SEISIMIC RETROFIT OF LARGE CABLE-SUPPORTED BRIDGES ON TOKYO METROPOLITAN EXPRESSWAYS

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Abstract

Three large cable-supported bridges of the Metropolitan Expressways are now under seismic retrofit work, in order to meet the standard determined after the Kobe earthquake. First of all, when the seismic retrofit methods were examined, a basic flow of assessment procedure against Level-2 design seismic ground motions was generated. Then, Level-2 input seismic waves were formed. And based on their reaction from Level-2 earthquakes by using nonlinear-dynamic analysis, individual damage-chain-reaction diagrams were created for three bridges. Then, retrofitting methods have been implemented to limit the damage within its acceptable level.

1. Introduction

Three large cable-supported bridges, the Yokohama Bay Bridge, Rainbow Bridge and Tsurumi Tsubasa Bridge on the Metropolitan Expressway, were opened to service in 1989, 1993 and 1994, respectively. Because all those were designed prior to the Hyogo-ken Nanbu (Kobe) earthquake occurred in 1995, Level-2 design earthquakes were

Yokohama Bay Bridge　　Rainbow Bridge　　Tsurumi Tsubasa Bridge

Photos-1　Long Span Cable-supported Bridges on Metropolitan Expressways

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not used. Level-2 earthquakes are defined after the Kobe earthquake, which have extremely strong acceleration level, however, low possibility to occur during the life time of bridges. Therefore, the seismic analysis and retrofitting against the Level-2 earthquake were needed for those three bridges. To begin with, the basic principles of seismic assessment were determined. The Level-2 seismic waves were prepared and nonlinear-dynamic analyses were carried out. Then, the damages on the bridges were evaluated and the seismic retrofitting methods were chosen based on the results of the analyses. In this text, these retrofitting methods are explained in detail.

2. Outline of the Three Bridges

Yokohama Bay Bridge is a three-span suspension bridge with a continuous steel stiffening truss. Its total length is 860m and the central span is 460m. The Daikoku wharf located at the entrance of the Yokohama port and the Honmoku wharf are directly connected to this bridge. The stiffening truss of the bridge is hanged by cables in a double-fan type layout which has a Metropolitan Expressway route on its top layer and the national route No.375 on the bottom. The national route No.357 has two traffic lanes and opened on April 4th, 2004. The multi pillar type was chosen as the substructure of the bridge, because the bed rock was located in deep down beneath unevenly. Short pendulum type links connect the towers and the girder. Its swinging motion in the longitudinal direction releases the thermal stress and isolates the girder seismically by stretching out the length of natural period of the bridge. This also reduces the seismic force on main towers and side piers while limiting the movement of the girder in the longitudinal direction (MEPC, 1994) (JSCE, 1999).

Rainbow Bridge, the total length is 798m, is a suspension bridge with steel stiffening trusses. It is located beyond a sea route between Shibaura and Daiba in the Tokyo bay with its center span of 570m and side spans of 114m. Its stiffening truss has

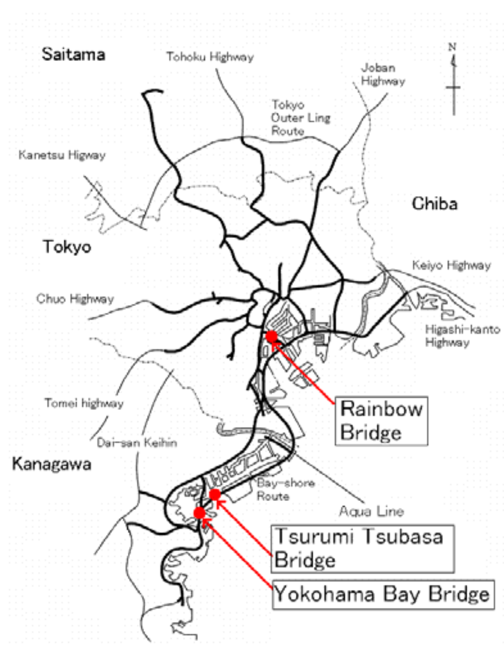


Figure-1 Location of Bridges

Table-1 Natural Period of the Bridges (Unit:Second)

Direction	Yokohama Bay Bridge	Rainbow Bridge	Tsurumi Tsubasa Bridge
Longitudinal	7.82	4.34 ～ 6.45	2.91
Lateral	3.55	8.57	4.00

two layered decks, too. The top layer has a Metropolitan Expressway route and the bottom has an ordinary route with sidewalk and the new transportation system "Yurikamome". The substructures of the bridge were constructed using the pneumatic caisson method (MEPC, 1996) (JSCE, 1999).

Tsurumi Tsubasa Bridge is located over the Tsurumi sea route in Yokohama area. This cable-stayed bridge has three continuous spans of which the total length is 1020m and the center span length is 510m. Its upside-down Y shaped main towers hang the flat box girder with cables in single faced fan-type layout. This center span length is the world longest among those types of cable-stayed bridges, so far. The main tower consists of two segments, the upper portion is made of steel and the bottom is from steel framed reinforced concrete. The substructure was constructed using the pneumatic caisson method on the bed rock which consists of diluvial deposits. Main towers and the box girder are connected each other in the longitudinal direction using steel cables. These cables elastically connect main towers and the box girder and vane-type dampers which have the pressure controlling system and work together to enhance the damping performance in case of a large scaled earthquake (MEPC, 1994, JSCE, 1999). The lengths of natural periods of those three bridges in main vibration mode are fairly long as shown in Table-1.

3. Principle of Seismic Assessment

For the bridges to be analyzed here, two types of "Level-2 design earthquake" are used as recommended in the Japanese bridge code (Japan Road Association, 2002). Level-2 earthquake is defined extremely strong but seldom occurs during the life time of the bridge and supposed to be originated at a border of continental plates or an in-land fault line. Therefore, the target of the seismic retrofitting of those three bridges against Level-2 earthquake is limited, so that the bridge does not collapse or the girders do not fall off. To be concrete, even though damaged parts of the bridge might need long time to be fixed, emergency vehicles can go through under supervision once temporary repair is finished. Also ordinary passengers can also use the bridge with some strict speed limitation until permanent repair works have been completed.

Figure-2 shows a rough flow of retrofitting design for those three bridges. As this design project was processed, large amount of related reports were referred to input earthquake wave, analysis method and verification of the analysis output.

Input seismic waves were prepared using earthquake prediction methods (Monthly Earthquake, 2002) which were developed based on earthquake engineering after the Hyogo-ken Nanbu earthquake in order to make regional disaster prevention plans or to seismically design variety of structures (Kataoka et al, 2002).

The analytical models of the bridges are built in consideration of the nonlinearity of the structure where some damage is predicted by the Level-2 earthquakes. And referring to vibration data obtained by the seismographs set on Yokohama Bay Bridge, structural damping factors of steel members are decided (Wakabayashi et al, 1993) (Yabe et al, 1993).

The damages on the three bridges caused by Level-2 earthquakes are assumed from

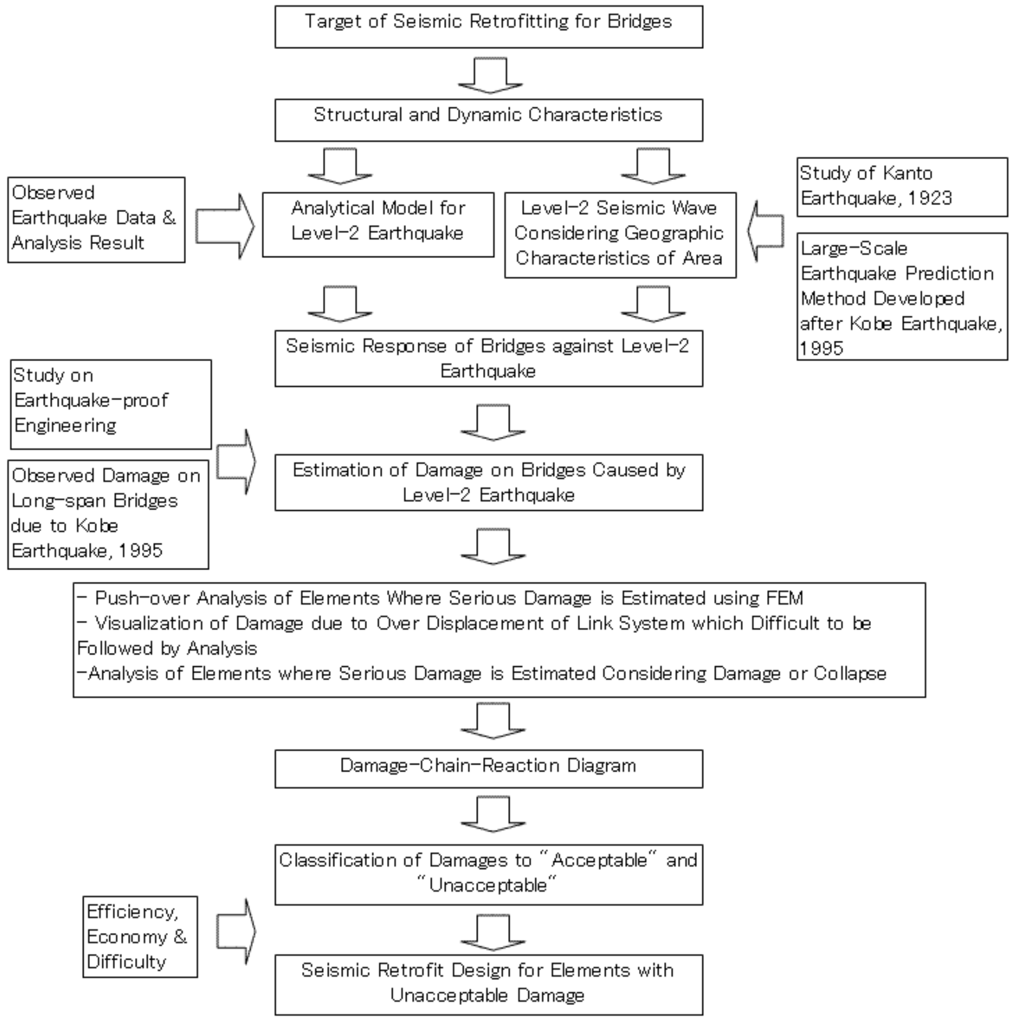


Figure-2 Flow of Seismic Retrofit Design

the analytical result. Also, previous reports concerning seismic design dealing with non-linear behavior of structures (PWRI, 1997-1999) (Zheng, 2000) and the actual damage caused by Hyogo-ken Nanbu earthquake on long-span bridges in Hanshin Expressway routes (Hanshin Expressway Public Co., 1996, 1997) are referred. Damages on long span cable-stayed or suspension bridges tend to have a chain reaction. The analytical models for each bridge are developed focusing on the critical elements towards the stability of the bridge in case of damage. Using these models, it is analyzed how the response of the bridge against the seismic waves and dead load are changed through the Level-2 earthquakes. Based on the analytical results, relations between damages on the main bridge are classified and a damage-chain-reaction diagram was made. Then, the possible damages are sorted into two groups, "acceptable" and "unacceptable".

The seismic retrofitting methods are chosen and designed based on this damage-chain-reaction diagram, considering the factors such as efficiency, cost effectiveness and easiness. Basic policy is that elements without enough strength are reinforced and displacement is followed by enlarging the allowable movements. Then members which can not avoid getting serious damage are substituted by additional devices, such as falling-off prevention device.

4. Input Seismic Wave

Considering the geological features of Tokyo Metropolitan area, two types of input seismic wave are formed for the analysis. One type of seismic waves is assumed to be occurred at a border of continental plates and its magnitude is approximately 8, and the other one is occurred at an in-land fault line and the magnitude is about 7. And those are categorized as Level-2 earthquakes defined in the Japanese bridge code.

A scenario type earthquake, which is formed based on the Kanto earthquake occurred in 1923 (Sato et al, 1989) (Takeo et al, 1997) (Wold et al, 1995), is classified as the continental-plate type earthquake, because the epicenter is located close to Yokohama Bay Bridge and Tsurumi Tsubasa Bridge, as seen in Figure-3. Concerning the scenario type earthquake, acceleration levels of frequency, which match the natural period of those bridges, are enlarged by changing the location and size of asperity and the starting point of the plate collapsing.

Figure-4 shows the response spectrum of the bedrock wave obtained using an epicenter fault model. The damping factor of 5% is used in the calculation. It is seen that the response level over 3 seconds is larger than other spectrums made for buildings located

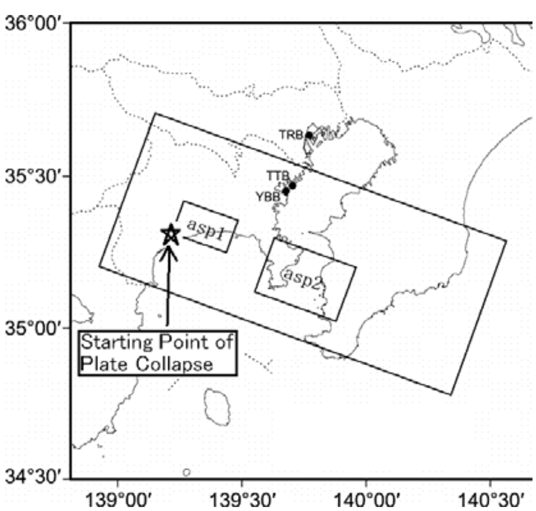


Figure-3 Epicenter of Kanto Earthquake(1923) And Three Bridges

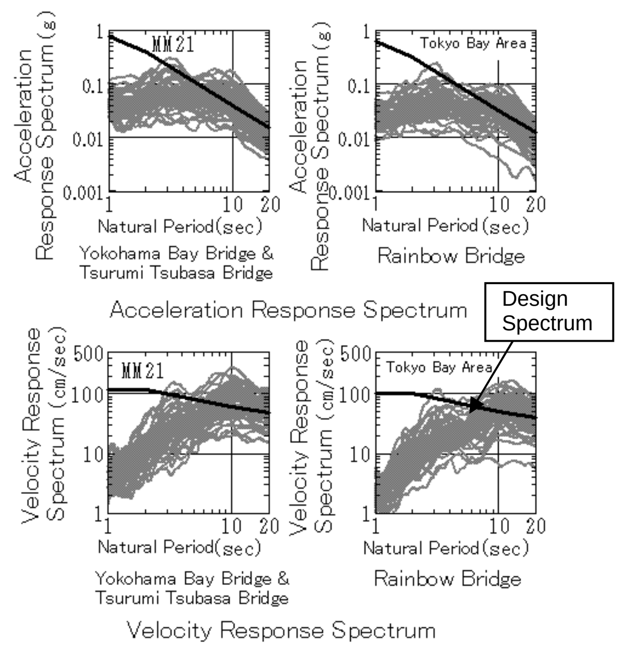


Figure-4 Response Spectrum of Formed Level-2 Seismic Wave based on Kanto Earthquake

in MM21 area as well as Tokyo bay redevelopment area (JSCA, 1992) (Japan Building Disaster Prevention Association, 1992).

A seismic wave actually obtained during the Hyogo-ken nanbu earthquake is used as the other Level-2 earthquake assumed to occur at a shallow point in an in-land fault line, because there is not enough information about similar earthquake possibly occurs around those bridges.

5. Design of Seismic Retrofitting

Non-linear analyses concerning the entire system of each bridge are conducted fulfilled using the models and input seismic waves mentioned above. Figure-5 shows an example of damage-chain-reaction diagram from the result of analysis. Retrofitting methods against unacceptable damages are explained in below.

1) Yokohama Bay Bridge

a. Collision of Stiffening Truss and Side span girder

As a result of the analysis, it is assumed that the displacement of the stiffening truss

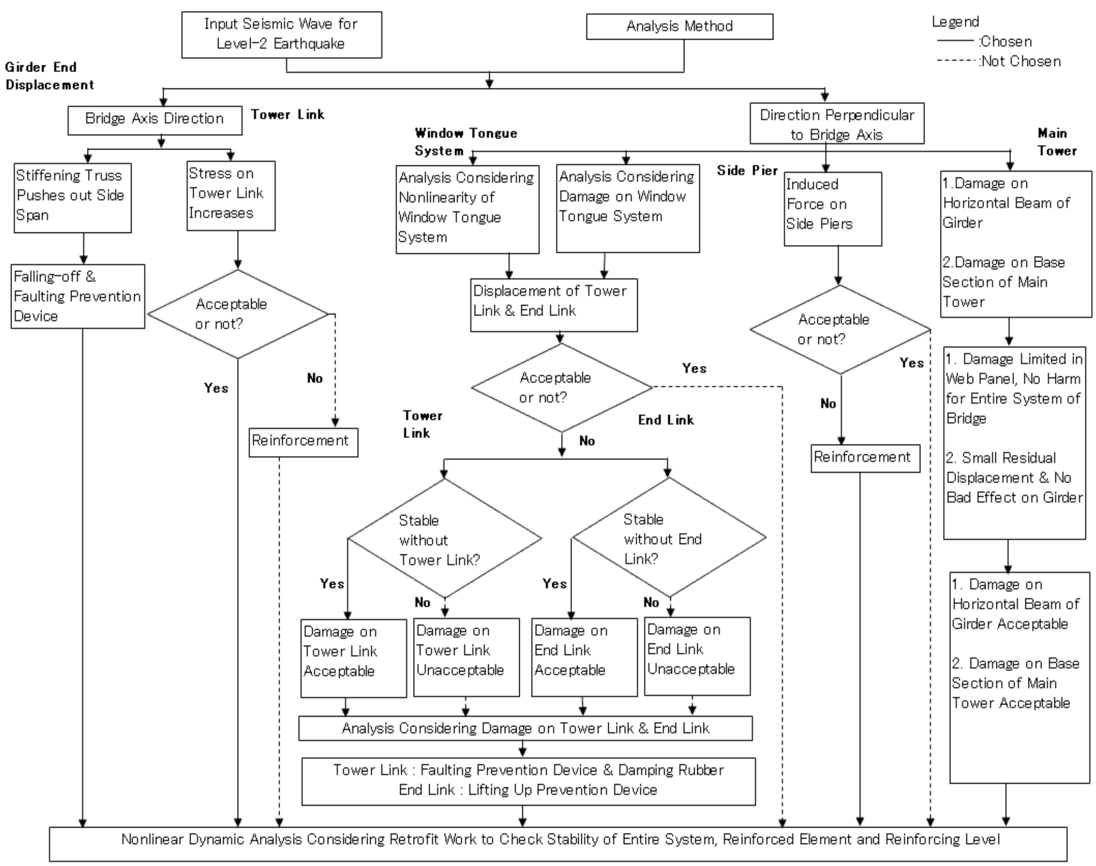


Figure-5 Damage-Chain-Diagram for Yokohama Bay Bridge

towards longitudinal direction is large enough to collide with the adjacent girders on the side spans and it may lead to fall off those girders during the design earthquake. Therefore, falling-off prevention device shown in Figure-6 is designed to be installed. In order to secure the safety for emergency vehicle, this device is designed to limit the difference in level of the road surface within 50mm which may be caused by earthquakes.

b. Window Tongue System, Tower Link and End Link

If the window tongue system is damaged, the supporting strength for the stiffening truss towards the direction perpendicular to the bridge axis is reduced then the tower links and end links may get damaged due to a movement larger than their capacities. It is highly possible that this phenomenon leads to fall off connecting pins, just as actually happened to

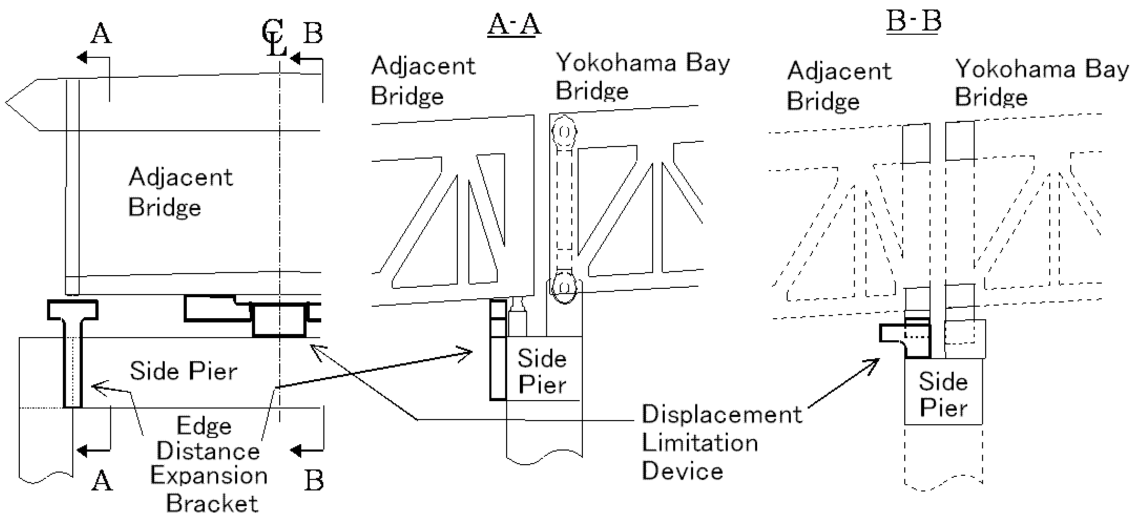


Figure-6 Falling-off Prevention Device for Adjacent Girder (Yokohama Bay Bridge)

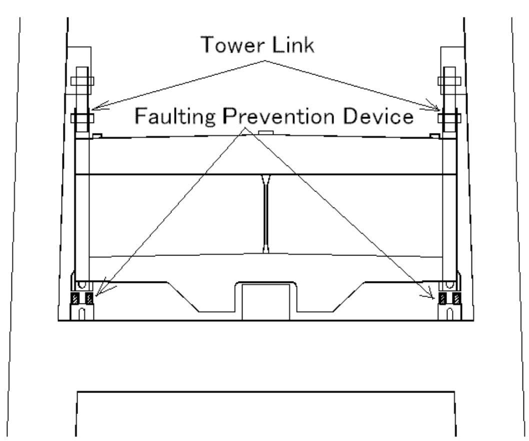


Figure-7 Faulting Prevention Device (Yokohama Bay Bridge)

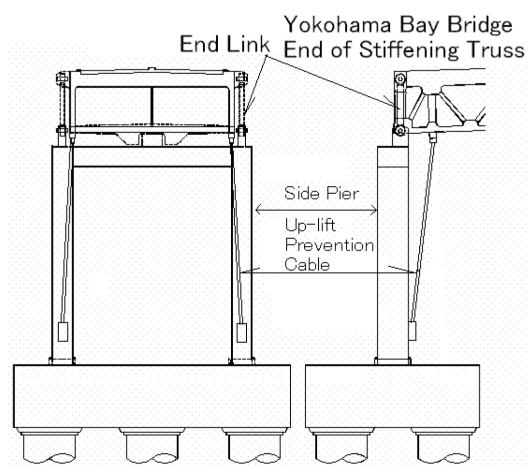


Figure-8 Up-Lift Prevention Cable (Yokohama Bay Bridge)

a pendulum type bearing of Ease-Kobe Bridge. It is quite difficult to reinforce the window tongues and links themselves because of their structures. Therefore, some other countermeasures should be applied to prevent the bridge system from being unstable in case of falling off the connecting pins.

From the further analysis, it is discovered that the stress of cables at the lowest position increase significantly due to the damages on tower links. If the lowest cable is damaged, it may cause other damages on other cables or main towers. In order to prevent this chain reaction, faulting preventing devices are designed to be installed between the bottom beam of the stiffening truss and the horizontal beam of the main tower (Figure-7). Moreover, damping rubbers are installed where the stiffening truss collides to the main tower.

The end link carries uplifting force from stiffening truss in usual loading cases. Because the end of stiffening truss is supposed to be raised in case of the disconnection of the end link, a countermeasure shown in Figure-8 is planned.

c. Side Tower

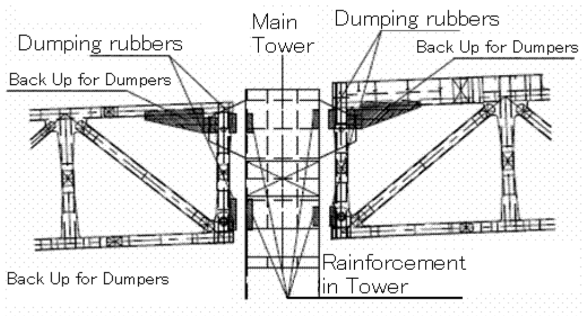
From the analysis, it is assumed that outside panels of the side tower buckle around the position where the panels with different thickness are horizontally welded. Additional vertical stiffeners are installed to prevent the panel buckling and secure the ductility of the tower.

2) Rainbow Bridge

Additional horizontal stiffeners are installed in side towers at their bottom section to keep their ductility during the design earthquakes. Also horizontal stiffeners are installed in top horizontal beams of the main towers to keep its ductility from the large curvature caused by large a displacement of the towers in the direction perpendicular to the bridge axis. As designed for Yokohama Bay Bridge, dumping rubbers are installed between stiffening truss and towers with some reinforcement (Figure-9). Falling-off prevention devices of approaching girders were reinforced against the collision of the stiffening girder (Figure-10). Additional horizontal stoppers are installed on the main towers and side towers to help the window tongue systems (Figure-11).

3) Tsurumi Tsubasa Bridge

The base section of the main tower has steel framed reinforced concrete structure as it is mentioned. This part is reinforced using the CFRP sheet jacketing method to prevent a shear collapsing (Figure-12). Devices to prevent falling-off as well as faulting are installed for the adjacent girders (Figure-13). Guide rails of horizontal bearings are elongated to follow large displacements during the design earthquakes (Figure-14). Openings on lower flange panels of the main girder, through which the pendulum type bearings are located, are expanded in order to avoid interference of the bearing and the flange panel (Figure-15). Anchor sections of girder connecting cables mentioned above are reinforced against high stresses which are assumed to be caused by design earthquakes (Figure-16).



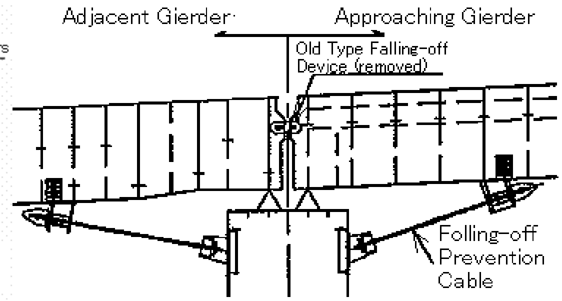
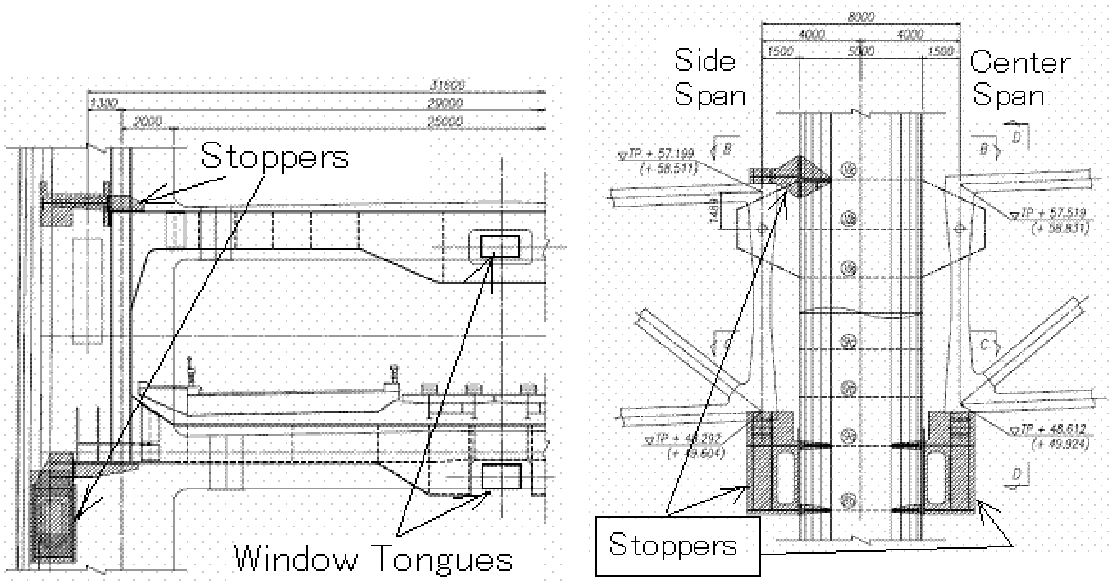


Figure-9 Dumping Rubber (Rainbow Bridge) **Figure-10 Falling-off Prevention Device**



Cross Section Longitudinal Section

Figure- 11 Stoppers for Stiffening Truss (Rainbow Bridge)

6. Conclusion

To summarize, three long-span cable supported bridges in the Metropolitan Expressway network are analyzed against two types of Level-2 design earthquake. Input seismic waves as Level-2 design earthquakes were arranged considering the geographical features of the area around the bridges. Elements of the bridges which get damaged during the design earthquakes went through non-linear analyses and classified either acceptable or unacceptable using the damage-chain-reaction diagram. Then, seismic retrofitting methods were chosen and designed based on the principles of its assessment.

These three bridges are now under retrofitting work based on the result which is explained in above. Those retrofitting works will be completed by the end of 2008 fiscal year.

Acknowledgments

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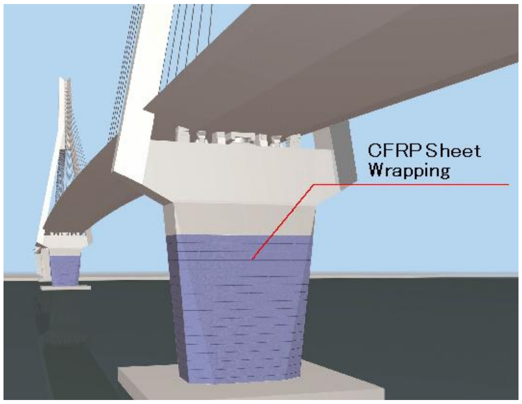

Figure-12 CFRP Wrapping
(Tsurumi Tsubasa Bridge)

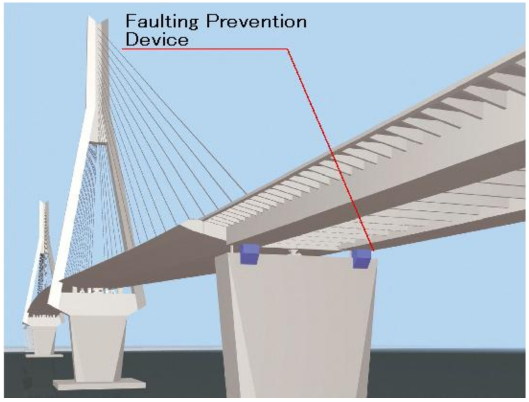

Figure-13 Faulting Prevention Device
(Tsurumi Tsubasa Bridge)

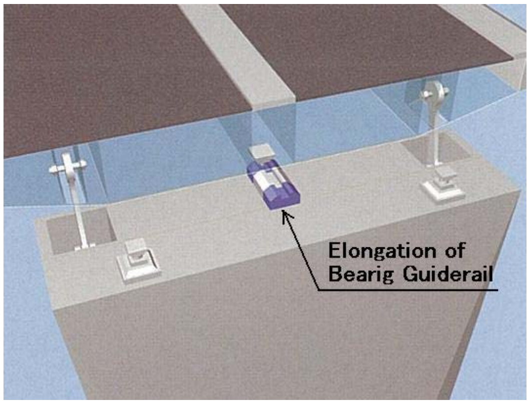

Figure-14 Elongation of Bearing Guide Rail
(Tsurumi Tsubasa Bridge)

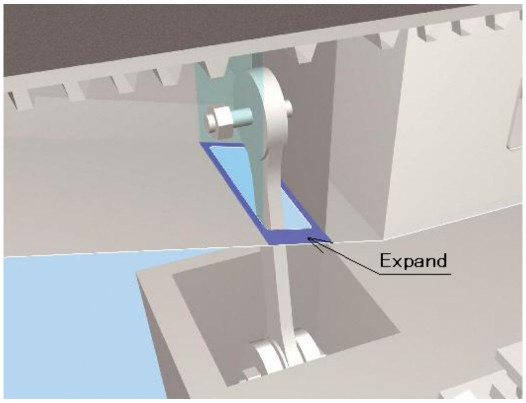

Figure-15 Expanding Opening
(Tsurumi Tsubasa Bridge)

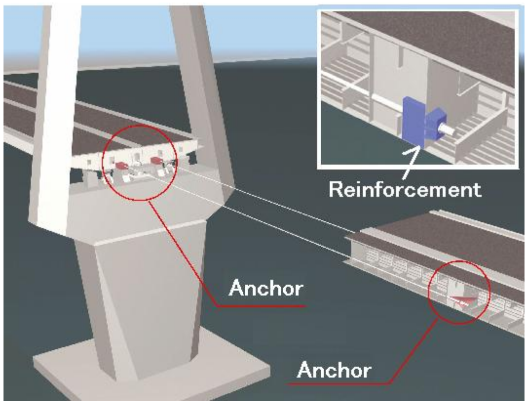

Figure-16 Reinforcement of Cable Anchor (Tsurumi Tsubasa Bridge)

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