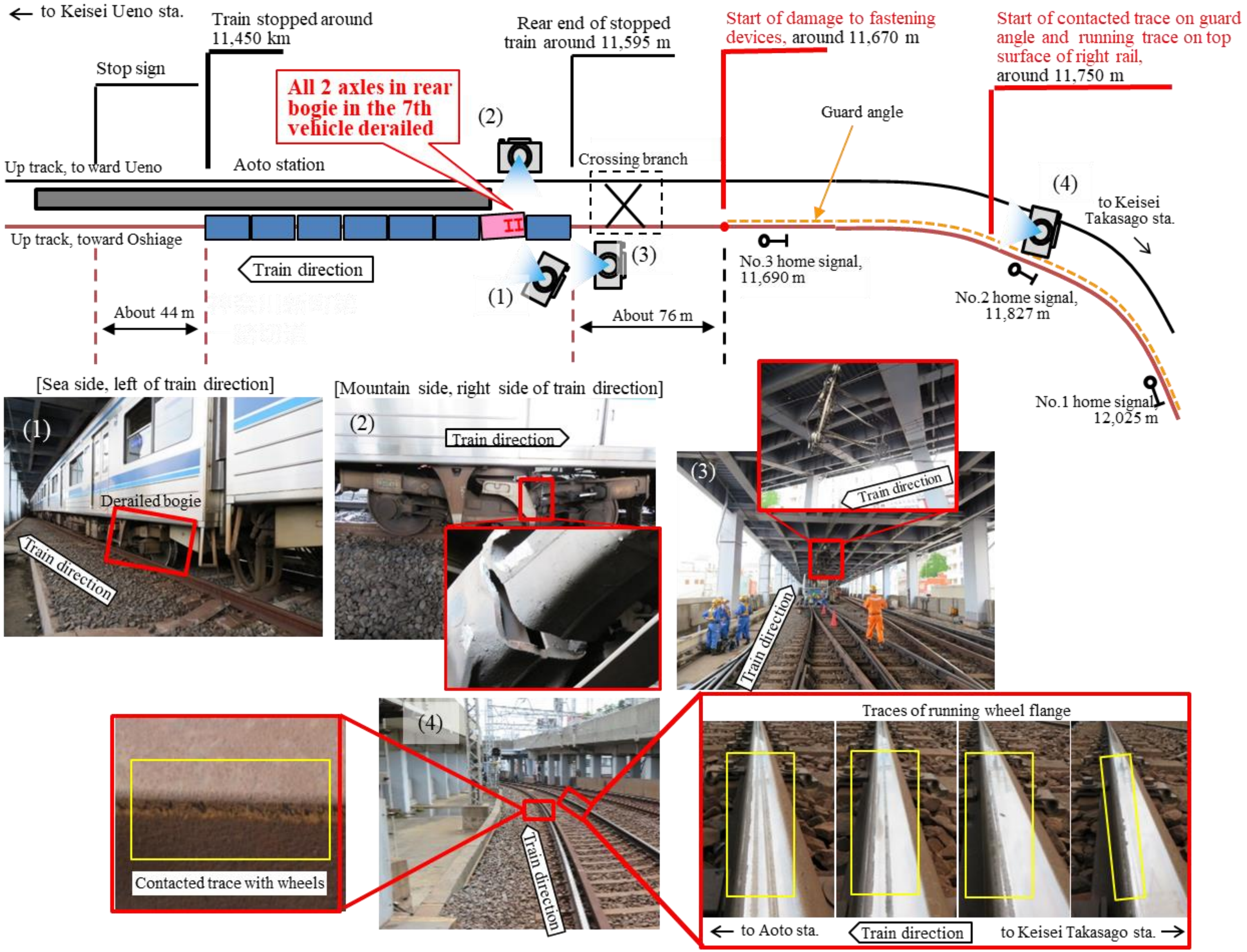


Attached Figure 2. Topographical Map of the Accident Site and Surrounding



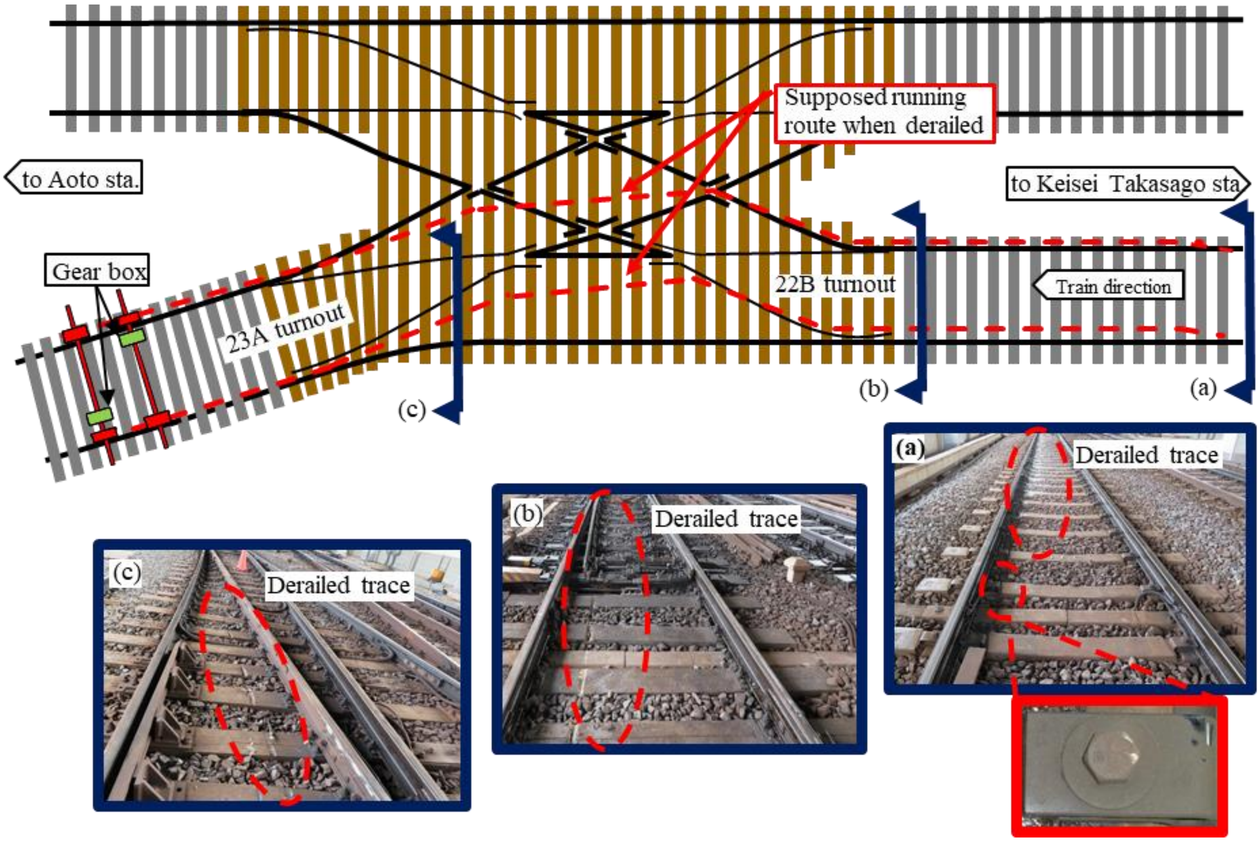
* This figure was made using the Geographical Institute Map, Electronic Country Web, of the Geospatial Information Authority of Japan.

Attached Figure 3. Rough Map of the Accident Site and Surroundings

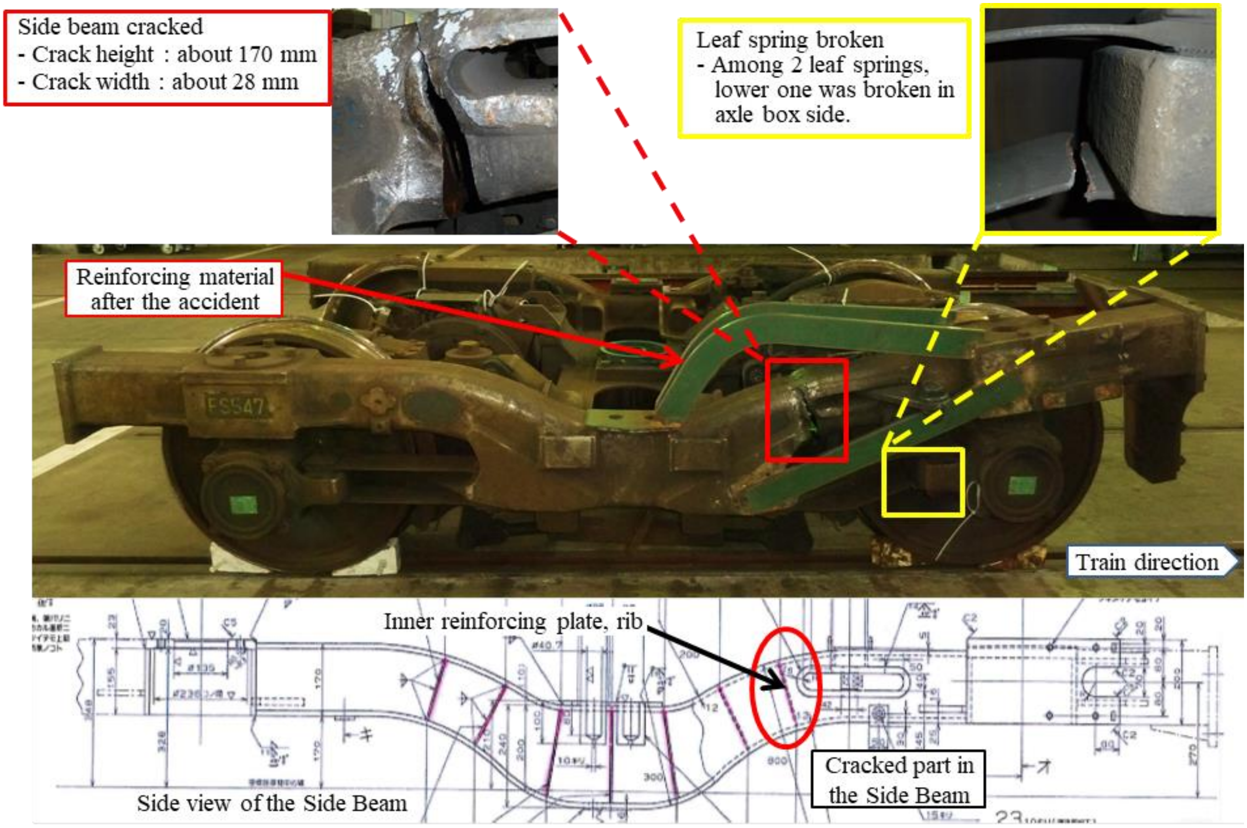


* This Figure shows rough layout of major facilities against track and roads based on the accident investigation, not in the correct reduction and positional relationships.

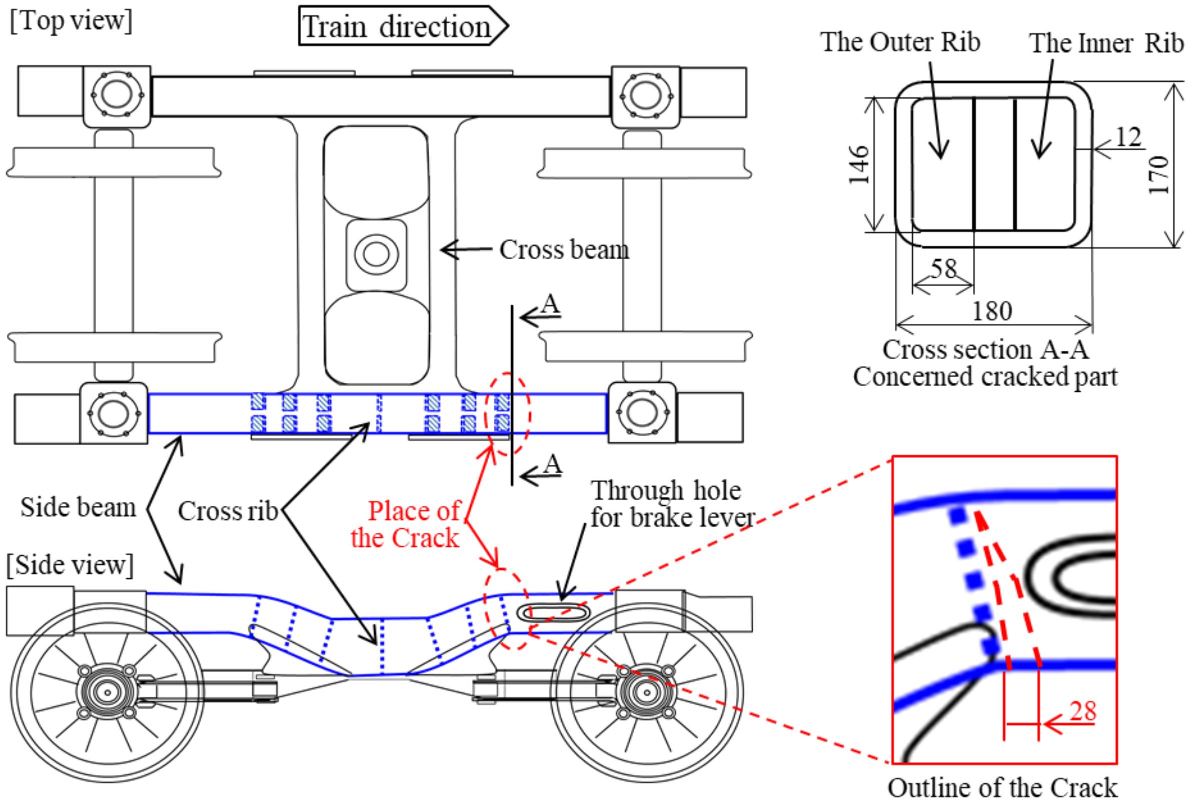
Attached Figure 4. Major traces, etc., of the Track



Attached Figure 5. Status of Major Damages to the Bogie



Attached Figure 6. Rough Drawing of the Bogie



* This figure indicates the image of the structures.

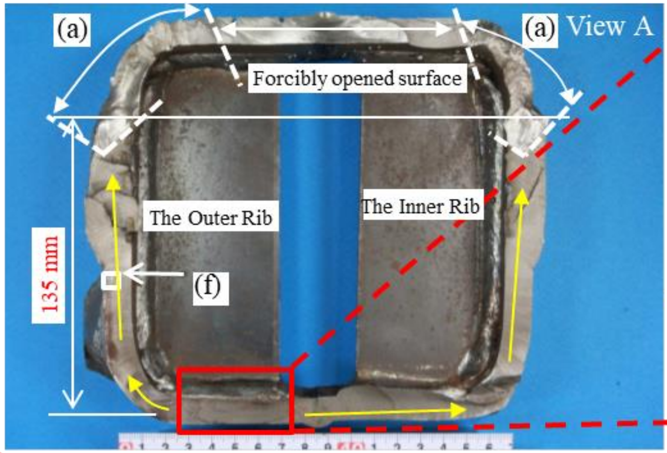
Attached Figure 7. Status of the Broken Surface of the Crack

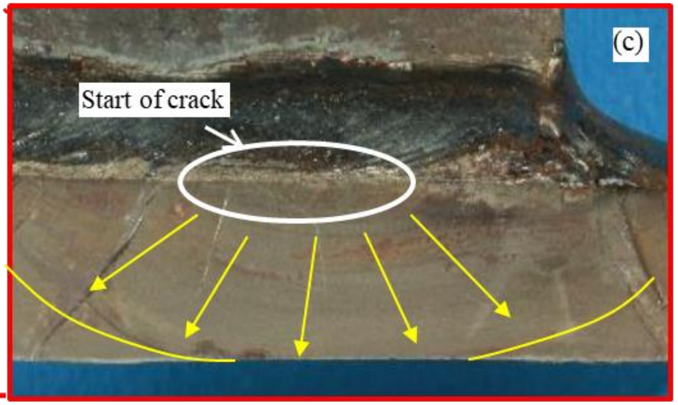
(a) Broken surface with the possibility of ductile fracture, from (d).

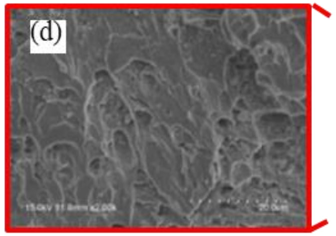
(b) Yellow arrows indicate the direction of trace of fatigue fracture.

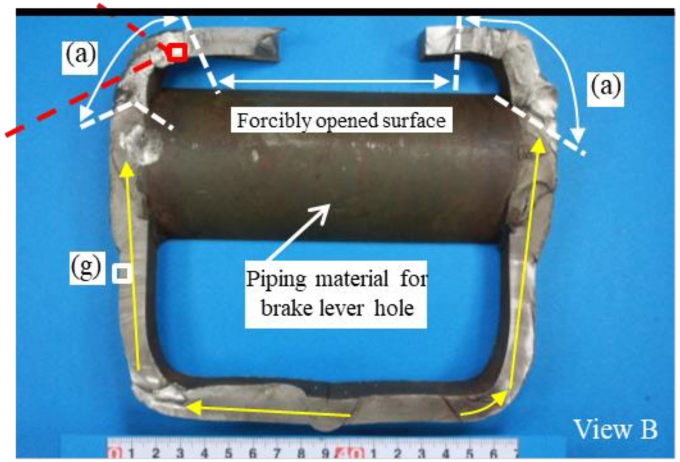
(c) Red arrows indicate the ratchet mark. There is arch shaped beach mark from weld end edge of outer rib to side beam bottom.

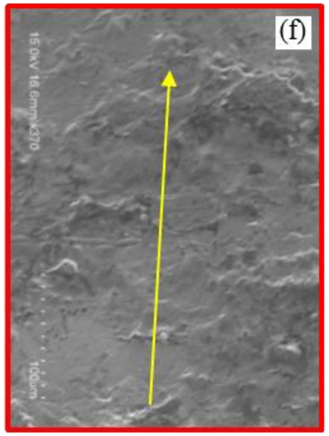
(d) Dimple pattern which is feature of ductile fracture.

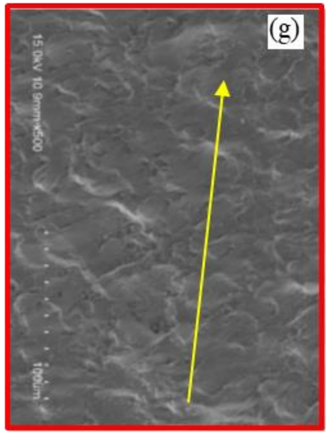




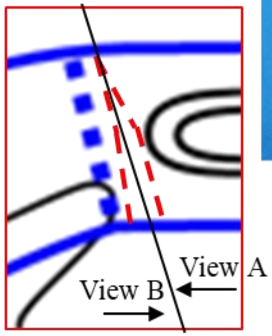








(e) Trace of fatigue crack existed to 135 mm, total length was 450 mm, from side beam bottom .



(f) and (g)
Enlarged figure of side surface of side beam.
Trace of the beach mark, striation, were found in the direction to yellow arrow.

* Striation is the typical stripe pattern found in the broken surface when fatigue crack expanded.

Attached Figure 8. Status of the Major Damages of the Train