Damage of Bridge Structures during Recent Earthquakes and the Effectiveness of Seismic Retrofit

by

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ABSTRACT

This paper presents the damage of bridge structures during recent earthquakes in Japan and the effectiveness of seismic retrofit works for existing bridge structures. The past seismic retrofit practices for bridge structures and the damage caused by recent earthquakes including the 2004 Niigata-ken-chuetsu earthquake are presented. Through the damage investigations, the effectiveness of the seismic retrofit works is discussed from the view point of damage.

KEYWORDS: Bridge, Damage, Effectiveness, Niigata-ken-chuetsu Earthquake, Recent Earthquakes, Seismic Retrofit

1. INTRODUCTION

Based on the damage experiences to bridge structures in the past earthquakes since the 1923 Kanto Earthquake, the earthquake disaster prevention technology for bridge structures had been developed and improved. With progress of such improvement of the seismic design and the construction technology, the damage to bridge structures by the earthquakes had been remarkably decreasing.

However, the Hyogo-ken-nanbu earthquake of January 17, 1995, caused destructive damage to bridge structures. Collapse and nearly collapse of superstructures occurred at 9 sites, and other destructive damage occurred at 16 sites [1]. The earthquake revealed that there were a number of critical issues to be revised in the seismic design and seismic retrofit of bridge structures. Based on serious damage experiences during the Hyogo-ken-nanbu earthquake, the seismic design code has been revised and the seismic retrofit works have been made throughout the country [2,3].

After the Hyogo-ken-nanbu earthquake, several damaging earthquakes have occurred including 2003 Miyagi-ken-hokubu earthquake (M6.4, JMA Intensity of VI Upper), 2003 Tokachi-oki earthquake (M8.0, VI Lower), 2004 Niigata-ken-chuestu earthquake (M6.8, VII), and 2007 Niigata-ken-chuetsu-oki earthquake (M6.9, VI Upper). During these earthquakes, the houses and some of infrastructures have been seriously damaged, but not so for bridge structures. It is understand that the progress of the seismic retrofit works contributes to increase the safety of bridge structures. So, it is important to investigate the effectiveness of seismic retrofit to decrease the earthquake damage in detail.

This paper presents the damage of bridge structures during recent earthquakes in Japan and the effectiveness of seismic retrofit works for existing bridge structures. The past seismic retrofit practices for bridge structures and the damage caused by recent

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earthquakes including 2004 Niigata-ken-chuetsu earthquake are presented. Through the damage investigations, the effectiveness of the seismic retrofit works is discussed from the view point of damage.

2. SEISMIC RETROFIT WORKS FOR BRIDGES

2.1 Past Seismic Evaluation and Retrofit of Bridges before 1995 Hyogo-ken-nanbu Earthquake

The MLIT made seismic evaluation investigation of bridge structures 5 times throughout the country since 1971 as a part of the comprehensive earthquake disaster prevention measures for highway facilities [4,5]. Seismic retrofit for vulnerable bridges had been successively made based on the seismic evaluations. **Table 1** shows the history of past seismic evaluations.

The first seismic evaluation was made in 1971 to promote earthquake disaster prevention measures for highway facilities. The significant damage of bridges caused by the San Fernando Earthquake, US, in February 1971, triggered the seismic evaluation. Bridges with span length longer than or equal to 5m on all sections of national expressways and national highways, and sections of the others were evaluated. Attention was paid to detect deterioration such as cracks of reinforced concrete structures, tilting, sliding, settlement and scouring of foundations. Approximately 18,000 bridges in total were evaluated and approximately 3,200 bridges were found to require retrofit.

Following the first seismic evaluation, it had been subsequently made in 1976, 1979, 1986 and 1991 with gradually expanding highways and evaluation items. The seismic evaluation in 1986 was made with the increase of social needs to insure the seismic safety of highway traffic after the damage caused by the Urakawa-oki earthquake in 1982 and the Nihon-kai-chubu earthquake in 1983. The bridges with span length longer than or equal to 15m on all sections of national expressways, national highways and principal local highways, and sections of the others, and overpasses were evaluated. The evaluation items included deterioration, unseating prevention devices, strength of substructures and stability of foundations. Approximately 40,000 bridges in total were evaluated and approximately 11,800 bridges were found to require retrofit. In the 1991 seismic evaluation, the highways to be evaluated were expanding from the evaluation in 1986. Approximately 60,000 bridges in total were evaluated ad approximately 18,000 bridges were found to require retrofit. Through a series of seismic retrofit works, approximately 32,000 bridges were retrofitted by the end of 1994.

Emphasis had been placed to install the unseating prevention devices in the past seismic retrofit. Because the installation of the unseating prevention devices was being completed, it had become important to promote the strengthening of substructures with inadequate strength, lateral stiffness and ductility.

2.2 Seismic Retrofit Program after 1995 Hyogo-ken-nanbu Earthquake

For increasing seismic safety of the bridge structures that suffered damage by the Hyogo-ken-nanbu Earthquake, various new drastic changes were introduced in the new design codes and seismic retrofit for bridge structures.

Because the damage concentrated to single reinforced concrete piers/columns with small concrete section, the seismic retrofit program had initiated for those columns, which were designed by the pre-1980 Design Specifications, at extremely important bridges such as bridges on expressways, urban expressways, and designated highway bridges, and also double-deckers and over-crossings, etc. which significantly affected highway functions once damaged. The program was 3-years program since 1995 and approximately 30,000 piers were evaluated and retrofitted by the end of 1997 fiscal year. Unseating devices were also installed for these extremely important bridges. After the 3-years program, the speed to promote the seismic retrofit works became a little slow but it had been steadily continued. In general, the bridge with easy construction condition sites had been completed but the bridge with the difficult condition sites were still waiting for the works .

2.3 3-years (2005-2007) Program of Seismic Retrofit Program

The MLIT has made the 3-years program of seismic retrofit of existing bridge structures in the fiscal year of 2005-2007. The objectives of this program were to promote the seismic retrofit and to complete the improvement for important emergency route rapidly. The program was initiated by the damage experiences caused by the 2004 Niigata-ken-chuetsu earthquake and Fukuoka-ken-seiho-oki earthquake. And also the urgency of the occurrence of large scale earthquakes anticipated at the pacific plate boundaries including Tokai, Tonankai, Nankai earthquakes. The period of the program was limited for 3 years and the retrofit works were to be made considering the effectiveness and efficiency for road networks.

The target bridges in the program were the bridges designed according pre-1980 design specifications including,

a) Retrofit for Columns

1) Single reinforced concrete column bents with termination of longitudinal re-bars at mid-height
2) Steel single column bents
3) Fixed reinforced concrete column bents at continuous girder bridges with termination of longitudinal re-bars at mid-height

b) Unseating Prevention Devices

4) Simply-supported girder bridges except single span bridge with abutments at both ends
5) Continuous girder bridges with the soil condition of the lateral spreading by the liquefaction effects

These bridges were given high priority to be retrofitted based on the past earthquake damage statistical data.

2.4 Seismic Retrofit Measures

Main purpose of the seismic retrofit of reinforced concrete columns is to increase their shear strength, in particular at the piers with termination of longitudinal reinforcements at the mid height without enough development length. This enhances the ductility of columns, because premature shear failure could be avoided.

However, if only the ductility of piers is enhanced, residual displacement developed at piers after an earthquake may increase. Therefore, the flexural strength should also be increased as necessary. However, the increase of flexural strength of piers tends to increase the seismic force transferred from the piers to the foundations. It was found from an analysis to various types of foundations that failure of the foundations by increasing the seismic force may not be significant if the increasing rate of the flexural strength of piers is less than 2. It is therefore suggested to increase the flexural strength of piers within this limit so that it does not cause serious damage to foundations. For such requirements, seismic strengthening by Steel Jackets with Controlled Increase of Flexural Strength was suggested. This uses steel jacket surrounding the existing columns as shown in **Fig.1**. Epoxy resin or shrinkage-compensation mortar is injected between the concrete surface and the steel jacket. A small gap is provided at the bottom of piers between the steel jacket and the top of footing. This prevents to excessively increase the flexural strength. To increase the flexural strength of columns in a controlled manner, anchor bolts are provided at the bottom of the steel jacket. They are drilled into the footing. By selecting appropriate number and size of the anchor bolts, the degree of increase of the flexural strength of piers may be controlled. The gap is required to introduce the flexural failure at the bottom of columns. Piers with a rectangular section also have H-beams installed around them at the lower end of the jacket. This prevents the bulging of longitudinal bars and keeps the confining effect of the jacket.

Conventional reinforced concrete jacketing methods are also suggested for the retrofit of reinforced concrete piers, especially for the piers that require the increase of strength. It should be noted here that the increase of the strength of the pier should carefully be designed in consideration with the strength of foundations and footings.

Also, retrofit for mid-height section of column bents have also used to prevent the brittle shear failure at the section. Steel jacketing or sheet jacketing using carbon fiber sheets or aramid fiber sheets, which are light-weight and so with relatively easy construction condition because of no need to use the construction machines, have been applied to improve the shear and bending strength at the section as shown in **Fig. 2**.

The steel jacketing method as described in the above was generally applied for reinforced concrete with circular section or rectangular section of a/b <3. The seismic retrofit concept for a wall-type pier is the same as that for rectangular piers. It is important to increase the flexural strength and ductility capacity with the appropriate balance. Generally, the longitudinal reinforcement ratio is smaller than that for the rectangular pier, then the flexural strength is smaller. Therefore, it is essential to increase the flexural strength appropriately. Since the longitudinal reinforcement was generally terminated at mid-height without appropriate anchorage length, it is also important to strengthen both of flexural and shear strength of the mid-height section.

During the Hyogo-ken-nanbu earthquake, some two-column bents were damaged in the longitudinal and transverse directions. The strength and ductility characteristics of the two-column bents have been studied and the analysis and design method was introduced in the 1996 Design Specifications.

The strength and ductility of existing two-column bents were studied both in the longitudinal and transverse directions. In the longitudinal direction, as the same as a single column, it is required to increase the flexural strength and ductility with appropriate balance. In the transverse direction, the shear strength of the columns or the cap beam is generally not enough in comparison with the flexural strength.

Fig. 3 shows the suggested possible seismic retrofit methods for two-column bents. The concept of the retrofit is to increase flexural strength and ductility as well as shear capacity for columns and cap beams. In the field practices, axial force in the cap beam is much smaller than that in the columns so that the enhancement of the shear capacity for the retrofit of the cap beam is more often essential. Since the jacketing of cap beam is difficult because of the existing bearing supports and construction space, the effective retrofit measures for cap beam such as application of jacketing by new materials with high elasticity and high strength and out-cable pre-stressing, etc. has been developed.

3. RECENT DAMAGE EARTHQUEKS AND THE EFFCETIVENESS OF SEIMSIC RETROFIT WORKS

3.1 Recent Damaging Earthquakes

After the Hyogo-ken-nanbu earthquake, several damaging earthquakes have occurred including 2003 Miyagi-ken-hokubu earthquake (M6.4, JMA Intensity of VI Upper), 2003 Tokachi-oki earthquake (M8.0, VI Lower), 2004 Niigata-ken-chuestu earthquake (M6.8, VII), 2005 Fukuoka-ken-seiho-oki earthquake (M7.0, VI Lower), 2007 Noto-hanto-oki earthquake (M6.9, VI Upper), and 2007 Niigata-ken-chuetsu-oki earthquake (M6.9, VI Upper). By these earthquakes, the houses and some of infrastructures have been damage seriously, but not so for bridges. In this section, some of the important examples to discuss the effectiveness of seismic retrofit for bridge structures are shown.

3.2 Example 1: 1995 Hyogo-ken-nanbu Earthquake

During the 1995 Hyogo-ken-nanbu earthquake, the Kobe route, No.3, of the Hanshin expressway was heavily damaged. Some bridges were collapsed or nearly collapsed and a number of superstructures, bearings, and columns were seriously damaged. Before the earthquake, based on the 1986/1991 MLIT seismic evaluation and seismic retrofit program, the Hanshin Expressway corporation initiated to retrofit some columns on the Kobe route at Tsukimiyama section [6]. Since the area was located by 1km from JR Takatori station that was almost in the area of the JMA Intensity 7, therefore, the intensity of shaking at the place was estimated to be strong.

The damage difference between two piers of P714 and P715, which were adjacent piers by 30m, is discussed here. They supported simply PC girder with span length of 30m. The height of pier was 11m and the piers were supported by the pile foundations with pile length of 10m. Soil condition was estimated as Type II medium ground.

Before the earthquake, P714 was already retrofitted using steel jacketing with steel plate of 12mm thickness at the column section. P715 was planned to be retrofitted, but was as-built without any retrofit at the time of the earthquake.

Photos 1 and **2** show two piers taken after the earthquake. No damage was found at superstructures and/or bearings, and other effects including the sand boiling caused by the liquefaction was not found. At P715, the cracks and spall of cover concrete and the buckling of longitudinal re-bars at mid-height section of columns, which was the termination section of the some on the longitudinal re-bars, was found. The pier was not collapsed but the damage was serious and significant. The bottom of the column was investigated after the earthquake by removing the surrounding soils but no damage at the bottom was found.

On the other hand, at pier P714, no damage was recognized from the outside view. No peeling of the coating paint of the steel jacketing was found. After the earthquake, the connection between steel plate and inside concrete was checked by hammering test, then the some separation was found at the some location. Based on the detailed investigation, no crack was found in the core concrete. This shows the effectiveness of the seismic retrofit for the column to prevent the bending and shear failure by the steel jacketing.

4.2 Example 2: 2003 Miyagi-ken-hokubu Earthquake

Miyagi-ken-hokubu earthquake occurred on July 26, 2003, at Sendai area which was located at the north of main island of Japan. The JMA intensity of VI Upper was recorded.

The effectiveness of the unseating devices was recognized at Ono bridge as shown in **Photo 3**. Ono bridge was constructed in 1935 and relatively old bridge. Superstructure was simply supported steel girder, and the bearing was simple steel plate and anchor bolts. Substructures were RC two column bents with caisson foundations. The bridge was located about 2 km from the epicenter. The strong motion observed at the nearest MLIT strong motion observation station, which was located 1km from the bridge, was the peak acceleration of 440gal and SI value of 51kine.

By the earthquake, all of the bearings at piers and abutments were damaged. Anchor bolts were failed in shear or pulled-out, and some of the steel plates of bearings were fractured at the welded section as shown in **Photo 4**. Some deterioration at the bearings was also found.

Ono bridge was damaged in the 1978 Miyagi-ken-oki earthquake as well. As the same as this time earthquake, the bearings were failed at 9 of 13 spans and the girder was displaced by 65cm in the transverse direction and 10cm in the longitudinal direction. The damage was repaired by installing the steel plates and anchor bolts. Then the unseating devices connecting the adjacent girders by steel plates and PC cables, and the steel bracket to increase the seat width to prevent falling down of superstructures by excessive displacement were installed.

During the earthquake, all girders moved in the longitudinal direction by about 20cm. The gap of about 10cm in the vertical direction at the expansion joints was developed. The largest displacement was found at the abutment but the unseating devices by PC cables worked effectively to restrain the excessive displacement as shown in **Photo 5**.

4.3 Example 3: 2004 Niigata-ken-chuetsu Earthquake

The Niigata-ken-chuetsu earthquake occurred October 23, 2004. The magnitude was 6.8 and the JMA intensity of 7 was observed, which was firstly recorded after the 1995 Hyogo-ken-nanbu earthquake. Several large aftershocks also occurred. The magnitude was not so large but the depth was shallow as about 10km, then the shaking became strong.

The effectiveness of the seismic retrofit at Shinkumi bridge is shown here. Shinkumi bridge was constructed in 1989 to overpass the railway as shown in **Photo 6**. The superstructures were of 2-span simply-supported steel girders and 3-span continuous steel girder. The substructures were RC columns with a circular section and supported by the pile foundations. Bearings were a steel plate type. The bridge consisted of two same but completely separate bridges, which had two inbound and down bound lanes, respectively. The columns of one bridge were already retrofitted by steel jacketing as shown in **Photo 7**. For the other bridge, the retrofit works were planed to be made in near future.

The damage was found at the bridge columns without retrofit works. The heaviest damage was found at the mid-height section of pier P5. That was the termination section of some of the longitudinal re-bars at mid-height. The cracks, spall-off of cover concrete, and buckling of re-bars were found as shown in **Photo 8**. At other piers of the same bridge, bending and shear cracks were observed. However, there were no damage at the retrofitted bridge and the retrofit works by the steel jacketing worked effectively.

4.4 Example 4: 2007 Nigata-ken-chetsu-oki Earthquake

The Niigata-ken-chuetsu-oki earthquake occurred July 16, 2007 in Niigata area. The magnitude was 6.8 and the JMA intensity was VI upper. As the same as the 2004 Niigata-chuetsu earthquake, the damage was serious and a number of houses were affected. Nuclear power plant was also affected by the earthquake.

There were two long-span bridges with seismic retrofit works. Agewa bridge and Yoneyama bridge are shown here. It should be noted here that the strong motion observation data recorded at the site closest to the bridges was peak acceleration of 659gal and SI value of 77kine.

The Agewa bridge was constructed in 1965. Superstructure was steel arch bridge as shown in **Photo 9**. Simple span steel gerber girders were at the both end of the arch section. The bridge length was 197m. The abutments were gravity type and wall type, and the foundations were spread type and pile foundations. Arch abutments were spread type foundation. Both ends were movable type bearing and fixed bearing at the both end of arch section as shown in **Photo 10**.

The bridge was already made retrofitted as shown in **Fig. 4**. The bearings at the both ends of arch section were made to be fixed. The light weight concrete was filled in the arch rib to increase strength and ductility of ribs. And the unseating prevention devices were installed.

By the earthquake, some movement was found at the both joints and abutments, but no remarkable damage was found at the main members such as arch ribs. Some buckling and deformation was found at connection section of the lower lateral beam. Although it is necessary to investigate more in detail, the seismic retrofit to increase the strength and ductility of the ribs was estimated to work effectively to resist the seismic inertia force.

One more bridge was Yoneyama bridge, which was constructed in 1967, which was located just close to the site where the large scale land slide occurred at the Oume railway station.

Superstructures were 3-span continuous steel box girder and 2 span continuous steel girder as shown in **Photo 11**. The bridge length was 279m. Abutments are wall type with spread type and caisson foundations. Piers were steel frame structures with height of about 44m. The bridge was retrofitted by the strengthening the bottom of steel piers, concrete infill to the steel columns, and added stiffeners to the lateral beams of piers, and the installation of the unseating prevention devises, were made as shown in **Fig. 5**.

During the earthquake, the bearings were damaged as the deformation of shear keys as shown in **Photo 12**. No damage was found at the columns and other main members. Although it is necessary to investigate more in detail, the seismic retrofit to increase the strength and ductility of the steel piers was estimated to work effectively to resist the seismic inertia force.

5. CONCLUSIONS

This paper presented the damage of bridge structures during recent earthquakes and the effectiveness of seismic retrofit works for existing highway bridges. The past seismic retrofit practices for highway bridges and the damage caused recent earthquakes including 2004 Niigata-ken-chuetsu earthquake were presented. Through the damage investigations, the effectiveness of the seismic retrofit works was discussed.

To verify the effectiveness of the seismic retrofit works in more detail, it is important to continue to add more data and to conduct the analytical investigation.

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Table 1 Past Seismic Evaluations for Bridge Structures

Year	Highways Inspected	Inspection Items	Number of Bridges: Inspected	Number of Bridges: Require Strengthening	Number of Bridges: Strengthened
1971	All Sections of National Expressways and National Highways, and Sections of the Others(Bridge Length≧5m)	①Deterioration ②Bearing Seat Length S for Bridges supported by Bent Piles	18,000	3,200	1,500
1976	All Sections of National Expressways and National Highways, and Sections of the Others(Bridge Length≧15m or Overpass Bridges)	①Deterioration of Substructures, Bearing Supports and Girders/Slabs ②Bearing Seat Length S and Devices for Preventing Falling-off of Superstructure	25,000	7,000	2,500
1979	All Sections of National Expressways,National Highways and Principal Local Highways, and Sections of the Others (Bridge Length≧15m or Overpass Bridges)	①Deterioration of Substructures and Bearing Supports ②Devices for Preventing Falling-off of Superstructure ③Effect of Liquefaction ④Bearing Capacity of Soils and Piles ⑤Strength of RC Piers ⑥Vulnerable Foundations (Bent Pile and RC Frame on Two Independent Caisson Foundation)	35,000	16,000	13,000
1986	All Sections of National Expressways, National Highways and Principal Local Highways, and Sections of the Others (Bridge Length≧15m or Overpass Bridges)	①Deterioration of Substructures, Bearing Supports and Concrete Girders ②Devices for Preventing Falling-off of Superstructure ③Effect of Soil Liquefaction ④Strength of RC Piers(Bottom of Piers and Termination Zone of Main Reinforcement) ⑤Bearing Capacity of Piles ⑥Vulnerable Foundations(Bent Piles and RC Frame on Two Independent Caisson Foundation	40,000	11,800	8,000
1991	All Sections of National Expressways, National Highways and Principal Local Highways, and Sections of the Others (Bridge Length≧15m or Overpass Bridges)	①Deterioration of Substructures, Bearing Supports and Concrete Girders ②Devices for Preventing Falling-off of Superstructure ③Effect of Soil Liquefaction ④Strength of RC Piers(Piers and Termination Zone of Main Reinforcement) ⑤Vulnerable Foundations(Bent Piles and RC Frame or Two Independent Caisson Foundation)	60,000	18,000	7,000 (As of the End of 1994)

Note) Number of bridges inspected, number of bridges that required strengthening and number of bridges strengthened are approximate numbers.

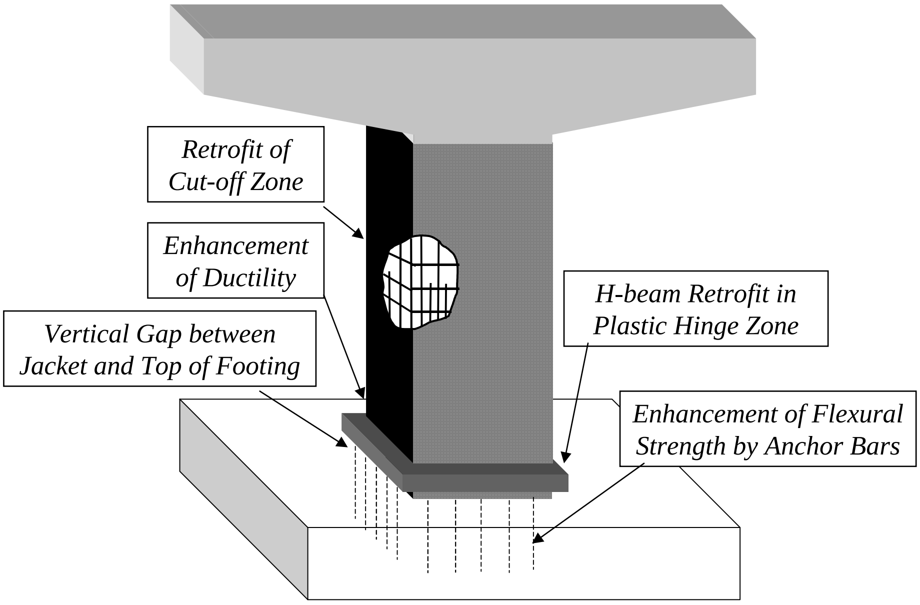

Fig. 1 Seismic Retrofit Measures for Single RC Columns (Steel Jacketing)

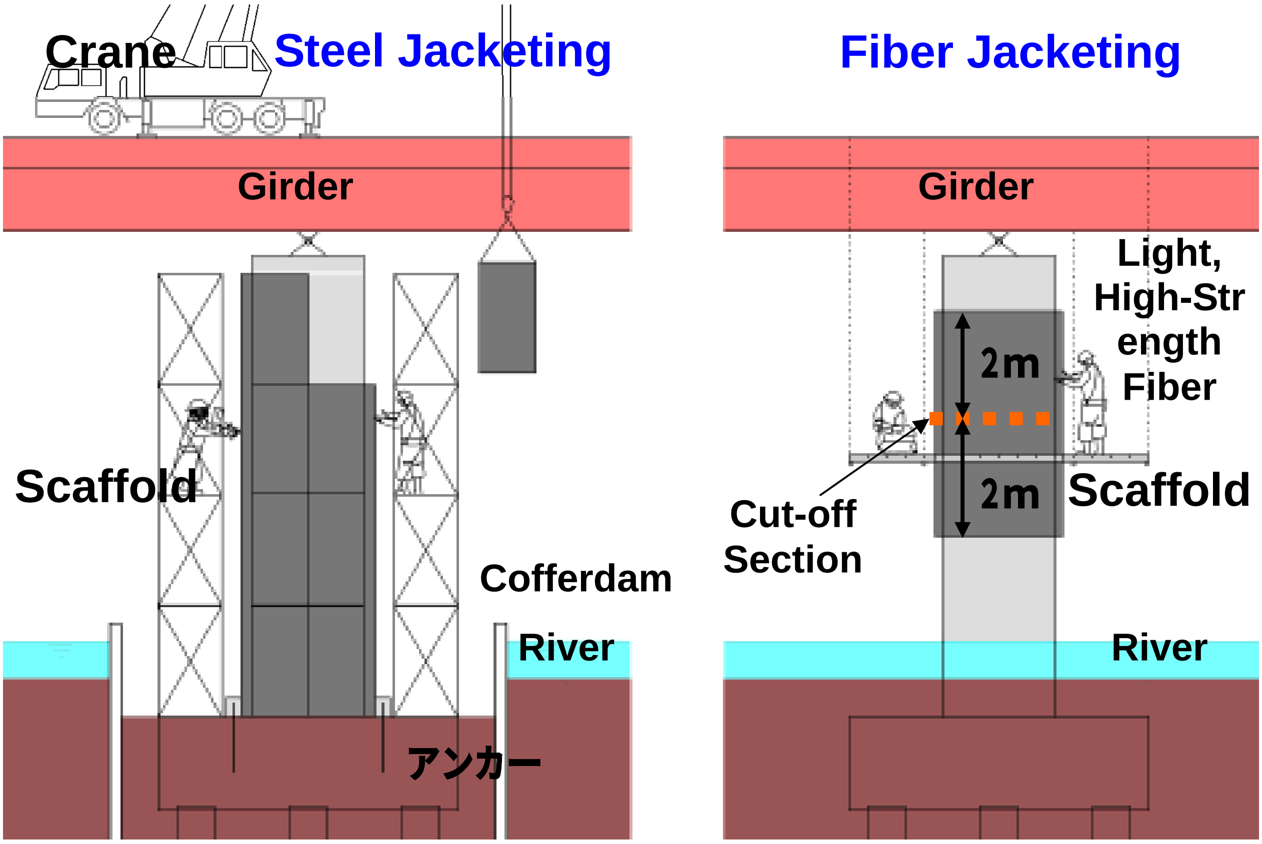

Fig. 2 Comparison of Construction Methods for Steel Jacketing and Fiber Sheet Jacketing for River Bridges

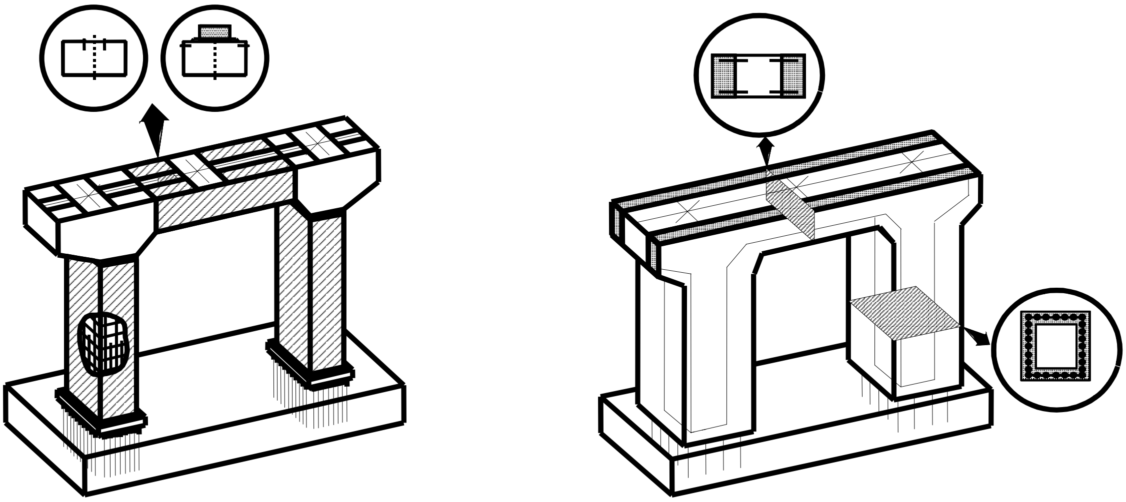

Fig. 3 Seismic Retrofit Measure for Two Column Bents

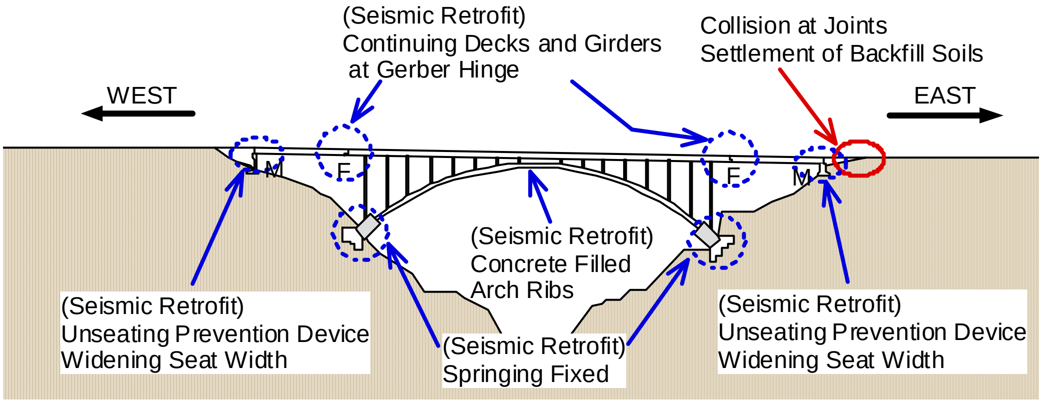

Fig. 4 Seismic Retrofit and Damage to Agewa Bridge

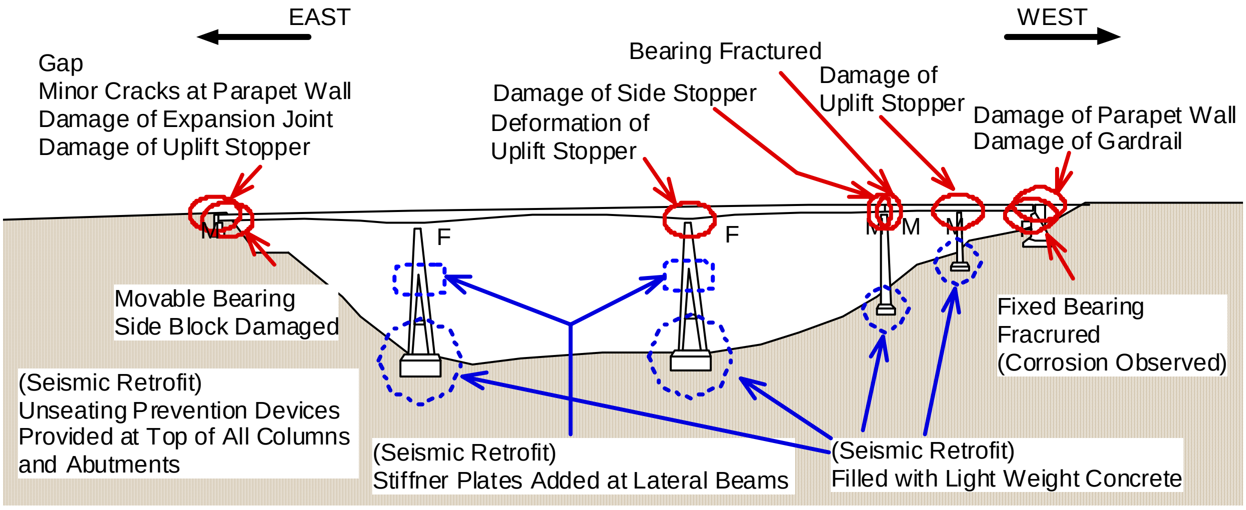

Fig. 5 Seismic Retrofit and Damage to Yoneyama Bridge

Photo 1 Retrofitted Pier P714 of Hanshin Expressway [6]

Photo 2 Pier P715 of Hanshin Expressway [6]

Photo 3 Ono Bridge

Photo 4 Damage of Bearings

Photo 5 Effectiveness of PC Cable Type Unseating Prevention Devices

Photo 6 Shinkumi Bridge **Photo 7** Retrofitted Columns with Steel Jacketing (No damage)

Photo 8 Damaged Pier P5 (Before Retrofit)

Photo 9 Agewa Bridge **Photo 10** Retrofitted Springing Section of Arch Rib (Concrete Jacketing)

Photo 11 Yoneyama Bridge

Photo 12 Deformation of Shear Keys and Pin Caps of Bearings

Photo 13 Unseating Prevention Devices (Cable Restrainers in Longitudinal and Uplift Directions)