INNOVATIVE SEISMIC STRENGTHENING AND ISOLATION OF BRIDGE STRUCTURES IN JAPAN

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ABSTRACT

After the Kobe earthquake in 1995, new seismic resistant design criteria were developed and intensive seismic retrofit work has been carried out in Japan. The seismic retrofit works were consisted of jacketing the bridge column for improving shear resistance and enhancing confinement, replacement of bearing for improving seismic behaviour of the bridges, and improving structural details. The seismic retrofit work was carried out for not only general bridges but also long-span bridges. Currently the advantage of damping enhancement technologies is widely recognized and this damping technology has been applied to existed bridges and new bridges. Those seismic improvement techniques are widely adopted in highway engineering field. However the aging effect of those techniques is not clearly studied yet. Currently study on the aging effect of those techniques, especially on seismic isolators, has just started in Japan. The paper summarize the current seismic retrofit technologies in Japan, innovative seismic improvement technologies in Japan, and the current summary of study on aging effect of seismic isolators for highway bridges.

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 continuously developed and improved. Recently, Japan experienced two different major earthquakes in recent 20 years history that triggered the major change of the seismic design criteria. One is the 1995 Kobe earthquake that is categorized to active fault type earthquake and the other one is the 2011 east Japan earthquake that is categorized to plate boundary type earthquake.
The 1995 Kobe earthquake caused the most destructive damage to bridge structures in the Kobe area. Collapse and nearly collapse of superstructures occurred at 9 sites, and other destructive damage occurred at 16 sites. The earthquake revealed that there were a number of critical issues to be revised in the seismic design and there was an urgent need of seismic retrofit of vulnerable structures. Based on serious damage experiences, the seismic design code has been revised to introduce the ductility design method considering level 2 earthquake ground motion caused by active fault and the seismic retrofit project has started to the existing bridges columns designed in accordance with pre-1980 specifications with high priority, to prevent the collapse of the bridge structure and unseating of the deck.
The 2011 East Japan earthquake also made variety damage to the bridges structures. Damage of the highway bridges due to this earthquake can be categorized as effect of strong ground motion, effect of tsunami inundation, and effect of soil liquefaction. It should be noted in this earthquake that the severe damage in highway bridges was mainly caused by tsunami inundation. The ground shaking of the earthquake was also intensive, but the seismic resistant capacity of almost all bridges in the affected region was already improved due to the intensive seismic retrofit work after the 1995 Kobe earthquake. The effectiveness of the seismic retrofit was reported based on the experience of Hanshin expressway [ADACHI et al, An analytical study of damaged viaducts due to the Great Hanshin Earthquake using estimated input ground motion, 1997]. Figure 1 shows the two expressway viaduct columns that suffered damages from 1995 Kobe earthquake. The seismic retrofit work was finished for one column

日本創新橋梁耐震補強及隔震設計

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摘要

日本自西元 1995 年發生阪神大地震後，即制訂了新版的耐震設計規範，並且展開全國的結構耐震補強工作。耐震補強的工作種類，包含透過橋柱的包覆補強，提升抗剪的強度，並且提高結構的圍束，及撤換橋梁上部結構支承座，以改善地震力下的功能表現，最後就是改善許多結構設計的細節。截至今日，透過結構減震的科技已經十分普及，如今不但用在既有橋梁的耐震系統，同時在新建橋梁上也開始運用此一工法。這些改善結構耐震性能的技術，均已運用在高速公路的領域。但是，至今對於這些消能系統老劣化的影響，相關研究尚不算多。對日本而言，隔震裝置的老劣化和其他補強技術老化所造成影響的相關研究是近幾年才開始的。這篇論文將日本當前的耐震補強技術作總結，並且介紹現階在日本所提出創新的耐震補強技術，最後也歸納出正在進行對高速公路橋梁，所使用的隔震裝置老劣化相同研究的成果。

背景介紹

日本橋梁地震災害的防護技術可追溯自西元 1923 年發生的關東大地震之後，歷經了多次的重大災損歷史教訓累積而來。近 20 年在日本也經過兩次大規模的地震災害，因此也促成了耐震設計規範的大幅修改，其中一次就是發生在西元 1995 年的阪神大地震，該地震主要是由活斷層所引起的地震，而另外一次是發生在 2011 年東日本所發生的福島地震，被分類為地球板塊之間活動所造成的大地震。

在 1995 年在阪神發生的大地震，在阪神地區大部份橋梁的損壞，造成至少有 9 處橋梁結構全毀或是上部結構幾近破壞，並且在至少 16 處造成各種的災情。阪神地震顯示出日本的耐震設計規範中，有許多極需修正的地方，並且使得結構耐震補強成為急迫的課題。基於地震所造成嚴重災損的經驗，日本的耐震設計經過修改之後，也納入了韌性的設計，將第二級因為活斷層所引起的地表活動，納入新規範內的設計考量，並且將制訂於西元 1980 年代之前，對於既有橋梁耐震補強的設計作優先的修訂，特別強化針對避免橋梁的崩塌及橋梁上部結構的震落而加以防止。

歷經西元 2011 年東日本的大地震之後，看見許多橋梁結構的各類損壞，最後也將橋梁受地震力破壞的災損歸納為三種造成的因素:第一是強烈的地表運動，第二類是海嘯所造成的損害，最後是土壤液化所造成的後果。值得注意的是，在這次的地震災害調查中顯示，對於高速公路所產生最大的破壞成因，乃是起於海嘯泛濫所造成的。雖然地表出現了強烈的運動，但是在經過 1995 年阪神大地震之後，許多橋梁已經成功地因為耐震補強而已有了明顯地耐震力提昇，特別是阪神高速公路於災後的報告，顯示出補強之後的成效〔ADACH1997〕。圖 1 呈現了兩個高架橋，在經歷了 1995 年阪神大地震之後的反應，當時圖 1 左處正好是一座橋柱，是在 1995 年阪神地震發生前一個月剛完成了耐震補強工程，並未出現任何的災情。對照圖 1 右處則是另一座尚未完成耐震補強的高架橋柱，在歷經阪神地震之後卻產生損壞，如此可以看得出，在橋柱使用鋼板包覆圍束補強所造成提昇耐震力的效果是值得肯定的工法。而此類鋼板包覆工法，是以增加橋柱在柱軸向鋼筋接合處提高抗剪力的作法。

just on month prior to the 1995 Kobe earthquake, and the neighbouring column waited the retrofit work at the time of the earthquake. The effectiveness of the steel jacketing method clearly is clearly recognized by Figure 1. Note that the steel jacketing was provided to increase the shear resistance at the longitudinal rebar termination.

Other experience was also found at the 2011 East Japan Earthquake reported by PWRI [HOSHIKUMA et al, 2012]. Figure 2 exemplifies one of the effectiveness of the seismic retrofit for bridge columns. The un-retrofitted bridge (Esaki Ohashi Bridge) shown in the right side of Figure 2 suffered from severe shear damage in concrete columns. Esaki Ohashi Bridge is 9-span continuous concrete box girder bridge designed in 1972 design specification. Near Esaki Ohashi Bridge (as close as 4,000m), there is the other bridge (Kanagasaki Ohashi Bridge) as shown in the left side of Figure 2, where this is three 3-span continuous steel girders bridge designed in 1974 and the columns were retrofitted by concrete jacketing. Comparison of the seismic performance with these two bridges indicates that the seismic retrofit for bridge columns work effectively, although structural type of these bridges are different and thus the natural period is not equivalent between two bridges.

(a) Retrofit column (b) Un-retrofitted column

Figure 1. Effectiveness of the seismic retrofit of bridges (The case of 1995 Kobe earthquake) (Tsukimiyama viaduct, Hanshin expressway) [ADACHI et al, An analytical study of damaged viaducts due to the Great Hanshin Earthquake using estimated input ground motion, 1997]

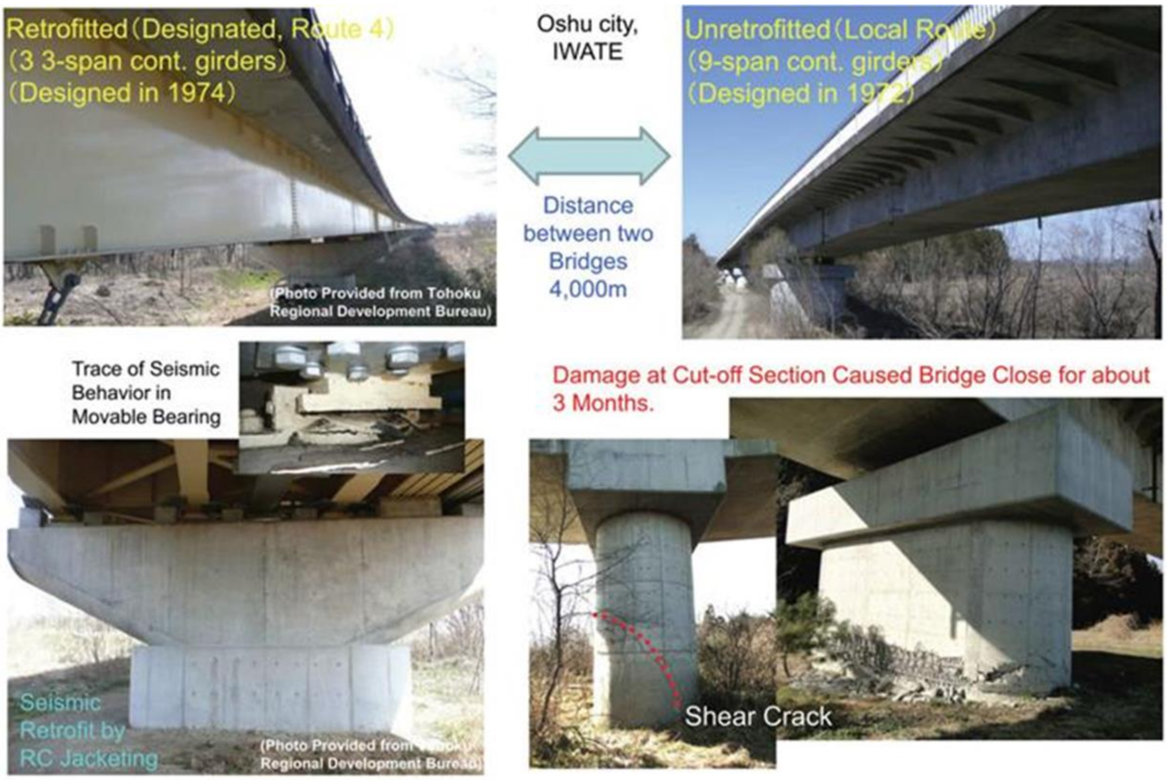


Figure 2. Effectiveness of the seismic retrofit of bridges (The case of 2011 East Japan earthquake)

經過 2011 年東日本的大地震之後，也由日本公共工程研究學院（PWRI）提供了許多寶貴的經驗〔HOSHIKUMA2012〕。圖 2 中的兩座相距約四公里的橋，在圖 2 右處，一座沒有經過耐震補強的橋(Esaki Ohashi 橋）在經過 2011 年大地震之後，其鋼筋混凝土柱中，顯示出嚴重的剪力破壞。該橋為一個九跨連續的鋼筋混凝土箱型梁橋，依據 1972 年的橋梁設計規範所設計建造。而距離該橋四公里遠的另外一座橋（Kanagasaki Ohashi 橋），如圖 2 左處所示，乃是同樣依據 1974 年橋梁設計規範所設計建造的一座三跨鋼構連續梁式橋，但其橋柱卻因為使用混凝土包覆圍束補強，而並未在經歷 2011 年地震之後造成任何的損害看來，證明混凝土圍束耐震補強有其實際的耐震效果。雖然這兩座橋的基本型式不同，自然其結構自然週期也不一樣，但是將這兩座鄰近的橋，在經過與其中一座的補強後沒有任何損壞的比較，看來橋柱的耐震補強有其相當的功效。

(a)補強後橋柱　　　　　　　　　　　　　(b)未經修補橋柱

圖 1. 橋梁耐震補強效益的比較(1995 年阪神地震分析)

圖 2. 橋梁耐震補強效益(2011 年東日本大地震分析)

圖 2－1. 補強案例（三跨連續梁式橋）使用 1974 設計規範

圖 2－2. 未經補強案例（九跨混凝土箱型梁，使用 1972 設計規範）

圖 2－3. 使用混凝土包覆補強

圖 2－4. 剪力裂縫

SEISMIC IMPROVEMENT OF STANDARD BRIDGES

Seismic retrofit work in Japan was started in 1971. The most major retrofit program was started in 1991 and major retrofit measures were to provide unseating devices, unseating beam width, and preventing device for excessive bearing displacement.

According to the lessons from the 1995 Kobe earthquake, various new drastic changes were introduced in the new design codes and triggered the seismic retrofit measures in order for increasing seismic safety of the bridge structures. The first intensive 3-year program was launched in 1995 just after the 1995 Kobe earthquake. 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. Following the first 3 year program, the second 3 year program was started to provide unseating devices for important expressway bridges. Continuing challenge was made to provide seismic strengthening of bridge columns and to provide unseating devises to other bridges and viaducts except the target bridges of the these 3-year program. However, the speed to promote the seismic retrofit works became a little slow.

The new seismic improvement program was initiated by the damage experiences caused by the 2004 Niigata-ken-chuetsu earthquake in order to accelerate the seismic improvement work and to complete the improvement for important emergency route rapidly. 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 the bridges listed in table 1. These bridges shown in Table 1 were given high priority to be retrofitted based on the past earthquake damage statistical data.

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. 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. 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. For such requirements, seismic strengthening by "Steel Jackets with Controlled Increase of Flexural Strength" as shown in Figure 3 was suggested by PWRI [UNJOH et al, 2008]. This uses steel jacket surrounding the existing columns and 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. 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.

Sheet jacketing using carbon fiber sheets or aramid fiber sheets, which are light-weight and need only relatively easy construction condition, have been applied to improve the shear and bending strength at

Table 1. Priority list for seismic improvement program in 2005-2007

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
Unseating Prevention Devices	
	1) Simply-supported girder bridges except single span bridge with abutments at both ends 2) Continuous girder bridges with the soil condition of the lateral spreading by the liquefaction effects

標準橋梁的耐震力提昇

自西元 1971 年開始，日本著手進行耐震補強工作，而最主要的補強計畫則始於西元 1991 年。其中最主要耐震補強策略是增設防落裝置、增長橋梁端支承寬度，並且針對大規模位移的支承防護設施。記取 1995 阪神地震的教訓，在設計法規中納入新的設計規範，並且啓動了增加地震影響下，增加各類橋梁安全的耐震補強工法。在 1995 年起，也就是阪神地震之後，日本展開了第一階段為期三年的補強計畫。首先針對那些在 1980 年之前，使用當時橋梁設計規範標準下，並且由於許多阪神地震造成損壞集中在單柱式橋墩，因此對於極具重要性的橋，例如：快速道路橋、都市內的重要道路以及作為高速公路通行的橋，雙層橋面板的橋和跨越橋等，在地震下會產生嚴重後果的橋，首先進行耐震的補強工作。繼第一期之後，再辦理另一期為期三年的橋梁補強計畫。第二期則以三年時間，增設重要橋梁防落的裝置，後續針對上述目標的橋梁之外，再增加對於橋柱耐震力的提昇及其他防落裝置。但是在這個階段之後，推展橋梁耐震補強的工作卻逐漸緩慢下來。最近一期的耐震補強工作，是在 2004 年歷經 Niigata-ken-chuetsu 地震之後，因造成了不少災損的情形之下，才又逐漸加速了耐震補強的工作，並且特別是加快完成了針對那些救災路線上，橋梁的耐震補強工程。而這段時期的補強工作，進一步考量了其補強的效益和對於道路網維持效能的觀點。這個時期所補強的標的結構，乃是如表一內所列舉，以 1980 年代之前設計規範下建造的橋梁為主。表一內所列出的橋梁係根據歷史的地震記錄會造成損壞作補強設計的基礎，也被列為最優先的補強目標。

對於鋼筋混凝土柱的補強首要措施，是將柱內軸向主筋於柱中央高度搭接，並且缺乏足夠的搭接長度的鋼筋混凝土柱，以增加其剪力強度為主。但是僅僅以增加柱的韌性，反而造成橋墩在地震之後側向變形量的增加，因此考慮增加撓曲強度，也同時需要列必要性的作為。一旦增加橋柱的撓曲度，這也意味著從橋墩傳遞地震力到基礎的地震力規模也隨之增加，研究報告也指出，若是只要將橋柱撓曲強度增加不超過 2 倍時，對於補強之後橋柱增加對基礎造成的額外地震力，也不會十分的顯著。根據這樣的原則，日本公共研究學院所建議的「鋼板圍束補強以限制橋柱撓曲強度」的規範如圖 3 所示〔UNJOH 2008〕。這項工法同時也在既有橋柱以鋼板包覆補強時，以環氧樹脂或是無收縮水泥填充砂漿灌注於鋼板包覆內部和既有橋柱之間縫隙，以達到良好的接合效果。並在鋼板圍束的底層與基礎頂部之間，仍舊保留一定的間隙，以防止過度增生撓曲強度的影響。在有計畫地增加橋柱撓曲強度的同時，在鋼板包覆接近底端之處，使用錨釘作固定。而這些錨釘係以鑽孔方式埋設於基礎，遇到矩形斷面的橋柱在包覆補強時，也使用 H-型鋼，佇立在橋柱包覆底部的四圍，如此做的目的，是在確保包覆補強的圍束力，並且不致於產生軸向柱主筋向外彎曲的狀況。當橋柱經計算，需要增加其撓曲強度時，傳統的鋼筋混凝土圍束補強工法也列為可行的方案之一。

當施工條件許可時，使用碳纖維或玻璃纖維作圍束補強，也因著其輕質和易施工性，成為改善抗剪力及彎矩強度的工法，如圖 4 所示。

表一、介於 2005 至 2007 橋梁耐震力提昇的優先名單

橋柱補強	
	1）單柱式橋墩，其柱主筋於柱中央高度搭接者。 2）單柱式鋼柱橋墩。 3）在連續梁中剛接混凝土橋墩，且柱主筋於柱中央高度搭接者。
防落裝置	
	1）除單跨之外的簡支梁式橋。 2）連續深橋並受到土壤液化影響造成嚴重側向偏移者。

the section as shown in Figure 4.

Currently, seismic retrofit of standard bridges designed accordance with old design specifications were almost completed except complicated bridges such that the bridges were built with subway stations or market stores. For the seismic retrofit of such structures, the most difficult construction requirements for retrofitting the columns are to accommodate the small construction space and limited construction time. In order to satisfy such requirement, the new seismic retrofit measures as shown in Figure 5 were invented by JR East Railway Company [JR East , 2014]. These techniques were also applied to road bridges.

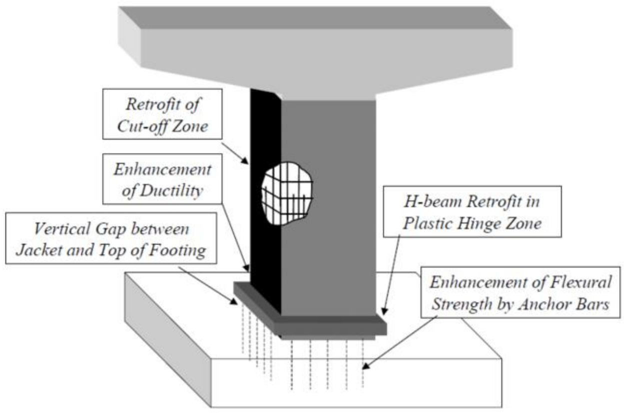
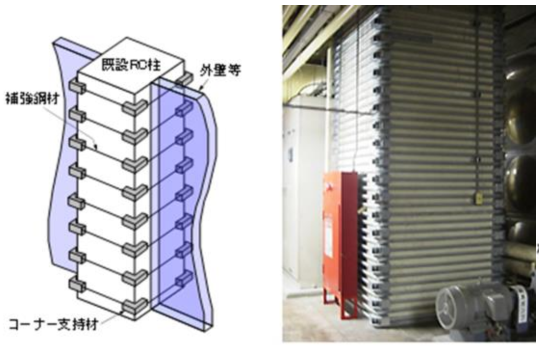
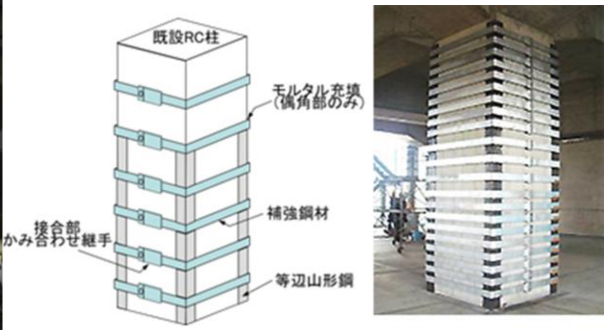


Figure 3. Concept of steel jacketing method with anchor [UNJOH et al, 2008]

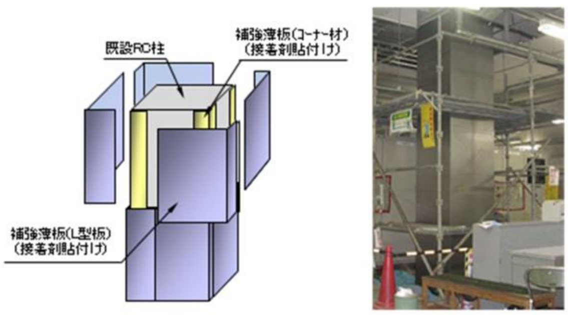
Figure 4. Carbon fiber jacketing method [OSADA et al, 2000]



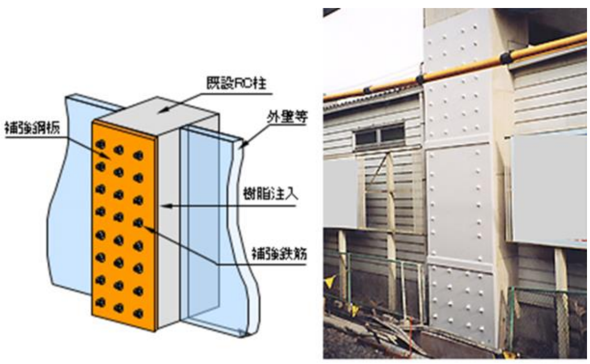
(a) Rib-bar confinement method



(b) Rib-plate confinement method



(c) Thin plate confinement method



(d) One side shear capacity enhancement method

Figure 5. New seismic retrofit measures for columns [JR East , 2014]

現階段舉凡所有依照舊設計規範條件標準橋梁的耐補強工作幾乎都告完工，僅剩下在地下鐵車站或是許多市場商店共構的橋。因為其複雜程度而尚未完成，對於這一類結構的補強工作，在施工時面臨最困難的條件，是如何在侷限空間內容納補強工程，並且其補強施工期也是受到限制的。為了滿足上述的條件，日本東鐵公司〔JR East 2014〕發展出許多創新的耐震補強工法，如圖 5 所示，這些工法同時也可以適用在公路橋梁的耐震補強工程上。

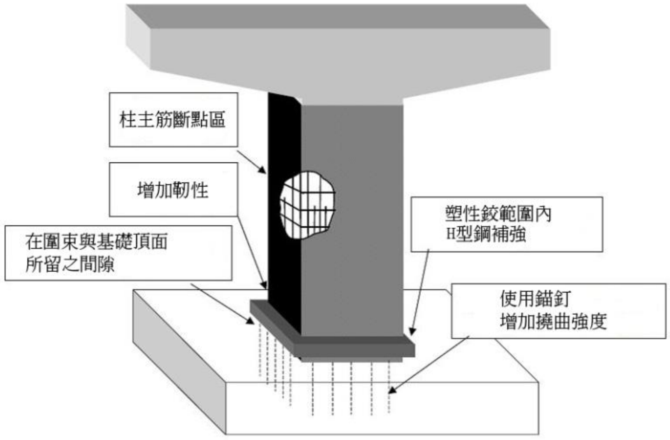
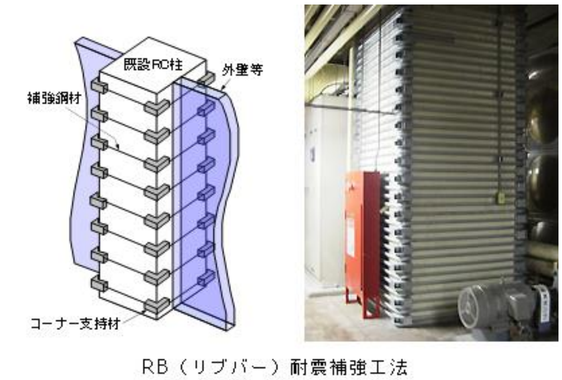
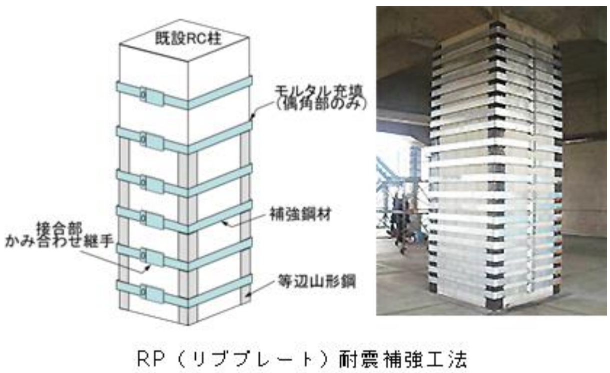


圖 3. 鋼板圍束補強使用錨釘示意圖[UNJUH 2008]

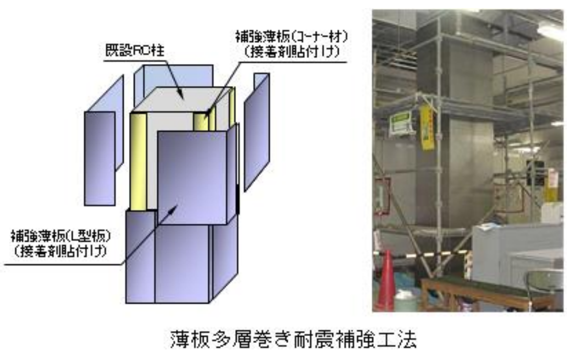
圖 4. 使用碳纖維圍束補強案例[OSADA 2000]



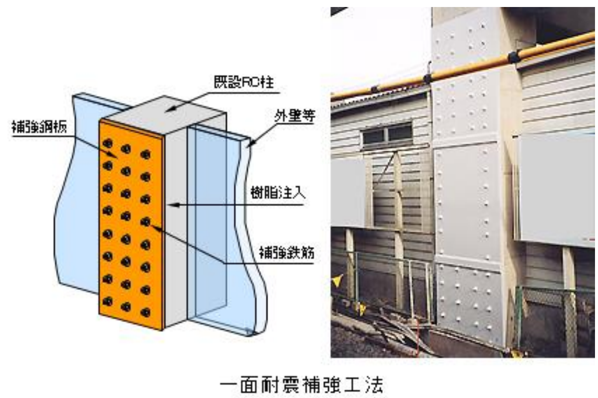
(a)肋紋鋼條圍束補強工法



(b)肋板圍束補強工法



(c)薄板圍束補強工法



(d)單側剪力增設補強工法

圖 5. 橋柱創新耐震補強工法［JR East 2014］

SEISMIC IMPROVEMENT OF LONG-SPAN BRIDGES

Seismic retrofit of long span bridges is difficult due to a high level of inertia force of superstructures and the increase of the size of bearings, anchors, piers and foundations, resulting in the increased cost and technical difficulty in manufacturing and implementation of the components and members. Moreover, since the seismic design of the existing long span bridges is based on the principle of reduced seismic load demand with the use of long natural periods of the structure, response horizontal displacement for the Level 2 earthquake becomes significantly large, making it impossible for bearings and expansion joints on the pier top to follow the girder movements. In addition, sufficient length of girder clearance between adjacent girders may not be secured, possibly causing problems including collision between girders or girder unseating from the pier tops.

Continuous challenge was made by Hanshin expressway in order to circumvent those difficulties in the seismic retrofit of the long span bridges. The Wangan Route of Hanshin Expressway running along the coast line of Osaka bay consists of various types of long span bridges; therefore, seismic isolation and response control design was positively employed with the application of seismic isolators and dynamic response control devices. The seismic isolators and response control devices utilized in the seismic retrofit project of Hanshin expressway are summarized in Table 2 and the design guideline of these devices, which consist of the provisions and comments are based on the knowledge acquired through the investigation in seismic retrofit project of those bridges was published [Hanshin Expressway Co., Ltd., 2013]. Table 3 through Table 7 show the case studies of each device, implemented location, and expected performance of these devices applied to long span bridge retrofit.

It should be noted that the design ground motions of those bridges were generated by fault rupture model considering bed rock formation and thick soft soil deposit of Osaka bay area. The design ground motions were generated by 3S concepts, source specific, site specific, and structure specific.

Table 2. Element method for seismic improvement of long span bridges

Seismic improvement method	Description
Floor Deck Isolation System	Device installed between traffic deck and girders or arch type bridges to isolate the deck from girders for reduction of seismic force of the system. The device consists of slide bearing with relatively low friction and laminated rubber bearings.
Seismic Response Control Brace With BRB damper	The brace of a truss type structure with energy absorption capability using inelastic and bucking behavior in the axial direction of the brace. It consists of core elements and sleeve which restrain the buckling of the core elements.
Shear Panel Damper at Bearing	A shear panel with inelastic energy absorbing capability works as a damper and stopper, as a countermeasure for excessive displacement at bridge bearings due to the Level 2 earthquake.
Shear Panel Damper at Gusset	An inelastic steel damper installed at the gusset which connects the horizontal beam and diagonal members in truss type structures.
High Damping Rubber Damper	A damper using high damping rubber bearing assemblies, which can absorb seismic energy by shear deformation without normal force. The implemented high damping rubber damper system consists of vertically and symmetrically arranged high rubber bearing assemblies and connecting cable.

長跨橋梁之耐震補強

長跨橋梁耐震補強的困難在於長跨橋受制於上部結構產生高規模的慣性力，並且支承座錨釘、橋墩和基礎的尺寸都隨著跨徑而不斷增加，以致於在成本製造技術上，以及對於其構造和配件裝設的複雜度都增加許多。甚至，許多既有的長跨徑橋梁當初在設計時，都曾經因為其長跨造成的長自然週期，對於地震力的需求採用折減的方式設計，因此在面臨使用更高規格的水平位移反應來估算則變形量變得十分可觀，以致於在橋墩頂部支承座或是伸縮縫都無法順應梁位移所產生的變位。此外，梁與梁之間原本應保持的淨寬，在地震影響之下也顯不足夠，以致於產生梁之間的碰撞，或是在橋墩頂部支承長度不足的疑慮。

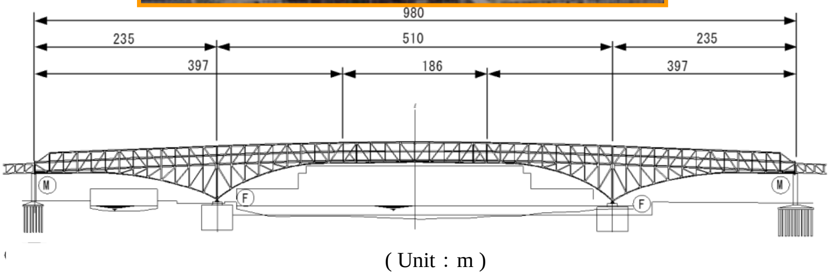
Hanshin 快速公路持續面臨著解決長跨徑橋梁耐震補強的挑戰，正因為沿著大阪灣週邊 Wangan 路線上，有許多各種不同類型的長跨徑橋梁，因此，對於長跨橋梁，許多隔震裝置和動態反制系統也列為耐震補強應用的選項之一。表二中歸納了許多 Hanshin 快速道路上，許多長跨徑橋梁所使用的隔減震及機動性反制設施，同時也將這些設施的設計指引，包含條文和補述都在歷經許多地震考驗之後，實際踏戡所得到的經驗記錄下來〔Hanshin Express 公司 2013〕。從表三到表七將上述各項設施的案例作進一步分析，包括施作的地點，和對於運用於這些長跨徑橋梁的預期功能表現都陳列出來。值得一提的是，這些長跨徑橋梁在地震下的表現，都是以大阪灣區的工址岩盤，並其所覆蓋的軟弱土層經過斷層錯動模擬的值所呈現出來的結果。而產出的設計地表運動，則是以假設特定震央位置工址特性及結構獨立等三項變數綜合而成。

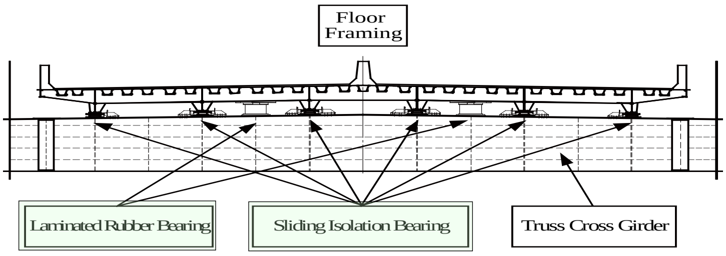
表二. 長跨徑橋梁的耐震補強基本工法

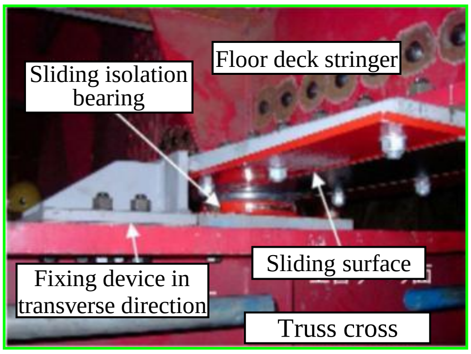
耐震補強工法	概　　述
橋面板隔震系統	在橋面板和梁之間或使用拱型裝置,將橋面板和梁之間分隔開來而成的隔震系統,這項裝置包含低摩擦係數的滑動式支承和合成橡膠支承。
制震斜撐加上 BRB 阻尼器	使用桁架式斜撐搭配非彈性及斜撐挫曲作為消能裝置,系統包括核心桿件及套筒來控制核心桿件的挫曲行為。
支承座抗剪阻尼器	將抗剪力平板加裝非彈性消能系統，當作是緩衝器和阻尼器，作為在大規模地震下產生過度位移抗衡的橋梁支承座。
連接板抗剪阻尼器	一套非彈性的鋼製阻尼器裝置於連接板上,使得水平梁和斜撐桿件以桁架型式連接起來。
高阻尼的塑膠阻尼器	使用高阻尼性質的塑膠支承組合，在沒有垂直受力的情況下，透過剪力變形吸收地震能量。這套高阻尼係數的塑膠阻尼器，包含以垂直方向有系統地疊起多層的高阻尼塑膠板及連接板。

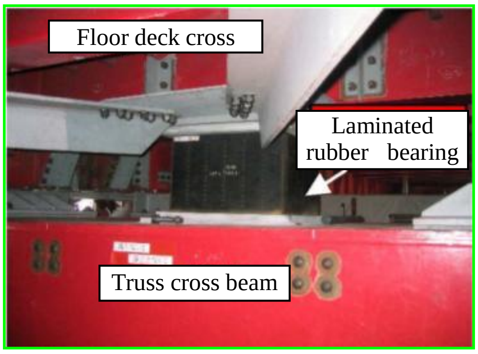
Table 3. Example of long-span bridge retrofit using deck-floor isolation technique

<table>
<tr><td>Bridge type</td><td>Minato Bridge (Truss bridge)</td></tr>
<tr><td>Installation location</td><td>



(Unit : m)


</td></tr>
<tr><td>Device Structure</td><td>




</td></tr>
<tr><td>Device performance</td><td>Floor-Deck Isolation System consists of the low friction slide bearing and the elastomeric bearings adjusting natural period of the floor-deck
Reduction of the inertia force on the floor-deck by seismic isolation (increase of natural period) reduces response sectional force on the main truss structure.
Performances of the low friction slide bearing and the elastomeric bearing are as follows.
(1) Low Friction Sliding Bearing
① Vertical support of the weight of the Floor-deck
② Reduction of the horizontal force transmitted from the Floor-deck system to the truss beam with low friction
(2) Elastomeric Bearing
① Adjustment of the longitudinal natural period of the floor-deck system to reduce its inertia force transmitted to the main truss structure
② Restoring the floor-decks to their original position with linear resilient force</td></tr>
</table>

表三. 以橋面板隔震工法補強之長跨橋案例

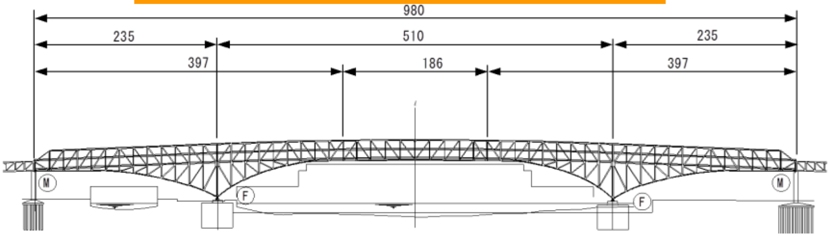
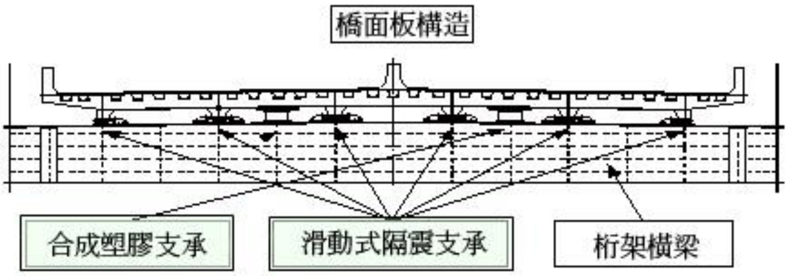
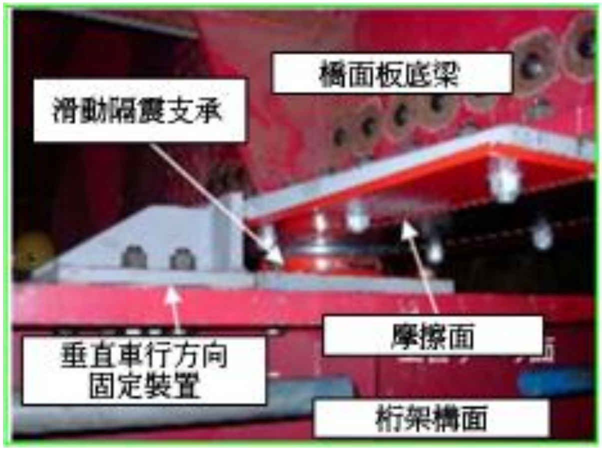
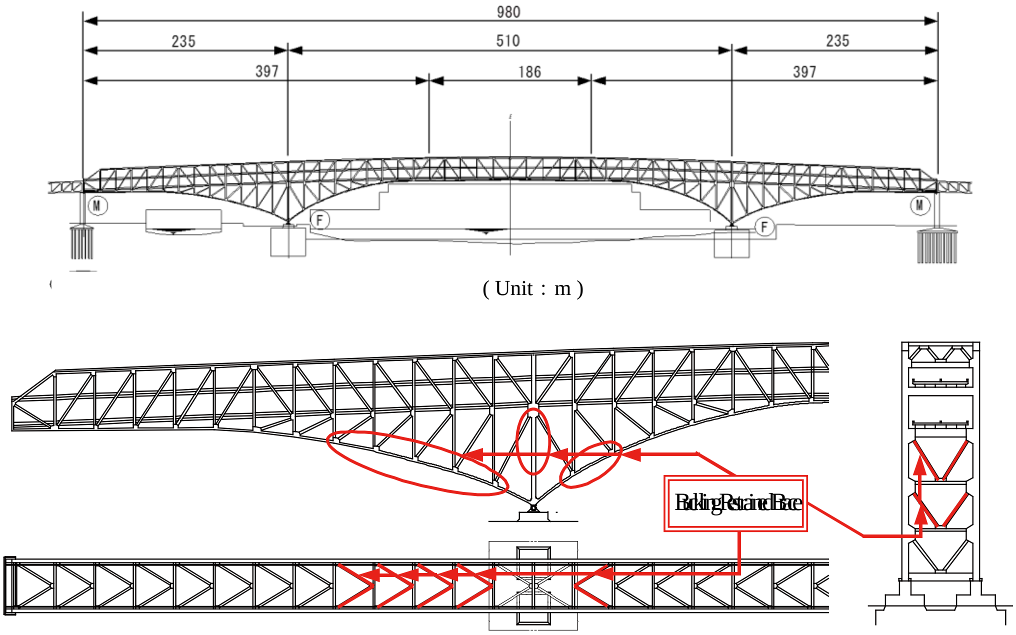
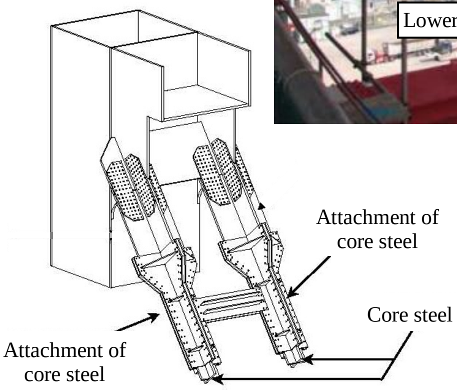
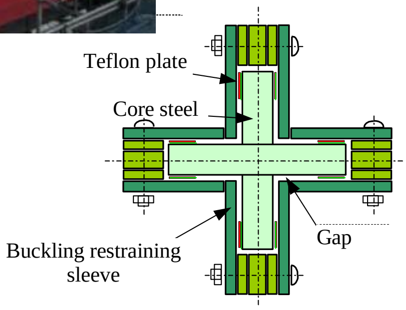
橋梁型式	Minato 橋（桁架橋）
隔震位置	  （單位：公尺） 
裝置構造	 
裝置 功能表現	橋面板隔震系統包括：低摩擦係數滑動支承和多重橡膠支承，以調整橋面板的自然週期。 只要透過橋面板隔震系統，將橋面板所產生的慣性力降低（增長自然週期原理），即可降低對於主桁架上斷面所產生的地震力反應。 對於低摩擦係數滑動支承及多重橡膠支承的功能表現要求如下： (1) 低摩擦係數滑動支承 ① 支撐橋面板的垂直載重 ② 透過低摩擦力，降低由橋面板系統所產生施加於橋面板底部桁架的水平力道。 (2) 多重橡膠支承 ① 調降橋面板於車行方向的自然週期，以達到對於橋面板底部桁架所施加的慣性力道。 ② 因為其線性的韌性特質，使得橋面板在地震力結束之後，使橋面板還原回復其原初始位置。

Table 4. Example of long-span bridge retrofit using BRB damper

<table>
<tr><td>Bridge type</td><td>Minato Bridge (Truss bridge)</td></tr>
<tr><td>Installation location</td><td>
</td></tr>
<tr><td>Device Structure</td><td>




</td></tr>
<tr><td>Device performance</td><td>The BRB consists of core steel that dissipates energy with yielding in tension and buckling in compression, and buckling restraining sleeves. As the core member, low yielding steel (LY225) is used.
BPBs come in pairs for use in the Minato Bridge in consideration of construction. The BRB performances are as follows.

(1) For the Level 1 design earthquake, the core steel shall not exceed their elastic limit.
(2) For the Level 2 design earthquake, plastic deformation is expected in the core steel to obtain hysteretic damping in the axial force for the reduction of seismic demand.</td></tr>
</table>

表四. 使用 BRB 阻尼器於長跨橋耐震補強案例

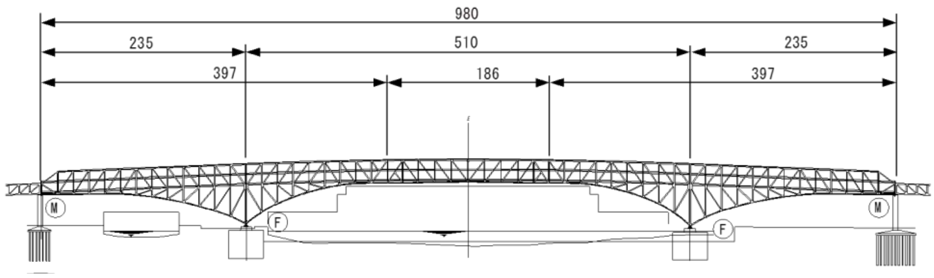
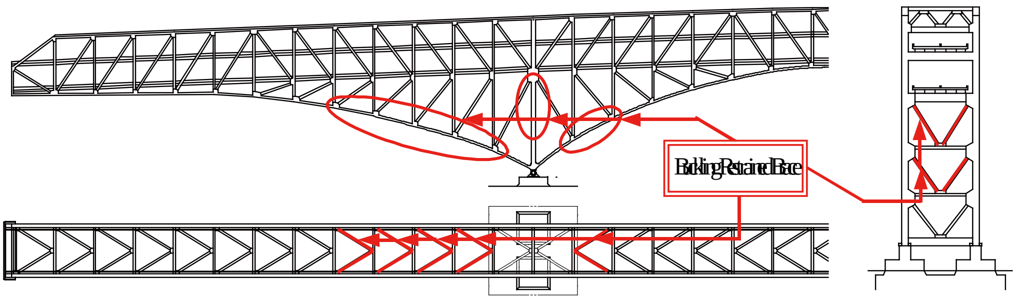
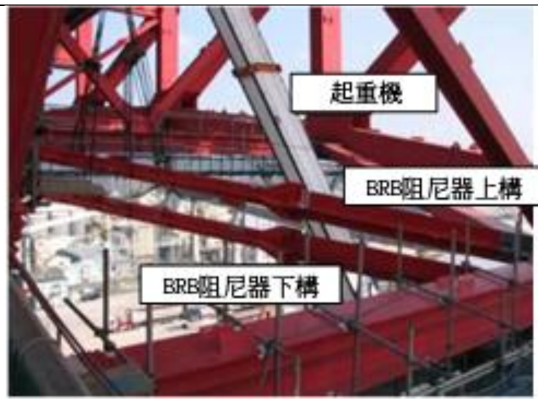
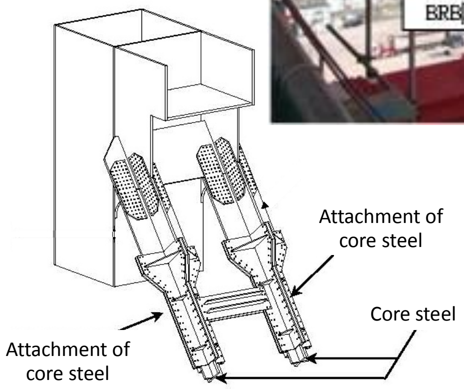
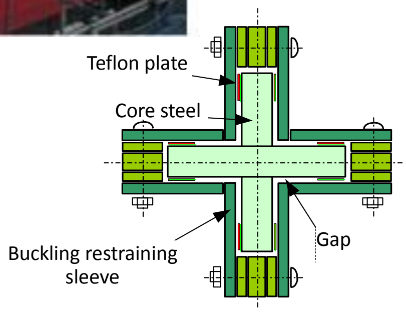
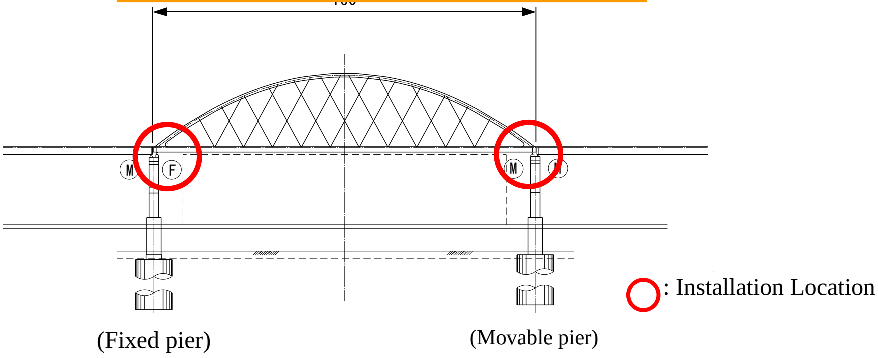
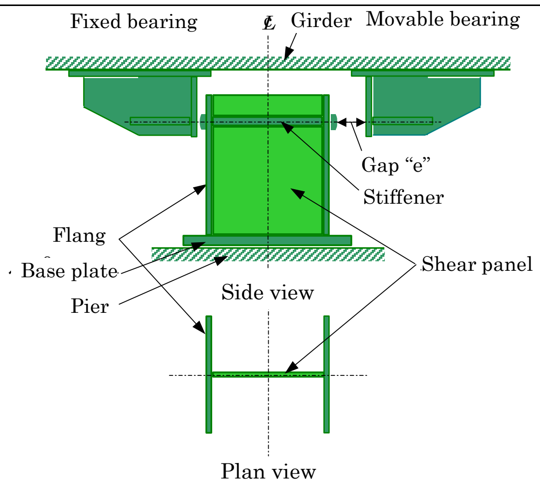
橋梁型式	Minato 橋（桁架橋）
裝置位置	 (Unit：m) 
裝置架構	  
裝置功能表現	BRB 阻尼器包含核心鋼桿件在（防挫曲套筒內）受拉時降伏，並受壓時挫曲以消能，核心鋼桿件使用低降伏強度鋼（LY225）。 在 Minato 橋使用 BRB 阻尼器，因施工方便，以成對型式裝置，對於 BRB 阻器的功能要求如下： (1)對於第一階段設計地震力影響下，核心鋼桿件以不超過彈性範圍為限制。 (2)對於第二階段設計地震力影響下，核心鋼桿件將呈現塑性變形，並在軸向力形成遲滯阻尼迴圈，以降低地震力需求。

Table 5. Example of long-span bridge retrofit using SP damper application to bearing part

Bridge type	Steel Arch Bridge
Installation location	 
Device detail	
Device performance	The performance of SP dampers at the bearings is as follows. (1) Performance of SP dampers at the fixed bearings ① To transmit the seismic inertia force of the superstructure to the fixed pier after the nock-off of the existing fixed bearings. ② To dissipate the energy with the hysteretic damping associated with the plastic deformation. ③To control the horizontal force acting on the fixed pier within the allowable limit. (2) Performance of SP dampers at the movable bearings ① When the inertia force of superstructure exceeds the allowable load limit of the fixed bearings, the load is distributed to additional SP dampers applied to the movable bearings. The dampers at both the fixed and movable bearings dissipate the energy, reducing the seismic response. ② To transmit the seismic inertia force of the superstructure to the movable pier within the allowable limit.

表五. SP 阻尼器應用於長跨徑橋梁耐震補強支承案例

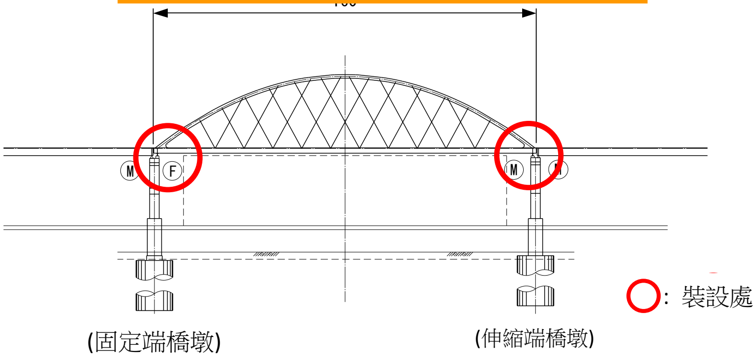
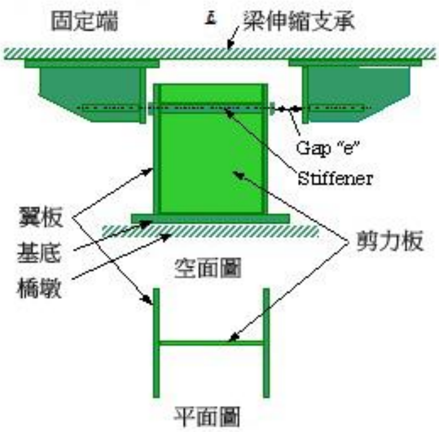
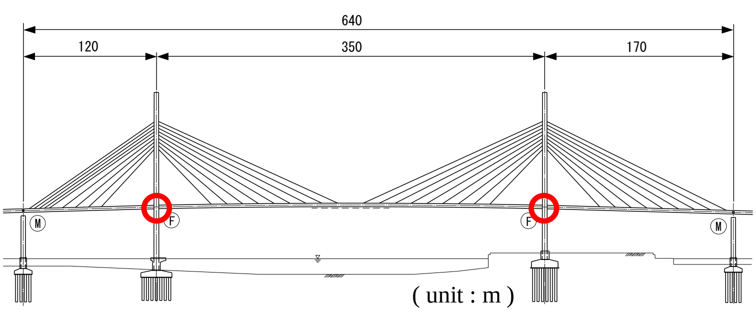
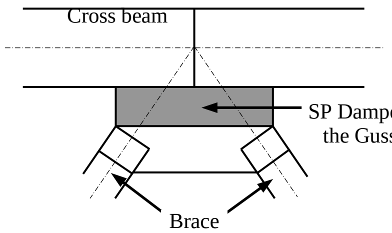
<table>
<tr><td>橋梁型式</td><td>鋼拱橋</td></tr>
<tr><td>裝置位置</td><td>

</td></tr>
<tr><td>裝置細節</td><td>
</td></tr>
<tr><td>裝置功能表現</td><td>SP 阻尼器在支承座的功能表現如下：
(1) 於固定端
① 在既有的固定支承一旦遭到地震力破壞之後，開始將上部結構因地震所產生的慣性力傳遞到橋墩。
② 經由塑性變形所產生之遲滯阻尼迴圈以消耗能量。
③ 將施加於固定端橋墩之水平力控制在可允許的範圍之內。
(2) 於可伸縮端
① 當上部結構所產生的慣性力超過固定端支承的容許承載限制時，荷載將由在伸縮端所設置額外的 SP 阻尼器承擔，所有裝置在固定支承及活動支承的阻尼器均能夠消能，減少對地震力的反應。
② 將上部結構所產生的慣性力在容許的承載範圍之內，傳遞到可伸縮的橋墩。</td></tr>
</table>

Table 6. Example of long-span bridge retrofit using SP damper application to gussets

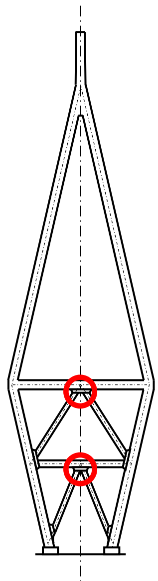
<table>
<tr><td>Bridge type</td><td>Steel Cable Stayed Bridge</td></tr>
<tr><td>Installation location</td><td>

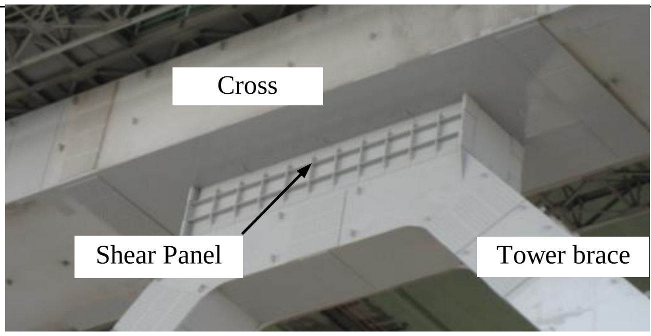
(a) Side view



(c) SP damper at the gusset



(b) Front view

○ : Setting location of SP damper at the gusset
</td></tr>
<tr><td>Device detail</td><td>


</td></tr>
<tr><td>Device performance</td><td>At the time of a seismic event such as the Level 2 earthquake, the compressive axial force will exceed the buckling strength of the braces. If shear panel dampers are installed at the gussets of the braces (SP damper at the gusset), the compressive axial force in the braces can be controlled within the buckling strength and the seismic inertia force of the superstructure can be reduced.
Required performance for SP damper is as follows:
1) To control axial forces acting on the braces within the buckling strength
2) To dissipate the energy with hysteresis damping to reduce the seismic inertia force
3) To control section forces of the columns and beams of the tower within the allowable values</td></tr>
</table>

表六. 使用 SP 阻尼器於連接板的長跨橋梁耐震補強案例

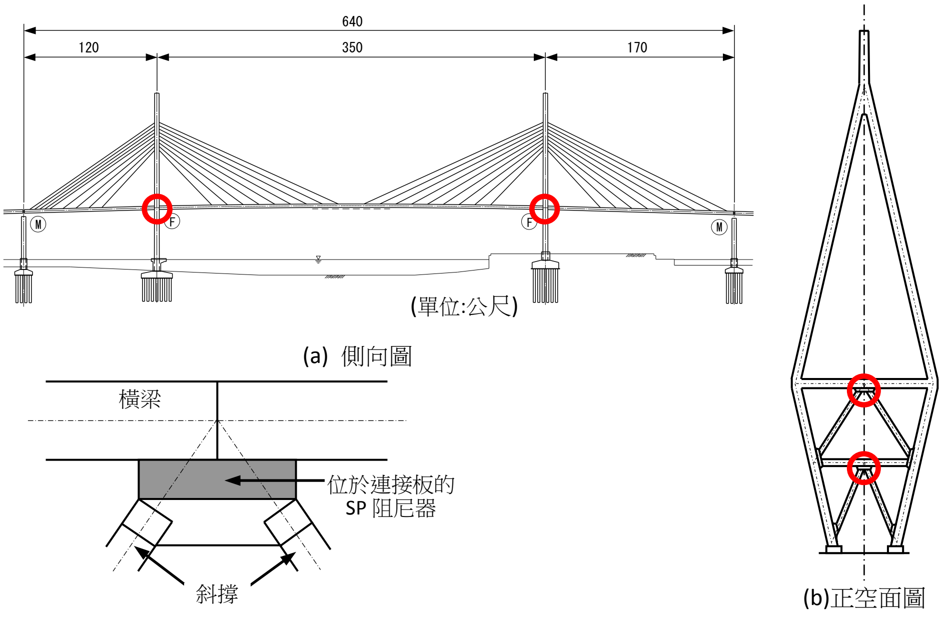
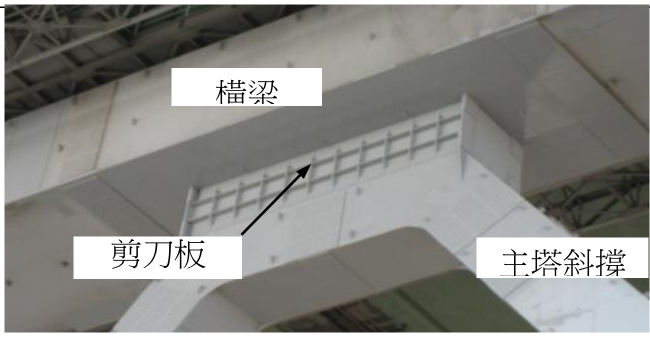
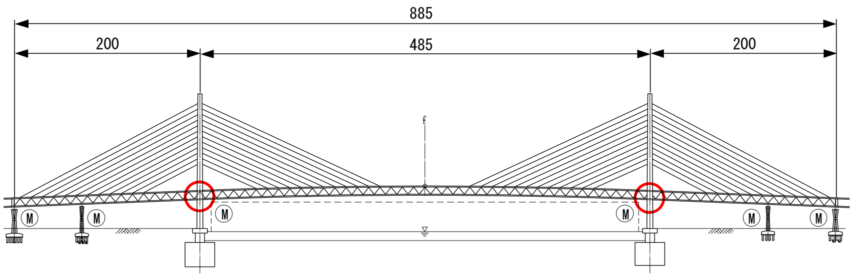
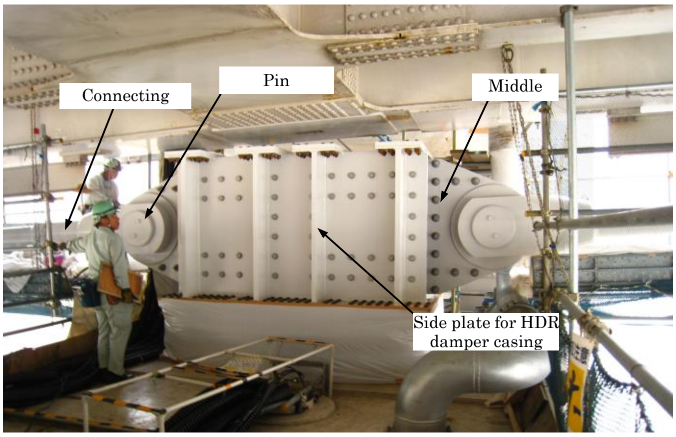
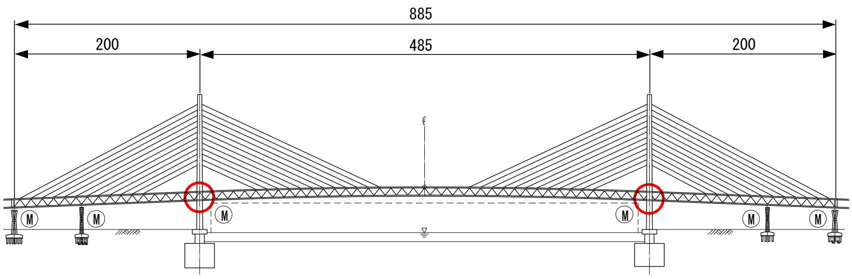
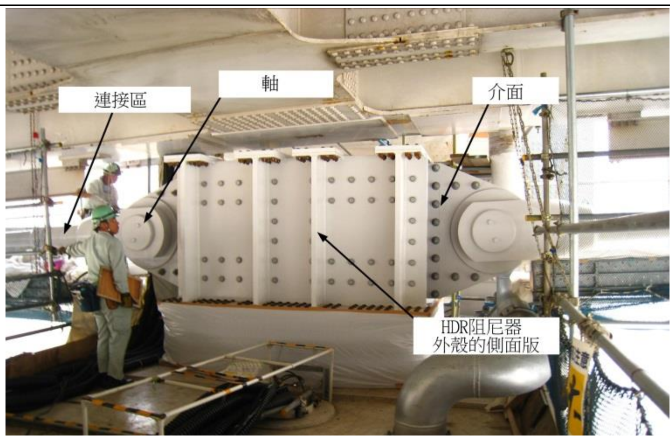
橋梁型式	鋼懸索橋
裝置位置	  (a) 側向圖 (b)正空面圖 (c) 連接上的 SP 阻尼器 ：連接板裝置 SP 阻尼器位置
裝置細節	
裝置功能表現	例如在第二階層的地震事件發生時，軸向的受壓力將造成斜撐超過容許值而產生挫曲，若將剪力板阻尼器設置於連接板內，將可以使軸向的壓力控制在斜撐不致於產生挫曲的極限值之內，因此使得上部結構所產生的地震慣性作用力降低。 剪力板阻尼器所需展現之功能表況如下： 1）將斜撐內所產生的軸向壓力，控制在產生挫曲的容許強度值範圍之內。 2）產生消能的遲滯阻尼，藉消能來降低地震慣性作用力。 3）將橋墩柱和懸索主塔的梁，所產生斷面上的力控制在一定的容許範圍之內。

Table 7. Example of long-span bridge retrofit using displacement control device system with HDR damper

Bridge type	Cable Stayed Bridge
Installation location	  Installation Location
Device Structure	 **Displacement Control System with the HDR**
Device performance	Control of longitudinal displacement using dampers is a very useful concept for all-free type cable stayed bridges. The displacement control system consisting of high damping rubber dampers (HDR damper) and connecting cables was adopted for the seismic retrofit of Higashi-Kobe Bridge. The performance requirement of the displacement control system with the HDR damper and connecting cables are as follows. (1) Performance of connecting cable 1) To transfer inertia force of the girder to the HDR damper 2) To absorb differential displacements in the vertical, transverse, and rotational directions between the girder and the tower. (2) Performance of HDR damper 1) To provide supplementary damping to the structure to reduce the inertia force of the girder. 2) To control the longitudinal displacement of the girder.

表七. HDR位移控制阻尼器使用於長跨橋梁耐震補強案例

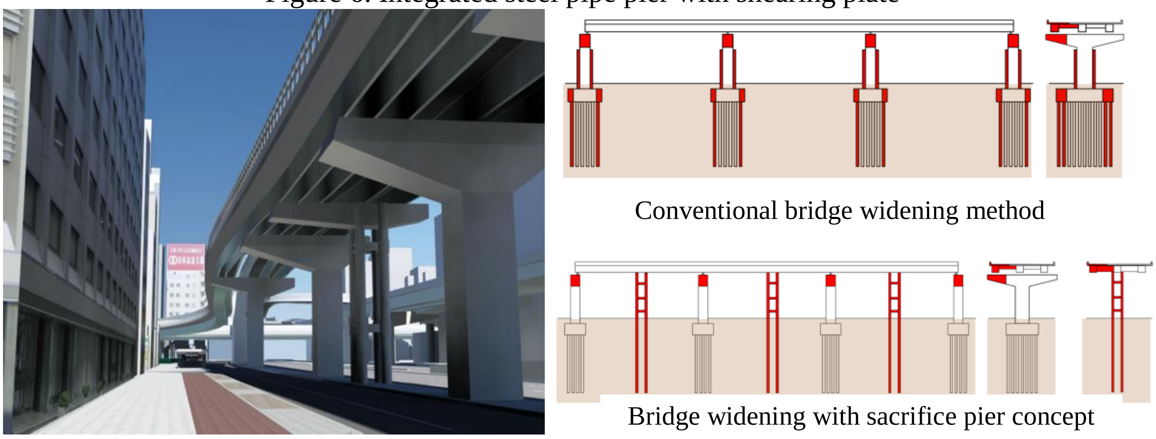
橋梁型式	懸索橋
裝置位置	  ○ ：裝置位置
裝置構件	 HDR 位移控制系統阻尼器
裝置功能表現	對於多方向自由度的懸索橋體，使用車行方向的位移控制，是一個很值得思考的發展方向。位移控制系統是由高阻尼器的塑膠阻尼器，並且透過連接鋼纜所組成，在Higashi-Kobe 橋耐震補強設計時所使用的工法，這兩項細節在地震力作用下，所需產生的功能表現規範如下： (1) 連接鋼纜 1) 將梁所產生的地震慣性力，傳遞到 HDR 阻尼器。 2) 吸收在梁與主塔之間垂直、橫向及旋轉方向不同的位移。 (2) HDR 阻尼器 1) 提供結構物額外的阻尼效果，以降低梁所產生的慣性作用力。 2) 控制梁所產生的縱向位量。

NEW SEISMIC IMPROVEMENT TECHNIQUES FOR NEW BRIDGES

The conventional seismic resistant design expects primal energy dissipation at the bottom of the piers. Even though the seismically isolated bridge that introduce isolation and damping enhancement, the collapse mode is designed that the plastic hinge should be made at the bottom of the column.
The new design concept is emerging “Damage control design” [KANAJI et al, 2002]. In this design concept, the major damages are allowed in only sub members that support lateral forces. These members are expected to behave in elasto-plastic condition and generate adequate hysteretic damping; whereas, the main members which support vertical force such as dead load and live load should be almost elastic. This concept has been already employed in the field of high-rise buildings.
The new innovative integrated steel pipe pier with shear link is composed of four steel pipes interconnected with shear links along its height. Steel pipes as main members, support vertical load (such as dead load and live load). Shear links as sub members resist horizontal load (such as seismic load). The application of the damage control design can reduce a response of the pier and it can keep steel pipes wholesome during earthquakes. So, not only emergency vehicles but also ordinary vehicles can pass immediately after earthquakes. Moreover restoration cost after such earthquake can be significantly reduced, because the main members remain almost elastic. Figure 6 shows the newly constructed integrated steel pipe pier applied to Ebie junction which connects the Yodogawa-sagan route to the Kobe route of Hanshin expressway [KOSAKA et al, 2012].
This new structure was also adopted to the bridge widening project of Hanshin expressway. Conventional design for the bridge widening project will be to strengthen the piers and footing to satisfy the additional dead load and horizontal load of the widening structures. But the due to the high density utilization of underground space sometimes did not allow the strengthening the existed pier and foundation due to lack of construction space in underground. The Nishi-Senba bridge widening project introduced this innovative pier as sacrifice pier that will support additional dead and whole lateral load. Design concept and image construction view are shown in Figure 7 [HORIOKA et al, 2014].

(a) General view (b) Connection between steel pipe and footing

Figure 6. Integrated steel pipe pier with shearing plate



Conventional bridge widening method

Bridge widening with sacrifice pier concept

(a) General view (b) Configuration of sacrifice pier

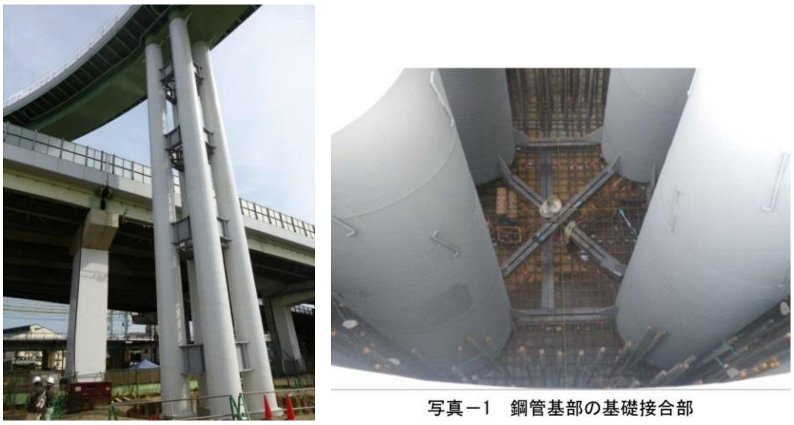
Figure 7. Sacrifice piers

新建橋梁耐震力提昇工法

傳統的耐震設計主要期待在橋墩底部產生消能的功能，即使使用隔減震設計並強化阻尼效果，仍舊在設計時預期塑性鉸發生在橋梁墩柱的底部。但是新的橋梁設計理念，卻是將損害控制的設計概念融入〔KANAJI 2002〕。而在這樣的設計原則之下，橋梁所產生主要的地震力破壞，只允許發生在側向力抵抗系統內的次要元素。這些構件在地震力作用下，將處於一個介於彈塑性狀態之間，以致於產生適度的遲滯迴圈阻尼效果，因而造就主結構體在地震力作用之下，仍舊能夠支撐垂直作用力，如自重和活重的情形下，依然保持在彈性的限度之內，同樣的設計概念都已普遍地應用在高層建築設計的力學要求上。

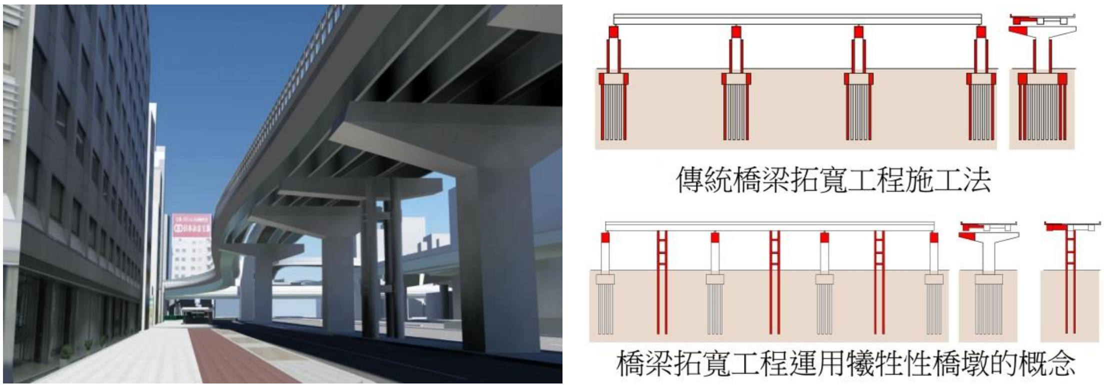
一種創新型結合四枝中空鋼管，並由剪力裝置隨著高度連接而成形的橋墩，其中鋼管為主要結構體，作為承載垂直力(如自重和活重)系統，而剪力連接裝置成為次要結構系統，用於抵抗水平力(如地震力)。而損害控制的設計，便是在地震力作用之下，藉以保全鋼管並且減少橋墩的損害。如此一來，不僅是救災的緊急救難車輛，同時，一般民間所使用的車輛，都可以在地震發生之後，仍使用橋梁通行。甚至，即使因地震造成災損，但其重建復原的成本可以大幅降低，正因為主結構系統仍保持在一定的彈性範圍之內。圖六即為連接 Yodogawa-sagan 與 Kobe 兩地之間的 Hanshin 快速道路 Ebie 交流道上，一座最近完工的複合型鋼管橋墩。

同樣的工法也應用在 Hanshin 快速道路的橋梁拓寬工程上，過去在橋梁拓寬工程的傳統設計思維，都以強化既有的橋墩，在增加橋墩及基礎因應拓寬部份所產生額外的垂直方向載重及水平方向的受力。但是常常因為都市的有限空間限制，並且地下空間也高度開發，對於既有橋墩或基礎的補強，幾乎是完全不能容許。就在 Nishi-Senba 橋拓寬工程案，這樣型式的橋墩，成為支撐額外拓寬段的自重，並擔負起全部水平力支撐系統，一種可在地震災損中犧牲的橋墩，圖七即為此橋墩的部份影像及設計概示意圖〔HORIOKA 2014〕。



(a)整體外觀　　(b)鋼管之間在基礎的連接狀況

圖六. 中空鋼管與剪力板複合式橋墩



(a)整體外觀　　(b)犧牲性橋墩外觀

圖七. 犧牲性橋墩

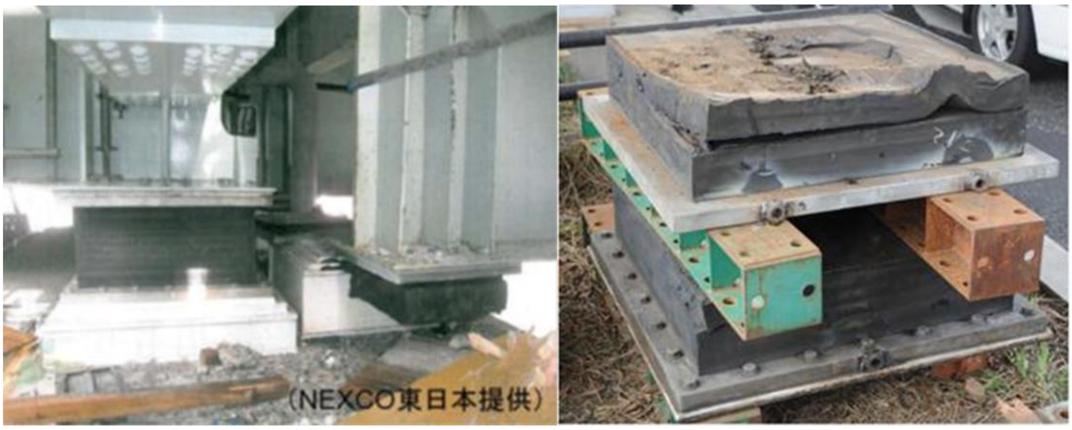
RE-EVALUATION OF SEISMIC ISOLATION DEVICES FOR BRIDGES

Since the 1995 Kobe Earthquake, the elastomeric bearings have been extensively used in construction of new bridges or in rehabilitation of existing highway bridges as the replacement of conventional steel bearings with the application of seismic isolation design in Japan. Rubber is made of a highly polymerized compound and the rubber has aging deterioration in nature. Long-term mechanical properties changes of elastomeric bearings result in stiffening due to continued vulcanization of the elastomer and degradation of elastomer due to exposure to ozone.

There are few reports that contain the information of aged properties of elastomeric bearings. Wide variety of aging information in US and UK [CONSTANTINOU et al, 2007] is reported. The report said that some tested elastomeric bearings showed stiffening in the horizontal shearing test and slight changes were found in the mechanical properties. However, no significant changes were reported. In Japan, high damping rubber bearing in-service for 10 years were removed from the bridge and tested the mechanical properties [SUDO et al, 2003]. No significant change in mechanical properties of bearing and rubber itself were found.

However significant damages of rubber bearings were found at the great east Japan earthquake. Figure 8 [TAKAHASHI, 2012] shows the rupture damage of elastomeric bearing observed at Sendai East Road / viaduct due to 2011 great east Japan earthquake. The bearings were ruptured at the bonding boundary between rubber and steel plate [HIROSE et al, 2011]. Such significant damage was found not only in earthquake loading condition but also in long-term service loading condition.

In case of Hanshin expressway, approximately 32% out of total assets about 87,000 were replaced to laminated rubber bearings. Most of the rubber bearings were replaced after the 1995 Kobe earthquake. Some aging deteriorations were found in those bearing as shown in Figure 9. Figure 9(a) shows the lead leaking out from the rubber surface of the lead rubber bearing. Figure 9(b) shows the ozone crack found on the surface of the laminated rubber bearing. The remaining seismic performance of those damaged bearings was not clearly studied yet. In order to study the remaining performance of aging



(a) Dislocation of girders due to RB damage (b) Close view of damaged RB

Figure 8. Seismic damage observed at the 2011 great east Japan earthquake

(a) Lead leaking out (LRB 17 years in-service) (b) Ozone crack (RB 27 years in-service)

Figure 9. Typical aging damage of LRB and RB under service loading condition

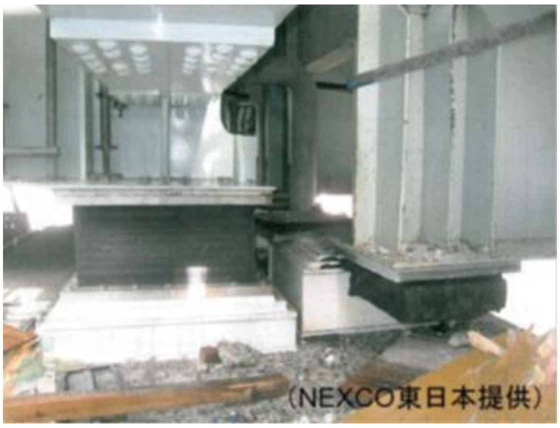
橋梁隔震裝置的重新評估

日本自 1995 年阪神地震之後，橡膠支承座廣泛地運用在新建橋梁，以及在既有橋梁的耐震補強計畫中，當作撤換傳統鋼支承的隔減震設計替代方案。橡膠是由高分子聚合物為基礎的原料，具有因年限老劣化的本性，在橡膠支承的物理性質中，會隨著塑膠質的部份脆化，且在暴露於大氣的環境下自然的劣化衰減。

對於橡膠支承座老劣化特性的相關研究報告並不多，在英國和美國的文獻中曾有廣泛地探討，雖然有部份測驗結果都顯示出橡膠支承座在水平剪力試驗出現固化，其材料基本物理性質也有變化，但其相關的變化量並不明顯。在日本只要使用超過 10 年以上的高阻尼性橡膠支承座都會被置換更新，並且測驗其物理性質〔SUDO 2003〕，在過去的報告中，也未曾發現支承或是橡膠材料本身有任何顯著的物理變化。

但是在東日本大地震期間，橡膠支承座受到許多嚴重的損傷，圖八即顯示出在 Sendai 東路高架橋上，因為 2011 年地震所發生的橡膠支承座撕裂的損傷。撕裂就發生在橡膠層和鋼板夾層兩者黏合的間隙〔HIROSE 2011〕，這樣型態的損傷，不僅出現在地震力影響的情況之下，同時也在長期荷載的狀況下出現。

以 Hanshin 快速道路管理公司為例，所管轄總共約 87,000 座橋梁中，大約 32%的支承座都已更換為橡膠支承座，而其中大部份是在 1995 阪神大地震之後所更換的。圖九可以看到許多老劣化的情形，在圖九左側（a）顯示在灌鉛支承座的橡膠表面已有鉛的滲漏，而圖九右側（b）的部份則是看出暴露於臭氧造成的裂痕，出現在橡膠合成支承座。而這些受損支承座，在地震力作用下的殘餘功能尚未被探討過，因此，為了研究老劣化支承座在殘餘壽命下，對地震力的反應表現，本單位特別將使用了 17 年的鉛心橡膠支承及使用了 27 年的橡膠支承座撤換下來，並且對支承座及橡膠材料本身的物理性質進行測驗。



(a)因支承座受損造成梁的異位

(b)受損後支承座之近照

圖八. 2011 年東日本地震後所觀察到的損傷

(a)17 年使用後鉛的滲透

(b)27 年使用期間暴露於臭氧環境所形成的裂痕

圖九. 在長期使用後鉛心支承座及橡膠支承座的劣化損傷

bearings, LRBs in-service of 17 years and RBs in service of 27 years were removed and tested the mechanical properties of bearings and rubber itself.

Figure 10 shows the horizontal cyclic loading test result of the LRB of 17 years in-service compared to the new product made by the old recipe of 17 years ago called “Reference” bearing [ADACHI et al, 2014]. The stiffness of the aged bearing was increased due to rubber hardening. This is the expected phenomenon. However, the hysteresis loop of the aged bearing shows much smaller compared to that of the reference bearing. This means that the energy dissipating capacity was drop or decreased due to the aging. These mainly reasons were considered of the damage of the lead plugs as shown in Figure 11 where the cross cut section of the tested deteriorated bearing was shown. The inside lead plug was completely fragmented and the colour of the lead turned to yellow due to oxidization.

Figure 12 shows the horizontal push-over loading test result of the laminated rubber bearings of 27 years in-service compared to that of the “reference” bearing [ADACHI et al, 2014]. The strength capacity of the aged bearings was pretty small compared to that of the reference bearing. Figure 13 shows the surface of the aged bearings with ozone cracks. This result shows that the ozone deterioration might reduce the strength capacity of the aged bearings.

These are a part of the facts obtained by the aging study on the seismic isolators conducted by expressway companies in Japan. The aging study of those seismic isolators is just begun. A lot of fundamental studies are needed to clarify the mechanism of the aging and deterioration of those isolators.

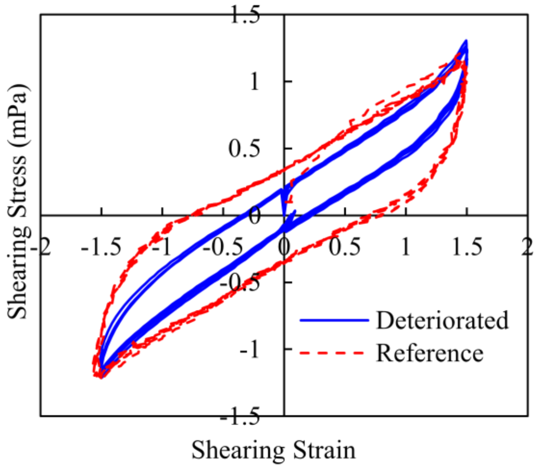


Figure 10. Remaining seismic performance of damaged LRB shown in Figure 9(a) (150% shear deformation test result)

Figure 11. Fragmented lead plug of damaged LRB shown in Figure 9(a)

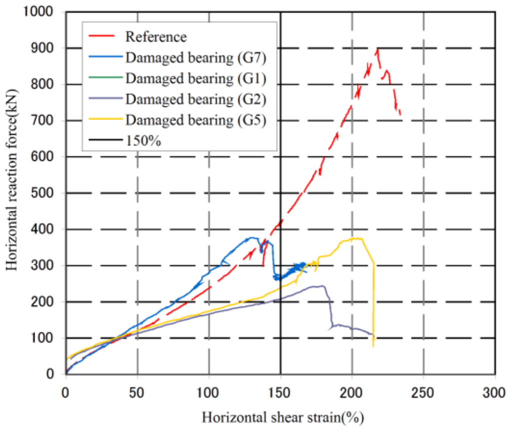


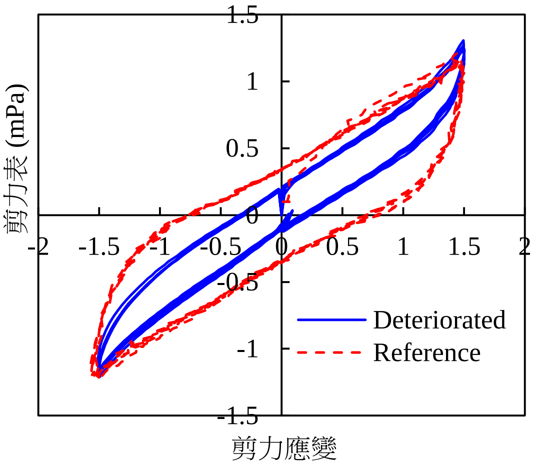
Figure 12. Remaining seismic performance of damaged RB shown in Figure 9(b) (Ultimate shear strain test result)

Figure 13. Ozone damaged elastomeric bearing

圖十展現出兩個支承座，在經過水平方向循環載重試驗之後的成果，其中之一是使用了十七年之後的支承座，對照相同的材料組合所製造的新支承座兩者之間的差異〔ADACHI 2014〕。老劣化的支承座因為橡膠材料的硬化而使勁度增加，這是可以想像的結果，但是老劣化橡膠支承座和對照組相比，其所形成的遲滯迴圈面積遠比新材料來得小很多，這表示老劣化支承座在消能的機制不斷下降，或是隨著使用年份而降低。在圖十一中展現了受測試的老劣化支承座在測試過後所切開的斷面，可以看出中心的鉛棒受損的狀況。其中的鉛棒已經完全的破碎化，並且因為氧化的原故，而使鉛呈現黃色。

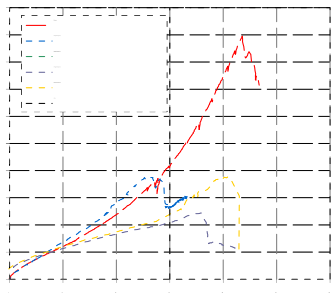
圖十二顯示出在使用 27 年之後的橡膠支承座，在經過水平側推實驗與對照組相比較的成果〔ADACHI 2014〕。經與對照組在強度的比較下，劣化支承座的承載力遠遠小於對照組，圖十三呈現暴露於臭氧環境下，老劣化支承所產生的表面裂痕。這些結果都是印證老劣化支承座，受大氣臭氧環境影響，對於材料強度的弱化現象。

以上是日本快速道路管理公司在針對橋梁隔減震支承座老劣化所作的一部份研究，相關的系列研究才正逐步展用，用於釐清老劣化的機制和隔震系統的衰減等相關探討。

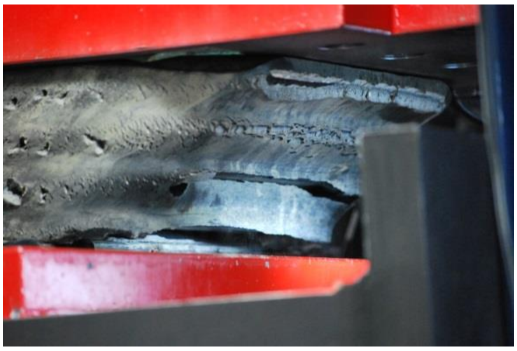


圖十. 受損鉛心支承座殘餘耐震性能
(圖九. (a)中以 150%的剪力變形極值)

圖十一. 在圖九(a)中鉛心棒受損狀況



圖十二. 受損橡膠支承座殘餘耐震性能
(圖九(b)中終極剪力應變試驗)



圖十三. 臭氧對於橡膠支承座的損害

CONCLUSIONS

This paper summarized the effectiveness of the seismic retrofit measures, the seismic retrofit measures for standard bridges, the seismic retrofit techniques for long-span bridges, new seismic performance improvement technology and the aging study on seismic isolators.

The seismic retrofit is the effective to reduce the seismic damage to the bridges. The effectiveness was verified by many experiences of the past earthquakes in Japan. The continuing effort should be paid to complete the retrofit work of all bridges in the country.

However, new problem, the aging or deterioration of the seismic improvement measures, especially isolators, is revealed. This is a quite new engineering problem. The aging mechanism should be clarified, the remained performance should be evaluated in engineering way, and the adequate maintenance measures for seismic isolators should be made in proper manner.

The continuing challenge is still needed.

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結論

本論文總結了耐震補強工法的效益，並且說明針對標準橋梁的耐震補強工法，介紹了長跨徑橋梁的耐震補強技術，同時也詳述了最新的耐震性提昇的新工法，和對於隔震系統老劣化的相關研究成果。耐震補強是降低地震造成橋梁損傷的有效方法，在日本經過多次的地震之後，其效益也得到了證實，下一步就是要針對日本全國所有的橋梁進行全面補強。

但同時工程所面臨補強所使用的許多工法的老劣化，特別是隔震系統成了新的研究課題，而這也是一個新的工程問題。造成老劣化的機制需要透過研究來探討，同時，殘餘材料的耐震表現也需要以工程的手段來評估，以致於對於隔震系統的維護也有適當的作法，因此仍有許多挑戰在前頭。

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