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DAMAGE CAUSED TO SHINKANSEN STRUCTURES BY THE GREAT EAST JAPAN EARTHQUAKE AND EARLY RESTORATION

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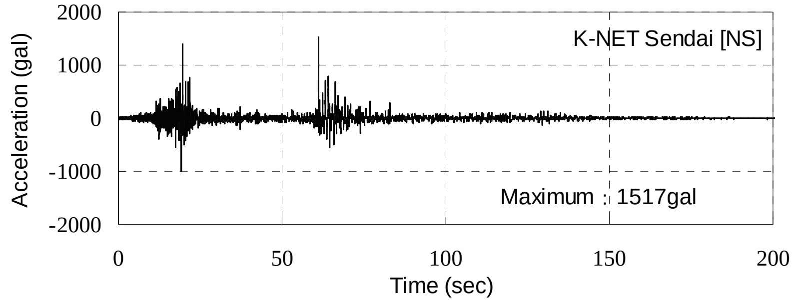
ABSTRACT: This paper outlines the damage to Shinkansen structures caused by the Great East Japan Earthquake and the early restoration of the damaged structures. Observations were made to investigate the severity of the damage to structures and the mechanism of the damage. Although there was some damage to viaduct columns and bridge piers, crippling damage such as the fall of bridge girders were not observed. We consider that the seismic rehabilitation of the columns and piers, based on the priorities set by the seismic performance of RC members is effective to prevent seismic damage.

Key Words: Great East Japan earthquake, seismic damage, failure mode, viaduct columns, bridge piers, seismic rehabilitation, seismic performance, restoration

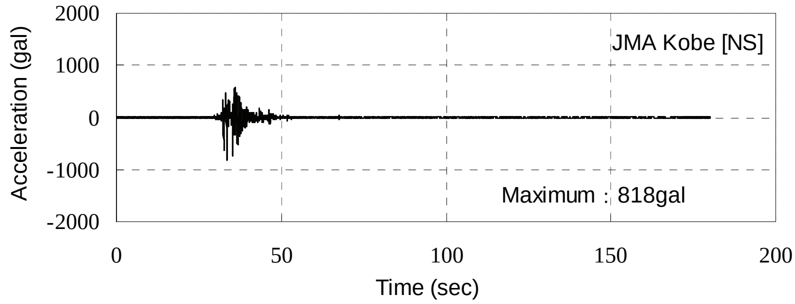
1. INTRODUCTION

This paper describes the outline of damaged structures of the Tohoku Shinkansen caused by the Great East Japan Earthquake and early restoration of the damaged structures. In this paper, authors mainly discuss the damage to reinforced concrete (RC) members, and especially, focus on the seismic performance of viaduct columns and bridge piers. Additionally, we confirmed that the Tsunami did not reach the Shinkansen.

The Great East Japan Earthquake struck on March 11, 2011, and recorded the largest earthquake in Japanese history at a magnitude of 9.0 on the moment magnitude scale. Furthermore, many strong aftershocks such as an earthquake recorded on April 7 also occurred. The main earthquake generated widespread and strong ground motion lasting for a long time, and caused damage to East Japan Railway Company (JR East) structures. Therefore, this earthquake caused the suspension of Tohoku Shinkansen operations. The recorded ground motion in Sendai by the main shock is shown in Fig. 1. To compare the duration of the earthquake motion, the motion by the 1995 Hyogoken-Nambu (Kobe) Earthquake is also shown in Fig. 1. From this figure, it is observed that the lasting time of the Great East Japan Earthquake was much longer than the 1995 Hyogoken-Nambu Earthquake in which serious



a) Ground motion by the Great East Japan Earthquake at K-NET Sendai



b) Ground motion by the 1995 Hyogoken-Nambu Earthquake at JMA Kobe

Fig. 1 Comparison of the ground motion between by the Great East Japan Earthquake and by the 1995 Hyogoken-Nambu Earthquake

damage was suffered to many RC structures.

To investigate the severity of the damage, immediate observations were made along the Tohoku Shinkansen. Fig. 2 shows the numbers and distribution of the damaged structures along the Tohoku Shinkansen Line. This figure excludes the damage to electrical structures such as electric poles and overhead wires. Shown in Fig. 2, the Shinkansen sustained damage at approximately 1,200 sites along about 500 km between Omiya and Iwate-Numakunai stations. Although there was some damage to viaduct columns, fatal damage such as the fall of bridge girders, which had occurred in the 1995 Hyogoken-Nambu Earthquake, was not observed. Main examples of the damage to JR East’s railway structures were damage to viaduct columns at about 100 sites, displacement of bridge girders at 2 sites, and damage to bridge shoes at about 20 sites.

With the results of the observations, we proposed an early restoration method in two steps: “permanent repair” and “reinforcement”. Technique for urgent and permanent repairs had been developed and refined through past restorations from seismic damage. JR East had started restoring the damaged structures caused by the main earthquake immediately following the observations. By this approach, more than 90 % of the damaged structures had been restored by the timing of the strongest aftershock on April 7.

As mentioned above, the characteristic of the earthquake is a large number of strong aftershocks. The aftershock on April 7 caused damage to the Tohoku Shinkansen structures at about 550 sites. The extent of the damaged structures caused by this aftershock was narrower than the extent of the main shock. However, more severe damage was observed at several locations such as between Sendai to Ichinoseki stations. Crippling damage was not confirmed. The aftershock on April 7 also caused the suspension of the Shinkansen operations. Main examples of damage caused by the aftershock on April 7 were damage to viaduct columns at about 20 sites, displacement of bridge girders at 7 sites, and damage to bridge shoes at about 10 sites.

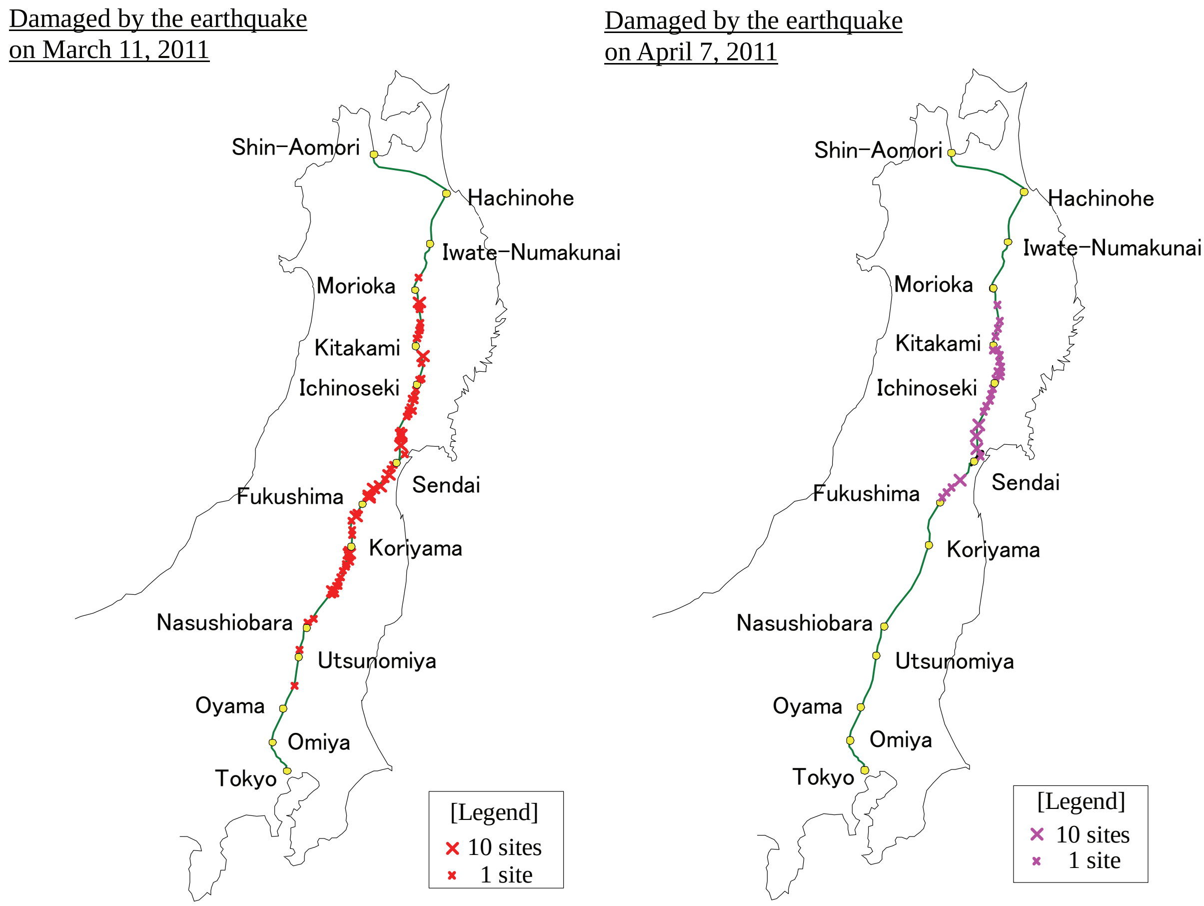


Fig. 2 Numbers and distribution of the damaged structures in the Tohoku Shinkansen Line

2. DAMAGE CAUSED TO RC SHINKANSEN STRUCTURES

2.1 Outline of the Tohoku Shinkansen RC structures

RC structures of the Tohoku Shinkansen Line from Omiya to Morioka stations were constructed in conjunction with the opening of the line in 1982. About 58 % of its length is RC viaduct and 13 % is bridges.

In Japan, several serious earthquakes have occurred, such as the 1995 Hyogoken-Nambu Earthquake, Sanriku Minami Earthquake in 2003, and Niigata Chuetsu Earthquake in 2004. Damage caused by the 1995 Hyogoken-Nambu Earthquake promoted the revision of earthquake resistant design codes in Japan which brought about the need to aseismically reinforce RC structures throughout Japan. RC railway structures in JR East also needed countermeasure works to improve the seismic performance of RC members and to prevent severe seismic damage such as the fall of girders and collapse of RC viaducts and bridges. JR East has accordingly been conducting the seismic rehabilitation of RC viaduct columns and bridge piers on a preferential basis in the seismic performance of the RC members.

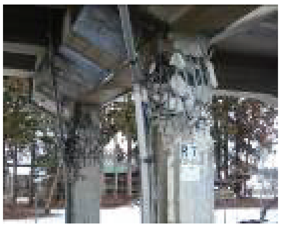
A	BB	B	C
Collapse of columns, fall of girders	Significant deformation of longitudinal bar, widespread fall of cover concrete, settlement of railroad track	Some amount of defo-rmation of longitudinal bar, widespread fall of cover concrete, no settlement of the railroad track	Cracks in cover concrete, partial fall of cover concrete
 *Photo shows example in Kobe Earthquake.			

Fig. 3 Gradation of seismic damage caused to RC column members

2.2 Damage to RC viaduct columns

Considering seismic damage, the failure modes of RC members are classified into two types according to the seismic performance: shear failure and flexure failure. The basic concept of seismic rehabilitation is to prevent shear failure of RC viaduct columns and bridge piers caused by large seismic temblors which result in the collapse of RC viaducts and bridges.

In Tohoku Shinkansen structures, the seismic rehabilitation to RC viaduct columns with deficient seismic performance classified as shear failure type has been completed. In addition, seismic rehabilitation has been planned for RC columns with low seismic performance classified as the flexure failure type. The damaged columns were categorized as flexure failure type and had been planned to conduct the seismic rehabilitation.

Fig. 3 shows the gradation of seismic damage caused to RC column members, the photos in Fig. 3 showing typical seismic damage of each level (Ishibashi et al. 1997). We consider that these levels could be classified by the degree of damage of RC members and restorability such as duration of work etc. In Fig. 3, damage level “A” indicates situations where the collapse of a structure such as RC columns or fall of the bridge girders is observed. Damage level “BB” shows situations where significant deformation of longitudinal reinforcing bar, widespread fall of cover concrete of RC columns, cracks penetrating into core concrete, and settlement of railroad track are observed. Damage level “B” indicates situations where some amount of deformation of longitudinal reinforcing bar, widespread fall of cover concrete of RC columns, and cracks penetrating into core concrete are observed, but settlement of railroad track is not observed. Damage level “C” shows situations where cracks in cover concrete and partial fall of cover concrete are observed, while settlement of railroad track is not observed. We consider that levels A, BB, and B are the types of damage sufficient to suspend Shinkansen operations. Furthermore, we consider that damage level C should not suspend the operations, but requires restoration in terms of durability.

Observations were made along the Tohoku Shinkansen to investigate the severity of the damage to RC structures caused by earthquakes and the mechanism of the damage. Table 1 shows the percentage of damaged RC columns as to the whole number of RC columns according to section between Omiya and Morioka stations. From Table 1, it is found that the level A damage was not observed, and that damaged columns in level BB, B, C, were observed in broad area. And, Table 1 suggests that the percentages of BB and B are both about 0.1 %, and that of C is 0.3%. Therefore, it can be determined

Table 1 The percentage of damaged RC columns as to the whole number of RC columns caused by the main earthquake on March 11, 2011, according to section

Sections	A	BB	B	C
From Omiya (30.3 km) to Nasushiobara (157.8 km)	0	0	0	0.0
From Nasushiobara (157.8 km) to Fukushima (272.8 km)		0	0.2	1.1
From Fukushima (272.8 km) to Sendai (351.8 km)		0	0.4	1.0
From Sendai (351.8 km) to Ichinoseki (445.1 km)		0.0	0.0	0.1
From Ichinoseki (445.1 km) to Morioka (535.3 km)		0.1	0.3	0.3
Total (Numbers of total columns about 50,000)	0	0.0	0.1	0.3

*Numbers in parentheses show the distance from Tokyo station. [unit: %]

Photo 1 Example of seismic damage of RC viaduct columns (damage level BB)

that the rate of damaged RC columns in the observed area is extremely low.

The example of the severest seismic damage of RC columns by the main shock is shown in Photo 1. We evaluated this seismic damage as BB. The seismic damage was located in the vicinity of the upper edge of columns. Settlement of railroad track of about 50 mm was also observed at this site. The damaged structure shown in Photo 1 is an RC rigid frame viaduct with 1 story and 3 spans, and supports the simple RC girders. The damaged columns are located at end of the block and their length is about 0.4 m shorter than the length of the columns located at the intermediate part of the block. It is found that the seismic damaged columns with track settlement are about 10 in total when we add the numbers of damaged columns caused by the main earthquake on March 11 and aftershock on April 7. Among these, damaged columns with falling of core concrete were observed. We assume that the column with prominent protrusion of core concrete damaged by the main quake was affected by its long duration.

As mentioned above, JR East has implemented seismic rehabilitation to RC columns with low seismic performance, and has completed implementation on very low-performance columns. In some RC railway viaducts, the space under the viaduct is used as stations, shops, and other buildings. Therefore, the seismic rehabilitation must deal with various obstructions such as partition walls and equipment. In this case, the rehabilitation site is a confined space, which means restrictions on the use of large construction equipment such as cranes. Often, construction schedule restrictions also apply, so a suitable method designed taking into account the various conditions at each site must be considered. JR East has developed various original kinds of the seismic rehabilitation techniques to resolve all restrictions adequately and economically.

Steel plate jacketing method (Ishibashi et al. 2004) is used most commonly for railway RC viaduct

Photo 2 Impact by earthquakes on columns with seismic rehabilitation by Steel plate jacketing method using indented joints

Photo 3 Impact by earthquakes on columns with seismic rehabilitation by Rib-Bar method

Photo 4 Impact by earthquakes on columns with seismic rehabilitation by Single-face method

columns for seismic rehabilitations of RC columns. Meanwhile, columns in limiting situations need to be reinforced by original techniques developed by JR East. Examples of impact on aseimically reinforced RC viaducts by the earthquakes of March 11 and April 7 are shown in Photos 2 to 4. In Photo 2, we observed that the column with the seismic rehabilitation only had the remarkably minor damage where the paint on the steel plate came off at butt joint. Furthermore, as shown in Photos 3 and 4, very minor damage was observed in columns that were aseismically reinforced by techniques developed by JR East. Thus, it is confirmed that the aseismically reinforced columns of RC railway viaducts suffered significantly less damage. Additionally, we consider that JR East's seismic rehabilitations of RC railway columns could be effective in preventing seismic damage.

2.3 Damage to RC bridge piers

We also investigated the severity of damage to RC railway bridge piers caused by the earthquakes along the Tohoku Shinkansen. Observations suggested that the damage of RC piers was mainly caused at cut-off of the longitudinal reinforcing bars. The categories of observed seismic damage included the partial fall of cover concrete and cracks, mainly occurring at cut-off. Additionally, we did not observe damage by shear failure leading to collapse of pier or fall of bridge girders. We consider that this could be the achievement of seismic rehabilitations to RC piers which JR East had been carrying out to the same degree as reinforcement of RC viaduct columns.

Fig. 4 shows gradation of seismic damage caused to RC bridge pier members, and the photos in Fig. 4 show typical seismic damage of each level. Each damage level was determined by the same situations as RC viaduct in Fig. 3.

Table 2 shows the percentage of damaged RC piers to the whole number of RC piers according to section between Omiya and Morioka stations. From Table 2, it is found that damage of piers in neither level A nor BB was observed, but damage of piers in levels B and C was observed over a broad area. In addition, Table 2 indicates that the percentage of B is about 0.1 % and that of C is 0.2%, respectively. Thus, it can be deduced that the rate of damaged RC piers in the observed area is extremely low.

An example of seismic damage in RC piers by the main shock is shown in Photo 5. We evaluated this seismic damage as B. The damaged structure shown in Photo 5 is on RC bridge pier 4.5 m in

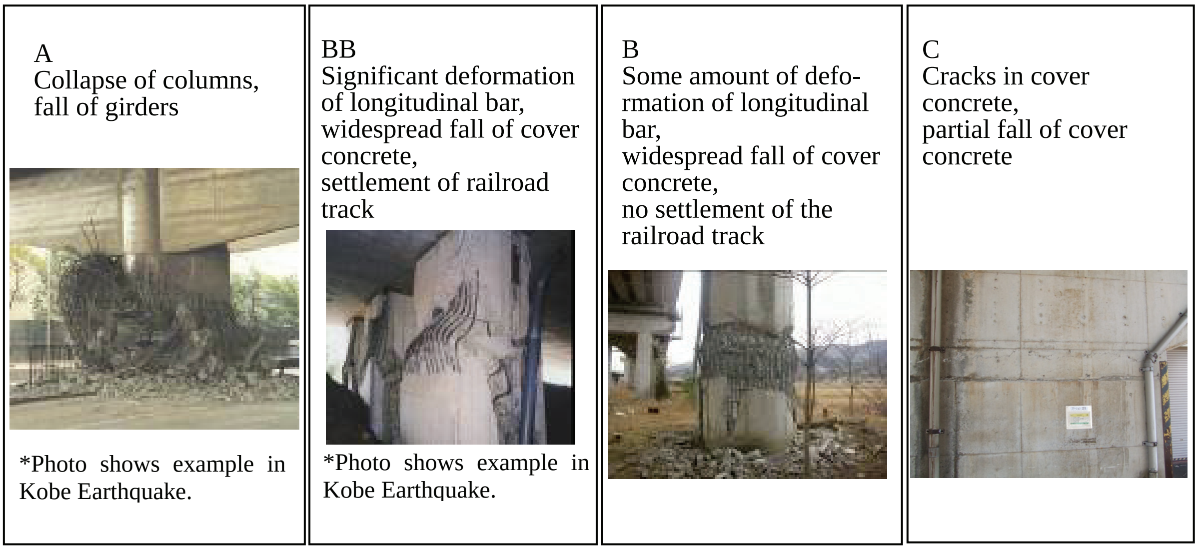


Fig. 4 Gradation of seismic damage caused to RC bridge pier members

Table 2 The percentage of damaged RC piers as to the whole number of RC piers caused by the main earthquake on March 11, 2011, according to section

Sections	A	BB	B	C
From Omiya (30.3 km) to Nasushiobara (157.8 km)	0	0	0	0
From Nasushiobara (157.8 km) to Fukushima (272.8 km)			0	0.2
From Fukushima (272.8 km) to Sendai (351.8 km)			0.3	0.5
From Sendai (351.8 km) to Ichinoseki (445.1 km)			0.1	0.1
From Ichinoseki (445.1 km) to Morioka (535.3 km)			0	0
Total (Numbers of total piers about 8,000)	0	0	0.1	0.2

*Numbers in parentheses show the distance from Tokyo station. [unit: %]

Photo 5 Example of seismic damage of RC bridge piers (damage level B)

diameter and 18.0 m in height, and supports pre-stressed concrete (PC) box-shaped girders. The box girders are 50 m and 35 m in length. We observed partial falls of cover concrete and cracks at cut-off at the seismically damaged pier.

JR East has also been implementing a program of seismic rehabilitation of RC piers with deficient

Table 3 Resumption date of the Tohoku Shinkansen operations and work duration of permanent repairs

Sections	Resumption date	Days from Mar. 11	Days from Apr. 7
From Tokyo (0 km) to Omiya (30.3 km)	Mar. 12	1	-
From Omiya (30.3 km) to Nasushiobara (157.8 km)	Mar. 15	4	-
From Nasushiobara (157.8 km) to Fukushima (272.8 km)	Apr. 12	32	5
From Fukushima (272.8 km) to Sendai (351.8 km)	Apr. 25	45	18
From Sendai (351.8 km) to Ichinoseki (445.1 km)	Apr. 29	49	22
From Ichinoseki (445.1 km) to Morioka (535.3 km)	Apr. 7	27	-
Re-suspended by aftershock on Apr. 7	Apr. 23	-	16
From Morioka (535.3km) to Shin-Aomori (713.7 km)	Mar. 22	11	-
Re-suspended by aftershock on Apr. 7	Apr. 13	-	6

*Numbers in parentheses show the distance from Tokyo station.

seismic performance, and has completed the program for low performance piers. The basic concept of the rehabilitation of RC piers is to improve seismic performance of the members at the base of pier and cut-off. Seismic rehabilitation method using RC jacketing is applied most commonly for railway RC bridge piers.

In some RC railway piers, the space around the pier is incorporated into river embankment, and is deeply buried. In other cases, some piers are located in the river. Therefore, the seismic rehabilitation must deal with various limitations, and we need to adopt suitable methods designed taking into account the various conditions on site. JR East has developed various original kinds of seismic rehabilitation which have adequate and economic application to RC bridge piers.

3. EARLY RESTORATION OF RC SHINKANSEN STRUCTURES

3.1 Outline of restoration work of the Tohoku Shinkansen structures and operations

RC structures of the Tohoku Shinkansen were restored quickly, by means of timely and adequate evaluation of the damaged RC members and permanent repairs. Table 3 shows the resumption date of Tohoku Shinkansen operations and work duration of permanent repairs. In Table 3, the duration of repair work includes the course of action from the earthquake occurrence, investigations, permanent repair work, running test of Shinkansen cars, and resumption of operation. Table 3 indicates that the elapsed time to re-operation suggests the severity of seismic damage of RC members. So, areas with most elapsed days required longer to restore. The earliest resumption was after 1 day, and the latest was after 49 days. Moreover, as mentioned above, work duration in Table 3 includes time of observation and commission. And so, we consider that permanent repair work to the damaged RC members was accomplished in short term considering the extent of the damaged area by the earthquakes. In addition, a strong aftershock occurred on April 7 which caused seismic damage to the Shinkansen structures again, and this aftershock required JR East to restart observations along the Shinkansen Line as an initial step in further restoration work. Although repair work prolonged as a consequence of the aftershock on April 7, it was found that the damaged structures were restored for operation of Tohoku Shinkansen within about 3 weeks.

Restoration techniques have been refined through adequate engineering judgment and timely decision-making as to method of repair work by JR East based on experience through past earthquakes. Engineers and techniques obtained from the past restoration work in maintenance and construction companies are also considered important. We consider that all of these factors facilitated the restoration of the Tohoku Shinkansen Line in just 49 days.

Photo 6 Restored RC columns

Photo 7 Restored RC pier

3.2 Restoration work of RC viaduct columns

Repair work of RC viaduct was conducted taking priority of the damage level of the members. Therefore, the severity of the damaged members through the observations was firstly determined, and then the principle to restore the damage was decided. As for the repair work, JR East proceeded with the restoration of damaged structures sequentially from damage level BB, B to C. With consecutive restoration, it is considered that the materials and labor power for the repair work were able to be obtained effectively, and the work duration shortened.

Photo 6 shows the restored columns which sustained level BB damage. The repair procedure of the damaged columns in level BB as follows: First, steel temporary support was placed beneath the cross beam, and then the longitudinal reinforcing bars were cut off tentatively. Next, the concrete slab supporting the railroad track was lifted by jacks. After being jacked up, the longitudinal reinforcing bars were rearranged at the appropriate position, and were connected up to the cut reinforcing bars with welded joint. After the treatments of the longitudinal bars, the transverse reinforcing bars were set at proper position. Then, the chemical materials were grouted between the cracks. And finally, the mortars were grouted to recover the member. With this course of work, we consider that the permanent repair work to restore the seismic performance of the damaged columns in level BB up to the original level or higher was conducted. Further, the work duration at the site shown in Photo 6 was about 7 days.

3.3 Restoration work of RC bridge piers

The repair work of RC piers was also carried out taking priority of the damage level of the members. Photo 7 shows the restored pier which sustained level B damage. The repair procedure of this damaged pier was as follows. The chemical grouting between the cracks was conducted first. And then, the transverse reinforcing bars were rearranged at the appropriate position. Finally, the cover was refilled with mortar. Further, the work duration at the site shown in Photo 7 was only about 8 days.

4. CONCLUSIONS

In this paper, authors have indicated the outline of seismic damage of the Tohoku Shinkansen structures and the early restoration. The conclusions from this paper can be summarized as follows:
(1) Although the extent of the damaged structures was broad, the percentage of damaged structures as to the total number of structures was extremely low.
(2) No fatal damage which led to the collapse of the structure systems in the Tohoku Shinkansen had been observed.
(3) The seismic damage caused to RC viaduct columns was mainly located in the vicinity of the upper edge of columns. And, that of RC bridge piers was mainly located at cut-off.
(4) The columns and piers with seismic rehabilitation had the significantly minor damage. Therefore, authors consider that the scheduled and consecutive seismic rehabilitation to RC structures by JR East is effective to prevent seismic damage.
(5) Work duration of the restoration of the damaged Shinkansen structures could be shortened through refined techniques.

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