Interpretive article

Clarification of Mechanism of Shinkansen Derailment in the 2011 Great East Japan Earthquake and Countermeasures Against Earthquakes

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The Great East Japan Earthquake of March 11, 2011 resulted in tremendous damage to JR East railway facilitates due to seismic vibration and the ensuing tsunami. One incident was the derailment of a Tohoku Shinkansen train making a test run near Sendai Station. This marked the second time a JR East Shinkansen train had derailed, following that in the 2004 Mid Niigata Prefecture Earthquake. This article will cover the derailment accident investigation and its findings along with issues and lessons discovered in the process of that investigation. It will also cover past countermeasures against earthquakes and future issues in R&D.

1 Introduction

Broad-ranging damage was suffered in the JR East area due to seismic vibration and the ensuing tsunami of the Great East Japan Earthquake of March 11, 2011. The earthquake was huge, measuring a magnitude (M_W) of 9.0 (approx. 1,000 times the energy of the 1995 Great Hanshin-Awagi Earthquake), but we were fortunate in that there were no major injuries to passengers. JR East did, however, suffer unprecedented damage including tsunami damage to railway facilities and rolling stock along the coast and deformation of structures and track inland as well as many cases of damage such as tilted and fallen power poles. Moreover, a Tohoku Shinkansen train running near Sendai Station derailed, marking the second Shinkansen derailment accident following that of the *Toki 325* in the October 23, 2004 Mid Niigata Prefecture Earthquake.

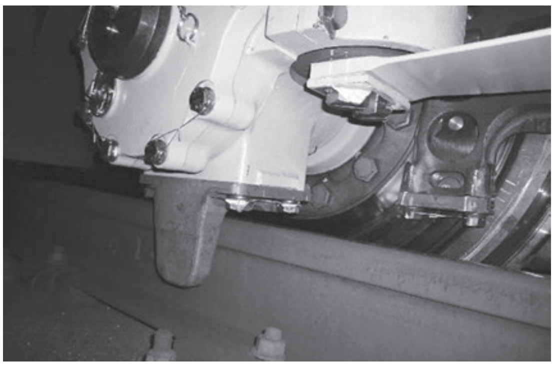

Fig. 1 Derailed Wheel
(viewed from front on right side of inbound train)

JR East went immediately to work after the earthquake in identifying the damage and restoring service. At the same time, we investigated and verified both physical and system-related earthquake countermeasures taken up to that point. As part of that investigation, we also attempted to clarify the mechanism behind the Shinkansen derailment. This article gives an overview of the process of clarifying derailment accident phenomena, lessons learned through that, and new issues that came up in light the recent earthquake.

In clarifying derailment accident phenomena, we received much technical guidance from the Railway Technical Research Institute (RTRI) related to issues such as analyzing response of structures affected by seismic motion and analyzing rolling stock behavior. I would like to take this opportunity to express our gratitude for their assistance.

2 Overview of the Derailment Accident

A train (series E2, 10-car train set) on a test run had departed the Shinkansen Depot north of Sendai and was passing through Sendai Station at 72 km/h when the emergency stop system activated the emergency brakes. The train received strong swaying force due to the earthquake when decelerating, the No. 1 and No. 2 axles of the bogie in the direction of Tokyo on Car 4 derailed to the left at approx. 14 km/h, and the train stopped after traveling a further approx. 2.6 m. In this situation, deviation prevention car guides at the right side of the No. 2 axle of the bogie contacted the rail, controlling deviation to the left.

3 Overview of Accident Investigation

3.1 Objective of Investigation

In the 2011 earthquake, strong shaking of an upper 6 in the Japan Meteorological Agency seismic intensity scale was observed in Sendai where the test run train derailed. However, Shinkansen trains running in all of Miyagi Prefecture and in parts of Fukushima and Ibaraki prefectures, which received similar shaking, did not derail. So, we set out to investigate the reason derailment occurred at that specific location.

3.2 Flow of Investigation

Investigation was done for two aspects: state of damage of structures, tracks, and rolling stock affected by seismic motion and re-creation by numerical analysis of the behavior when structures and rolling stock were affected by seismic motion.

Damage and traces of derailment were left on the track that the train affected by seismic motion was running, and damage and deformation occurred on the bogies and carbody suspension systems due to large rolling behavior, so we looked at those in the investigation of the actual state of damage. We found no remarkable damage to the viaduct at the location of derailment. But we did find large widening of the gauge and damage to the rail fastening system at some locations as well as remarkable damage to the bogies as well as to dampers, stoppers, and the like that make up the carbody suspension system.

In analysis, we worked to identify the point where the largest swaying was assumed to have been received by the train as shown in Fig. 2. That was done by bringing together the car's ATC operation record and records of seismic motion observed by the seismometer closest to the train. Matching the time histories of those, we found the kilometerage and speed of the train at the time when the swaying was greatest and set that kilometerage as the location of the analysis point.

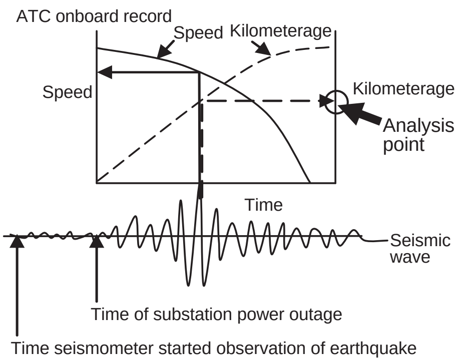

Fig. 2 Method of Identifying Analysis Point

Next, we estimated the seismic motion of the ground surface at that point and the response (frequency of swaying perpendicular to the track, acceleration, displacement, etc.) on the viaduct that was affected by seismic motion.

In the process of analysis, we first converted the seismic motion to the location with relatively hard ground to remove the influence of the surface ground, as shown in Fig. 3. In this, seismic motion observed by a seismometer close to the analysis point was used as reference. Next, we added compensation based on knowledge gained in observations of aftershocks, and we took into account seismic amplification by the surface ground at the analysis point for that waveform to estimate seismic motion at the ground surface ((1) to (3) in Fig. 3). After that, due to the effects of ground condition, natural frequency of the structure, and damping affect, we measured swaying on the ground surface and structures simultaneously for multiple aftershocks to identify response tendencies in those structures. From those measurements, we estimated structural response in the earthquake ((4) in Fig. 3).

Finally, we estimated from car kinematic analysis the behavior cars would express when they are affected by the response of the structures. We used that to judge whether or not a train would derail ((5) in Fig. 3).

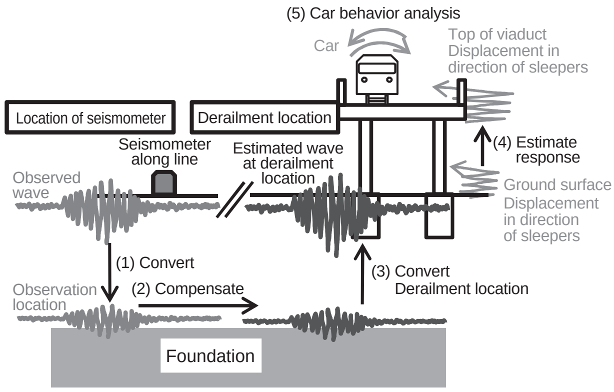

Fig. 3 Process of Analysis

3.3 Actual Investigation

The aforementioned course for the investigation was decided in late March, more than 10 days after the earthquake. It would have been ideal to start work earlier, but the damage from the earthquake was tremendous and broad ranging. It thus took a long time to assess the damage and establish an overall plan for the course of recovery.

The actual investigation was conduced from late March through mid April, but we were faced with situations that impeded sufficient investigation. For example, trains on lines in northern Kanto and north of Morioka, where recovery started earlier, were operated in provisional sections during that time, overwriting their onboard records. While we were forced to leave some trains in areas with severe damage for a long period of time, the limited means of transportation and major aftershocks made the investigation difficult.

In measurement of aftershocks required for estimating structural response, we discovered that the scale and frequency of aftershocks declined as time from the main earthquake passed. That made us aware of the importance of making observations at an early stage.

4 Results of Investigation and Analysis

4.1 Analysis of the Mechanism of Derailment

The details of this derailment accident were reported in railway accident investigation report RA2013-1 (February 22, 2013) by the Japan Transport Safety Board. The results in that report were similar to those of the JR East investigation. The report states, regarding the process leading to derailment discovered from results of analysis, that frequency components generally matching the natural frequency of the viaduct where the train derailed were amplified due to the resonance phenomenon of the structure, causing large displacement on the viaduct. There, the frequency components were in a frequency band that causes top center rolling to easily occur on cars, so top center rolling occurred, leading to derailment.

Specific analysis results were that response perpendicular to the track at the location of derailment on the viaduct was a maximum acceleration of approx. 1,067 gal, dominant frequency was between 1.5 and 1.7 Hz, and maximum displacement was approx. 167 mm (approx. 140 mm around the time of derailment). Behavior of the car that received the response was, according to analysis results, that the left wheel flanges of the four axles of the front and rear bogies climbed the left rail surface, the left wheels continued to be displaced to the left, derailing the train. (Actual derailment was on the two axles of the front bogie, which differs from the analysis results.)

4.2 Actual Track and Car Damage

In terms of track damage confirmed, remarkable widening of the gauge was found at the rear of the location of derailment, and this matched the position of the car with remarkable damage. This was the location where large response displacement of the analysis covered in 4.1 occurred.

For cars, the damage particularly at the bogies and carbody suspension system was damage to air spring level controlling valve coupling rods due to rolling behavior of the cars, damage to pistons of active suspension lateral dampers, and remarkable deformation of attachment for the lateral displacement stopper rubber bogie-side due to the body center pin forcibly striking the lateral displacement stopper rubber.

Bent coupling rod　　Broken coupling rod

Fig. 4 Case Example of Damage to Air Spring Level Controlling Valve Coupling Rods due to Rolling Behavior of Cars Affected by Seismic Motion

4.3 Comparison of Analysis Results and Actual Damage

The car's active suspension lateral dampers have a failure recording function, and upon reading that out there was a record of acceleration of ±1 G at around 1.5 – 1.6 Hz as shown in Fig. 5, backing the results of response analysis on the viaduct as mentioned in 4.1. And from car kinematic analysis, we can estimate the lateral force that acted on the axles and force that acted on the lateral displacement dampers. This backs the findings that tremendous force widened the gauge due and deformed and damaged the bogies and carbody suspension systems.

As demonstrated, the analysis for this earthquake matched with high accuracy the actual damage. We thus confirmed that it would be effective in studying earthquake countermeasures in the future.

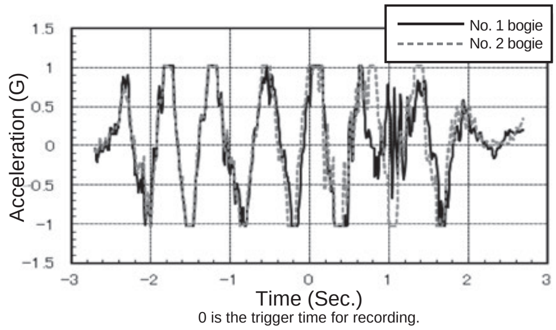

Fig. 5 Acceleration Record at Earthquake for Active Suspension Lateral Dampers of Derailed Car (Upper limit of recording is ±1 G. Peaks greater than that are not shown on the graph.)

5 JR East Earthquake Countermeasures and Future Efforts

5.1 JR East Earthquake Countermeasures

Structures of the then-under-construction Tohoku Shinkansen being damaged in the 1978 Miyagi earthquake became an incentive to advance aseismic designing methods. We later experienced the 1995 Great Hanshin-Awaji Earthquake and 2004 Mid Niigata Prefecture Earthquake, leading us to stipulate targets per process as shown in Fig. 6 (stop trains as soon as possible in an earthquake, prevent wayside structures from being heavily damaged even if affected by seismic motion, and prevent damage from spreading even if a train derails) and take various countermeasures for those.

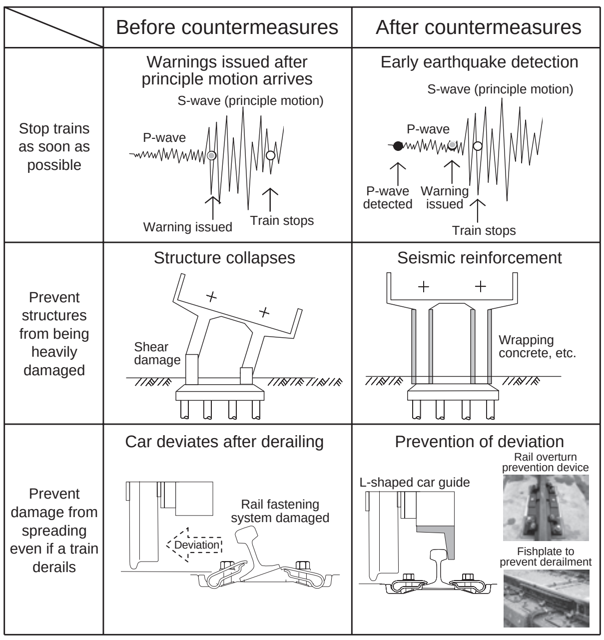

Fig. 6 Previous Countermeasures Taken against Earthquakes

Even in the 2011 earthquake, the system to stop trains as soon as possible in an earthquake functioned for trains in a broad area, and remarkable damage did not occur to structures thanks to seismic reinforcement construction that had been continuously conducted for viaduct columns and piers. Moreover, deviation prevention car guides introduced for use in times of derailment as a result of lessons learned in the Mid Niigata Prefecture

Earthquake performed their function, even though the derailment was as relatively low speed.

The report by the Japan Transport Safety Board also mentions that the guides performed well, but it also states the need for measures to prevent reoccurrence of such derailment. Specifically, it states that it would be desirable to scrutinize vibration properties of the location of the derailment and, if necessary, take measures on resonance and the like upon verifying their effects.

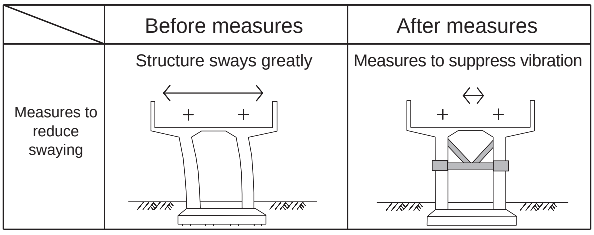

Fig. 7 Measures for Location of Derailment (Image)

It also states the following in terms of Shinkansen structures upon which trains run at high speed: Research to identify locations like in the accident where the phenomenon of resonance that would be a problem in terms of running safety is assumed to occur would be desirable. Also, proceeding with R&D on conducting appropriate measures would be desirable.

5.2 Efforts Taken after the Great East Japan Earthquake

In light of the damage sustained in the earthquake, JR East has increased the number of seismometers so as to enhance the detection system for emergency stopping of trains. We also linked Japan Meteorological Agency earthquake early warnings with the Shinkansen Early Earthquake Detection System in 2012. In seismic reinforcement, we have completed reinforcement on Shinkansen lines and lines in the greater Tokyo and Sendai areas for shear-critical viaduct columns and piers, for which the risk of damage in an earthquake is high. On the remaining flexure-critical viaduct columns and piers, we have moved up countermeasures for those where there is a risk of damage in strong seismic motion. We will also continue to conduct seismic reinforcement of power poles and station and platform ceilings along with wayside construction for car deviation prevention measures used in derailment, a lesson learned form the Mid Niigata Prefecture Earthquake.

Identifying locations where the phenomenon of resonance that would be a problem in terms of running safety is assumed to occur, which was an issue in the aftermath of the 2011 earthquake, is considered to be a difficult theme involving various parameters. Those parameters include seismic motion (acceleration response spectrum), ground conditions along Shinkansen lines, response characteristics that differ by individual structure, and motion characteristics. R&D on effective assessment methods is currently underway.

In measures for rolling stock, R&D is underway for methods of making cars more resistant to derailment even under larger swaying. Attenuating vibration centering on rolling behavior of car bodies as shown in Fig. 8 is effective in keeping in check derailment of rolling stock affected by seismic motion. We discovered from car kinematic analysis the effectiveness of increasing the attenuating force of lateral dampers between the bogies and body or, if rolling behavior cannot be suppressed, widening the stopper gap to suppress strong lateral force generated by the body center pin striking the bogie. As a result of those discoveries, the Railway Technical Research Institute (RTRI) is developing lateral dampers to suppress seismic motion and crushable lateral displacement stoppers, both of which have such functions to make cars more resistant to derailment. JR East plans to study assessment of lateral dampers as countermeasures against seismic motion on rolling stock with a goal of practical implementation of those.

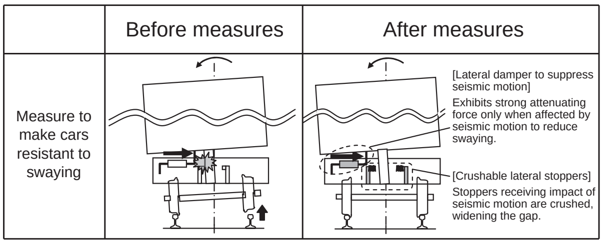

Fig. 8 Measures to Make Rolling Stock Affected by Seismic Motion Resistant to Derailment

6 Conclusion

This article has covered some of the lessons I learned and issues I faced as one of the personnel involved in investigating the cause of the Shinkansen derailment accident in the Great East Japan Earthquake. It goes without saying that, in investigating the cause of accidents, it is important to gather as much data as possible including that on the detailed situation at the site and from observations. Even so, personnel at affected sites after a major earthquake are under pressure to rescue people affected, identify the damage conditions, and restore service. In fact, progress is often not being made in investigating the cause, making that an issue that needs to be tackled.

I felt that establishing policies and procedures at an early stage is important in an efficient investigation, and to do so, keeping records of past lessons and utilizing the advice of veterans would be effective. At the same time, progress in computerization of social infrastructure and railway systems has made analysis once considered difficult to become possible through utilization of data recorded by rolling stock and wayside equipment. I believe that by utilizing such data we will be able to effectively investigate the causes of accidents.

The risk of large-scale earthquakes cannot be avoided in seismically active Japan. While countermeasures against earthquakes are imperative if we are to increase safety, those also involve an economic burden. I would thus like to see us approach rational countermeasures in terms of both safety and economy from a viewpoint of R&D into the future.