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PRACTICES OF SEISMIC DAMAGE CONTROL DESIGN OF BRIDGES IN JAPAN AND SOME LESSONS FROM 2011 TOHOKU EARTHQUAKE

Y. Fujino[1], M. Abé[2], Y. Takahashi[3]

[1] *Distinguished YNU Professor, Institute of Advanced Sciences , Yokohama National University, fujino@ynu.ac.jp*
[2] *Director, Department of Research and Development, BMC Corporation, masato@hashimori.jp*
[2] *Associate Professor, Department of Civil and Earth Resources Engineering, Kyoto University, takahashi.yoshikazu.4v@kyoto-u.ac.jp*

Abstract

Seismic damage control technology has advanced rapidly and been widely applied to not only new construction but also retrofit of existing bridges, especially after 1995 Kobe Earthquake.

At the first part of paper, development of design and performance evaluation of base-isolated bridges before 2011 Tohoku Earthquake are reviewed. In Kobe Earthquake, elevated viaducts in metropolitan Kobe area were most severely damaged, which neutralized transportation function of the entire city. Since observed severe damage were due mainly to damage of columns, strengthening measures of bridge columns were aggressively pursued. Isolation between bridge column and girder was found effective to reduce seismic damage without altering major geometry, and was widely applied to newly built and existing elevated viaducts. Base-isolation effect for elevated bridges is extensively studied and verified by numbers of field observation. Effects of soil conditions and details of isolation devices were studied in depth based on observed data.

The design concept has further been extended to seismic damage control and applied to seismic retrofit of long span bridges. Minato Bridge, whose central span of 510[m] is the longest truss bridge in Japan, was retrofitted with extensive use of seismic damage control concept. In the retrofit, floor deck systems were isolated from main truss frame and energy absorbing braces with low yield point steel were attached to reduce main frame response. In Yokohama Bay Bridge, possible damage scenarios were identified and countermeasures were taken for each scenario to prevent worst consequences resulting in human loss.

In 2011 Tohoku Earthquake, most structures designed by post-Kobe code were not damaged by ground motion. However in some bridges designed by post-Kobe code, rubber bearings and dampers were severely damaged. Although recorded ground motion continued over 300 seconds, and the peak ground acceleration is very large, in most records the response acceleration around 0.5 – 2.0 second was less than design spectra. Cracks of rubber bearings were observed in the wide region and rupture of bearings were occurred in two highway viaducts. The damage was concentrated near the edge of continuous girders. In some bridges, the attachments of dampers were damaged..

Keywords: bridges, seismic damage control, base-isolation, 1995 Kobe Earthquake, 2011 Tohoku Earthquake

1. Introduction

Basic idea of seismic response control is to reduce natural frequency to avoid severe seismic load, or to increase damping to suppress dynamic response. Importance of natural frequencies and damping ratios had been known to bridge engineers before introduction of base-isolation, and considerable attentions were paid in analysis and field measurement. Earlier research [1,2] provides comprehensive study on damping of bridges for various structural types and materials based on measurement of real scale bridges and experiments as shown in Figs. 1 and.2. Fig.1 shows relationship between damping and span length. Longer bridges tend to be more flexible, while damping is decreasing. Fig.2 also shows similar tendency where damping ratios and natural frequencies are roughly proportional. It has also been observed by seismic response record that natural frequencies decrease and damping ratios increase at larger seismic events to non-linearity of responses of structures and foundations. Current Japanese design code for common bridges assumes damping ratios of 2% for steel bridges and 5% for concrete bridges in consideration to this nonlinear effects.

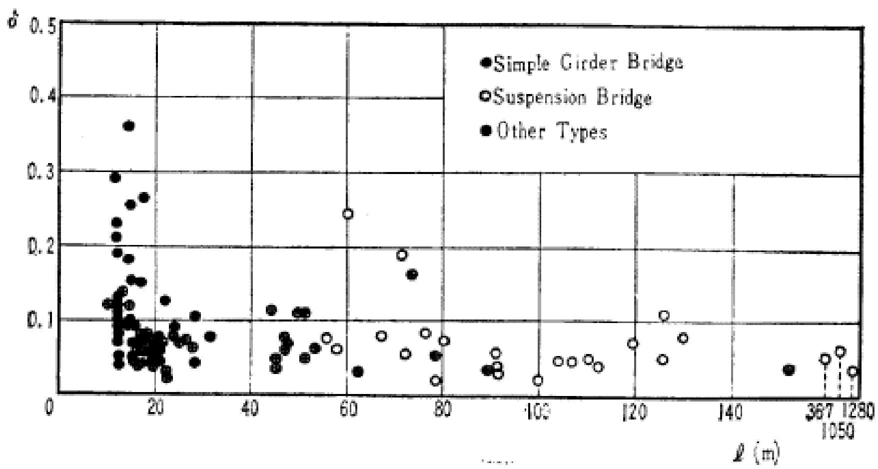


Fig. 1 Measured logarithmic damping ratios and span lengths[1].

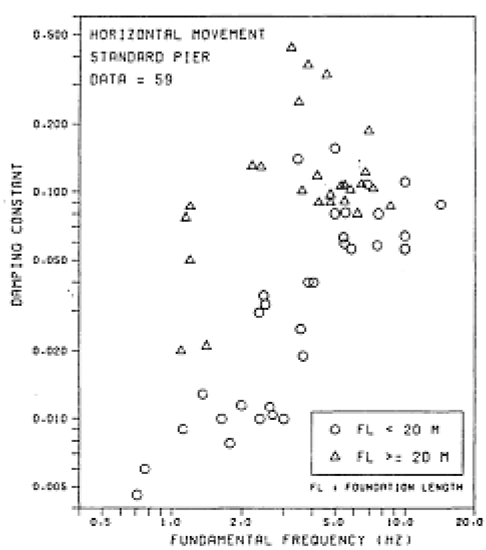


Fig. 2 Natural frequencies and damping ratios[2].

More positive use of damping and natural frequencies started around 1980s. This paper starts with development of base-isolation of bridges using rubber bearings where design and construction has been standardized and applied to large number of not only new constructions but also retrofit. Then, another trend of response control developed to reduce seismic damage of long span bridges are reviewed. Both of these practices were tested by recent 2011 Tohoku and 2016 Kumamoto Earthquake, and are being developed to seismic damage control to control not only response by means of natural frequencies and damping ratios but also distribution of damage within structural systems.

2. Development of base-isolation

Bearing is one of the most vulnerable parts of bridges. Fig.3 shows earlier development of bridge bearings in Japan[4]. The first one is the original design by British Engineer Pawnall, which then gradually developed from plate to bearing. The last one is right after 1923 Kanto Earthquake, bearings are strengthened by anchors reflecting observed severe damage, which is basically the same as the current bearing design.

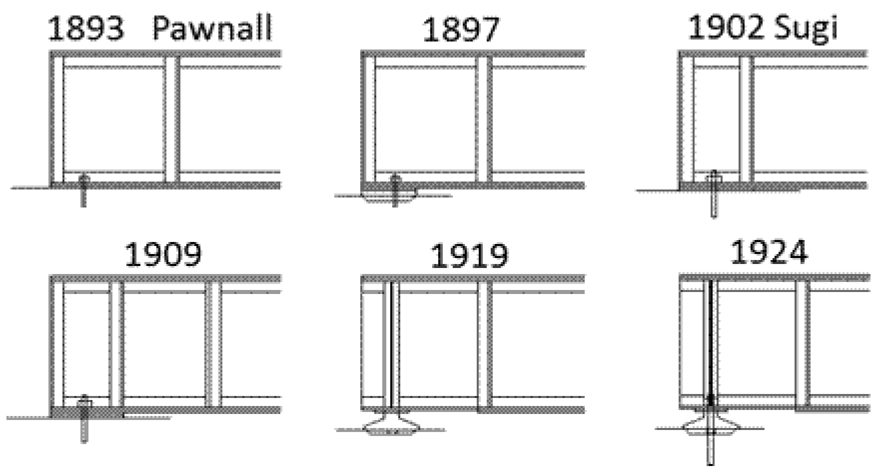


Fig.3 Development of girder end and bearing details

In 1978 Miyagi Earthquake, damage of piers and bearings were widely observed and limitation of conventional seismic design method based on allowable stress design with seismic coefficient established after 1923 Kanto Earthquake became apparent. To reflect realistic nonlinear behavior after damage, “level 2” earthquake is first introduced in 1982 for the design of Trans-Tokyo Bay Highway. Conventional seismic coefficient is redefined as level 1, and two level design method where elastic response is assumed for level 1 while nonlinear response with limited damage is allowed for level 2, is developed and forms basis of contemporary Japanese seismic design.

Base-isolation design which employs rubber bearings fit to this two level design concept to reduce dynamic response for level 2 earthquake[5]. In 1989, “Guideline for seismic isolation of highway bridges” was published and first base-isolated bridge using lead rubber bearings was constructed in 1991, which is a three span continuous girder bridge, shown in Fig.4[6].

At 1995 Kobe Earthquake, response were recorded at some of the base-isolated bridges. Fig. 5 shows identified natural frequencies and damping ratios. Clear softening behavior with increasing damping were observed and design assumptions were verified[7].

Base-isolated bridges became particularly popular after Kobe Earthquake. Fig.6 shows the damage and reconstruction of Fukae Viaduct at Hanshin Expressway. The reconstructed bridge uses rubber bearings to isolate response between girders and piers. Fig.7 is reconstructed Benten viaduct which is isolated at the bottom of the columns by rubber bearings.

Fig.4 Miyagawa Bridge

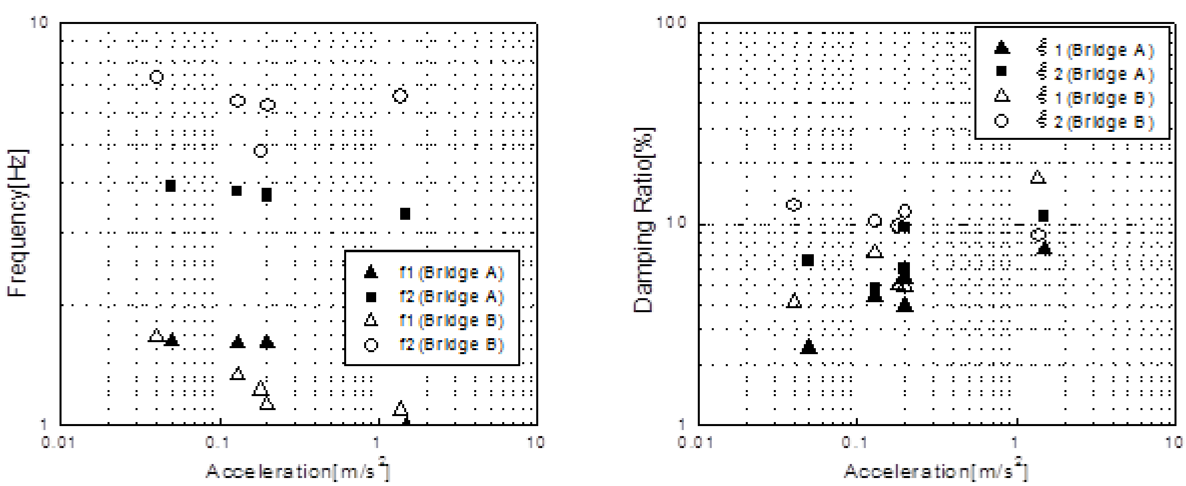
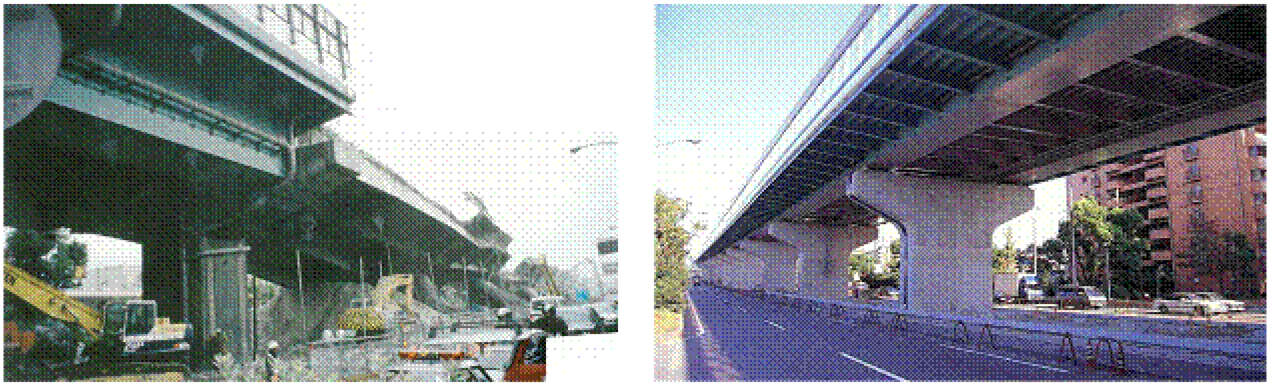


Fig.5 Identified natural frequencies and damping ratios at Matsunohama Viaducts.

The base-isolation concept is extended and further applied to multi-span continuous bridges. Ohito Viaduct, constructed in 1998, is a 29 span continuous prestressed concrete girder bridge with total length of 725[m]. Fig. 8 is the longest base isolated multi-span bridge in Japan, Tenryu-River Bridge, with 23 span continuous prestressed concrete girder bridge with total length of 1585[m]. Seismic responses for mild earthquakes are recorded at Ohito Viaduct, and is shown to behave as expected as design by comparison with dynamic simulation[8].

Verifications of performance of base-isolated bridges are also reported at many other sites based on relatively mild earthquake record[9,10,11,12]. Through these studies, importance of soil-structure interaction effects and details of bearings is revealed. In most cases, isolators are placed between bridge piers and girders. Since piers also dynamically respond and deflect, optimal design values for natural frequencies and damping ratios to reduce both girder and pier responses are proven to exist due to this geometrical constraint[14]. Hence, necessity of careful consideration on bearing details is indicated from both observation and theoretical basis. Behaviors of rubber bearings at complex multiaxial loadings are also studied and precise modeling is also developed[15].



(a) at 1995 Kobe Earthquake (b) reconstructed base-isolated bridge

Fig.6 Fukae Viaduct at Hanshin Expressway

Fig.7 Benten Viaduct of Hanshin Expressway

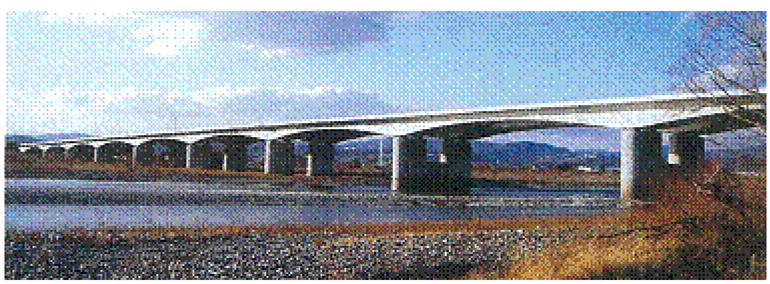
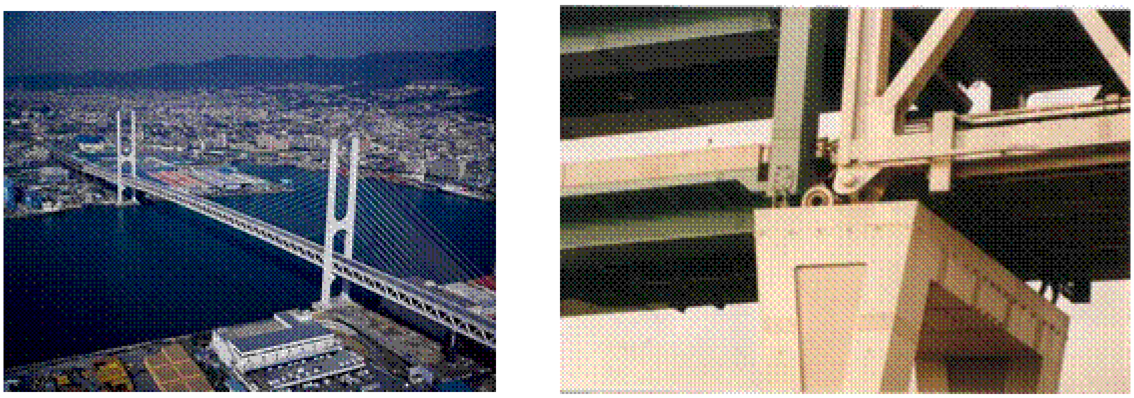


Fig. 8 Tenryu River Bridge

3. Response control of long-span bridges

Long span bridges are flexible, and seismic load is usually considered to be lower compared to wind load. However, inertia load by superstructure seismic response can be large due to heavy weight of long span girder. Therefore, further reduction of natural frequencies are explored.

Higashi Kobe Bridge, shown in Fig.9 is an example. The girder is supported only by stay cables in longitudinal direction to reduce natural frequencies and eventually seismic load. In Kobe Earthquake, its bearing link systems connecting end girders and piers failed as shown in the Figure 9 (b), losing vertical support to prevent uplift. Failure of wind shoe, which was to prevent transverse motion of the girder, due to excessive transverse motion of the girder end, lead to this failure of the link[16]. Although flexibility reduces seismic load, excessive motion may be induced. At Yokohama Bay Bridge, shown in Fig.10, the girder is supported by link from the main tower as shown in Fig.11 for isolation. In the same figure, measured response at 2011 Tohoku Earthquake is shown and spike like response indicating collisions are observed[17]. This is also unexpected response due to excessive motion. Treatment of excessive motion should be well considered for long span bridge isolation. Fig.12 shows uplift prevention restrainer attached to Yokohama Bay Bridge as a part of recent seismic retrofit. The restrainer is supposed to support uplift of girder even in case of excessive motion or unexpected damage.



(a) overview (b) damage at 1995 Kobe Earthquake

Fig. 9 Higashi Kobe Bridge

Fig. 10 Yokohama Bay Bridge

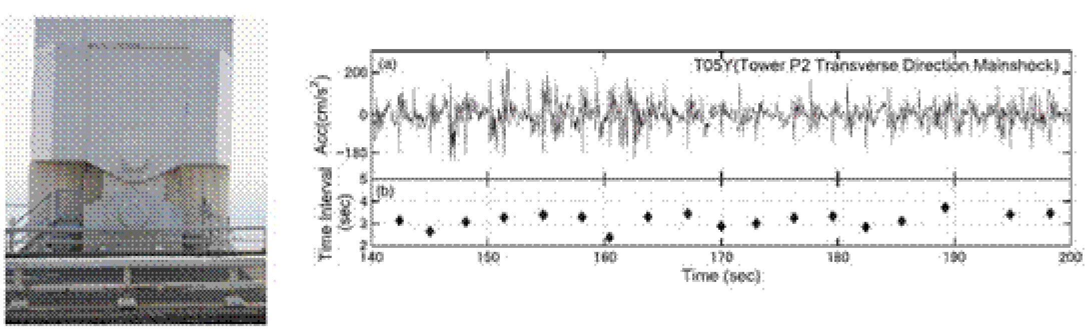


Fig.11 Tower link at Yokohama Bay Bridge and seismic response at 2011 Tohoku Earthquake

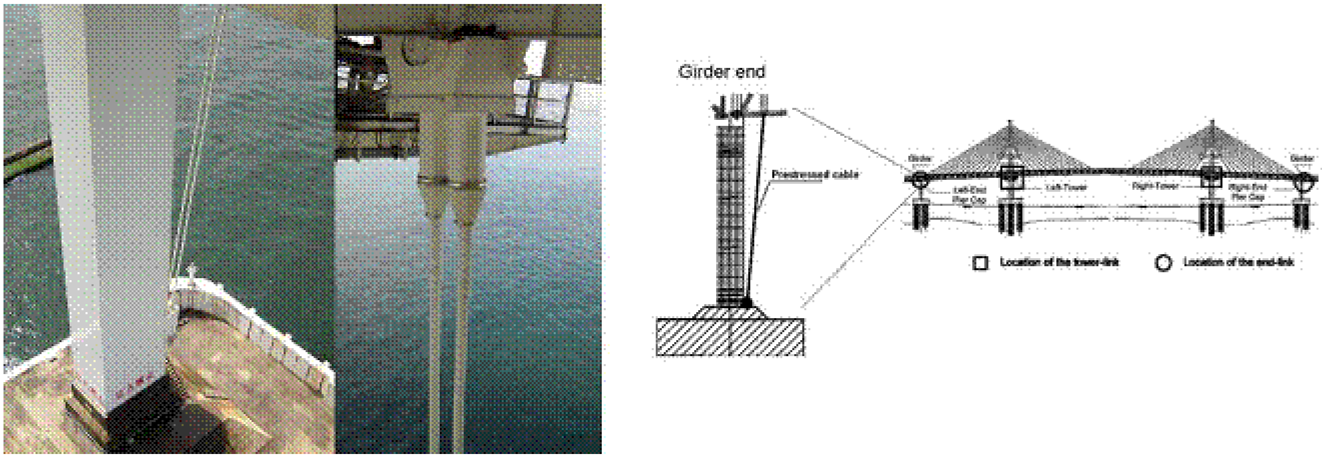


Fig.12 Uplift prevention restrainer at Yokohama Bay Bridge

4. Seismic damage control and lessens from recent earthquakes

Natural extension of seismic response control is control and localization of damage. Retrofit of Minato Bridge, shown in Fig.13 is the first trial to apply damage control explicitly[18]. Isolation of heavy floor decks using sliding isolators was adopted to reduce the longitudinal inertia force. In addition, some of the truss members are replaced by buckling restrained braces to absorb seismic energy and to reduce the transverse response. Hence damage is localized to these replaced braces to increase seismic performance of the entire structure.

Arakawa Bay Side Bridge in Fig.14 is damaged by 2011 Tohoku Earthquake as shown in Fig.15. Several gusset plates were severely damaged though stability of the entire structure was not affected. Although this phenomena were not intentional, it indicates feasibility of damage localization and control.

In 2011 Tohoku Earthquake, damage to vibration control devices are observed. Fig.16 shows an example of damage of dampers. Supports of dampers are observed to be vulnerable. Fig.17 shows an example of failure of rubber bearing at a cable stayed bridge. In 2016 Kumamoto Earthquake, complete failure of bearings are observed at a continuous steel girder bridge as shown in Fig.18. Unfortunately, none of these bridges were instrumented nor monitored continuously, and no record of response characteristics is available. Nevertheless, forensic investigation of these recent damage with remaining evidence would reveal challenges of seismic damage control of bridges.

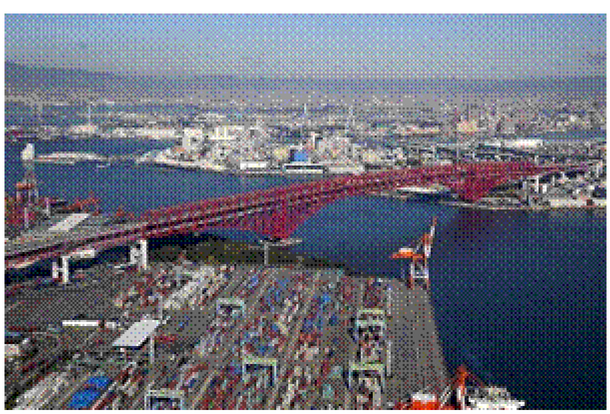


Fig.13 Minato Bridge

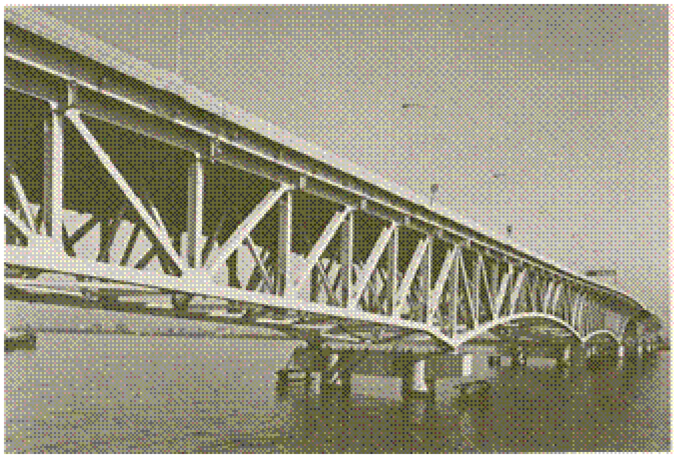


Fig. 14 Arakawa Bay Side Bridge

Fig.15 Damage at gusset plates of Arakawa Bay Side Bridge.

Fig.16 Nakanose Viaduct and observed damage of dampers

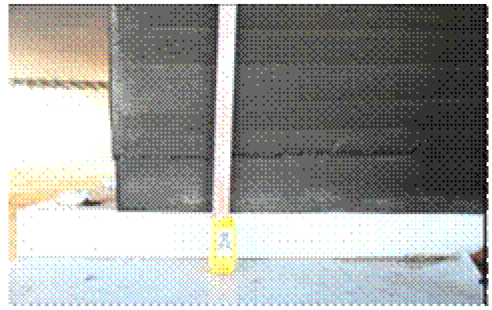


Fig.17 Shin-Nakagawa Bridge and failure of rubber bearing

Fig.18 Bearing damage at Okirihata Bridge.

5. Conclusions

Development of seismic response control of bridges of Japan and its evolution to seismic damage control is reviewed.

Earlier studies on bearing design, and measurement of natural frequencies and damping ratios evolved into control of these dynamic characteristic by means of base-isolation. Also, reduction of seismic inertia force through elongation of natural frequencies is developed in seismic design of flexible long span bridges. After 1995 Kobe Earthquake, base-isolation becomes popular and damage control concept is developed and applied, as typically observed at Minato Bridge retrofit.

Damage to control devices and unexpected excessive motion are observed in recent earthquakes. These observations indicates challenges of seismic damage control of bridges.

Currently, entire Japanese land is monitored by distributed seismic sensor network with more than 1000 stations. Owing to this network, ground motion data are available and utilized from research to emergent actions. The network is now being extended to undersea to extend possibility of early warning of earthquake and tsunami. Extension of this nationwide network to structural response would not only reveal unknown damage mechanism but also ensure structural safety even during seismic events and further accelerate rescue and emergent actions.

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