

Seismic Protection Devices for Bridge Retrofit: Applications and Production Control According to the European Code EN15129:2009.

Samuele Infanti, Maria Gabriella Castellano, Gian Paolo Colato

ABSTRACT

The retrofit of existing bridges and viaducts often represents a challenge to engineers because of the constraints imposed by existing geometry and materials. Seismic isolation and energy dissipation devices can be a powerful tool in the hands of engineers to retrofit bridges with a favorable cost-benefit ratio. In Italy, the use of seismic isolation and energy dissipation devices for retrofit purposes started in 1986. Since then, FIP Industriale has produced thousands of seismic devices of different types to retrofit bridges and viaducts - not only in Italy but in other countries as well. In most cases, protection systems comprise fluid viscous dampers or steel hysteretic dampers. The reason for this is that the very high energy dissipation capacity of said dampers is particularly useful in retrofits, as it reduces displacements for a given maximum force (fixed to a value lower than the piers or foundation capacity). Quite often the static scheme of the bridge/viaduct is changed from simply supported to statically indeterminate by connecting the beams through the slab, and thus reducing the number of expansion joints along the deck. Sometimes, different types of devices are combined in the same bridge, e.g. steel hysteretic dampers in the transverse direction and fluid viscous dampers in the longitudinal direction.

Since its official approval on 2009, the European Code EN15129:2009 “Anti-seismic Devices” has been in service and the related rules used in order to control the quality of the products.

This paper discusses some of the most frequent intervention schemes, presents some recent examples and provides indication on the typical testing procedures.

INTRODUCTION

For the last three decades, seismic isolation and passive energy dissipation technologies have undergone great development, finding many applications in both new and existing conventional bridges as well as major structures like suspended and cable-stayed bridges. A recent example in Europe is the Rion-Antirion cable-stayed bridge in Greece, where the largest fluid viscous dampers ever built were applied to control the transverse movement of the bridge deck during strong earthquakes [Infanti et al, 2003 a; Infanti et al., 2003 b]. This bridge, struck by an earthquake on 2008 performed satisfactorily during the event with no service disruption [Infanti et al., 2011].

The use of seismic isolation and energy dissipation devices in the seismic retrofit of bridges started very early - in the 1980s - due to the relative ease in substituting bridge bearings with seismic isolators [Skinner et al., 1993]. This paper summarizes the experience of FIP Industriale in bridge retrofits using seismic isolation and energy dissipation devices.

ITALIAN SEISMIC ISOLATION SYSTEMS FOR BRIDGES

Seismic isolation and energy dissipation devices have been used in Italy since the seventies for the seismic protection of different structures, and in particular bridges and viaducts. Hence, Italy soon became the country with the largest number of seismically isolated bridges (over 150 bridges and over 100 km of seismically isolated bridges by 1992 [Skinner et al, 1993]). Since the late eighties, Italian seismic devices have been applied in other countries too – ranging from European and Mediterranean seismic-prone countries to Bangladesh, the USA to Azerbaijan, and South-America to South Korea.

The isolation systems developed in Italy for use in bridges were those offering large amounts of energy dissipation through strong non-linear behavior. In effect, in the overall evaluation of a bridge seismic protection, the main goal is to reduce seismic forces as well as deck movements, providing a solution to the need to minimize expansion joints and bearings' stroke and resulting costs thereof. Thus, in order to reduce both stroke and force, a solution has been found in high damping devices (more than 30% of equivalent viscous damping) and in particular, strongly non-linear devices such as steel hysteretic dampers (alone or combined with sliding bearings in single units), based on the yielding of metals, exhibiting an elastic-plastic behavior that can limit the forces transmitted to piers (Fig. 1), or non-linear viscous dampers. More detailed description of both these types of

歐盟橋梁地震保護系統設計規範指導原則

Samuele Infanti, Maria Gabriella Castellano, Gian Paolo Colato

摘要

現存橋梁和高架橋的補強受限於幾何學與材料，對工程師而言經常是一大挑戰。隔震與消能裝置的本益比是工程師補強橋梁喜歡採用的有效工具。在義大利，補強用途之隔震與消能裝置的採用始自1986年。之後FIP Industriale生產數以千計的各式地震保護裝置來補強橋梁和高架橋，擴及義大利以外的國家。這些絕大多數的保護系統包含流體粘性阻尼器或是鋼遲滯阻尼器。原因是阻尼器的高消能承载力在補強中特別管用，它可以減少最大施力所造成的位移(固定低於橋墩或基礎承载力)。常見的是，將橋梁/高架橋的靜力理論從簡支撐改變為靜不定連接梁與厚板，因此減少橋面板方向的伸縮縫數量。有時候，不同裝置合用在同一橋梁，例如，鋼遲滯阻尼器用在橫向，流體粘性阻尼器用在縱向。2009年經官方許可，歐規EN15129:2009“耐震裝置”已經生效與相關法規制定以控制產品品質。這篇論文討論一些最常使用的導入理論，揭露一些新的案例並且提供典型測試程序。

引言

過去三十年，隔震與被動式消能技術有很大的進展，應用在新的或已存在的傳統橋梁，以及主要結構體如懸索和斜張橋。歐洲有一個最近案例是希臘的Rion-Antirion斜張橋，採用已知最大的流體粘性阻尼器去控制強震時橋梁的橫向位移[Infanti et al, 2003 a; Infanti et al., 2003 b]。這座橋梁經過2008年地震襲擊卻毫無損傷[Infanti et al., 2011]。隔震與消能裝置用在地震橋梁補強始於80年代早期，相對容易使用隔震裝置代替橋梁支承座[Skinner et al., 1993]。這篇論文總結FIP Industriale使用隔震與消能裝置的橋梁補強經驗。

義大利橋梁隔震系統

義大利從70年代開始使用隔震與消能裝置保護不同的結構體，特別是橋梁和高架橋。因此義大利很快成為擁有最多隔震橋的國家(1992年以前超過150座橋梁與超過100公里長的隔震橋梁[Skinner et al, 1993])。80年代後期，義大利地震裝置也被其他國家採用，範圍從歐洲與地中海地震多發國家到孟加拉，從美國到亞塞拜然，從南美洲到南韓。義大利發展的橋梁隔震系統透過強烈非線性行為提供大量消能。在效果上，橋梁地震保護的總體評估，主要目的是降低地震威力與橋面板位移，提供所需的方案以最小化伸縮縫和支承座的衝擊並反應在成本上。為了降低衝擊與地震威力，高阻尼裝置方案被採用(超過30%是等效粘性阻尼)以及特別是強力非線性裝置如鋼遲滯阻尼器(單獨或聯合單元滑動支承座)，基於金屬的降伏，展現一種彈塑性行為去限制力量傳遞到橋墩(圖1)，或是非線性粘性阻尼器。更多這類型裝置的細部說明會在後續章節中介紹。彈性隔震裝置使用高阻尼橡膠合成或是鉛核心，曲面滑塊也都有用於義大利與其他國家。然而他們在橋梁和高架橋的用法常僅限於橋面板由多根梁組成的案例，即每根支承座的垂直載重不太大且現場地震規模不高。其他地震裝置也使用在義大利[Castellano&Infanti, 2005]。

devices is given in the following paragraphs.

Elastomeric isolators, both utilizing high damping rubber compounds or lead cores, and Curved Surface Sliders are also used in Italy as well as other countries. However, their use in bridges and viaducts is usually limited to those cases where the deck comprises many beams, i.e. the vertical load on each bearing is not that great and the site seismicity level is not very high. Other types of seismic devices have also been used in Italy [Castellano & Infanti, 2005].

Steel Hysteretic Dampers

These devices are constructed using metallic elements of various shapes made of high ductility steel. For the most part, they are based on flexural yielding. Even though the first steel hysteretic dampers in the world were used in the South Rangitikei viaduct, in New Zealand [Skinner et al, 1993], the country in which they have found the widest development and application is Italy.

Amongst the many different shapes of steel hysteretic dissipating elements developed by FIP Industriale, the most widely used are (Fig. 2): 1) crescent moon elements; 2) tapered pin or double-tapered pin elements; 3) X-shaped or butterfly elements (similar to the ADAS elements applied in USA mainly within braces in framed buildings, while in Italy they are usually applied at abutments in bridges).

Once the shape of the element and its correct size are selected according to design displacement, the steel dissipating elements are so arranged as to achieve the required function (uni-directional or multi-directional) depending on where they are to be installed. The required maximum force, elastic and post-elastic stiffness of a steel hysteretic damper are obtained by setting the proper number of dissipating elements working in parallel. This provides the advantage of redundancy: i.e., any defect in one or more elements does not put a seismic device out of service.

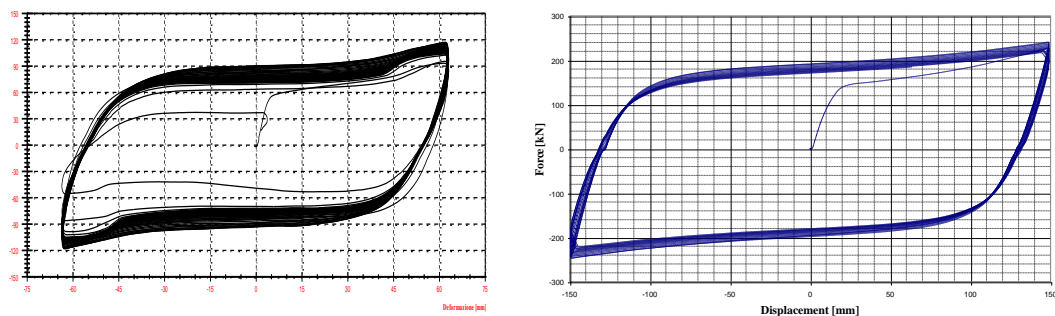
Steel hysteretic dampers in bridges are usually combined with sliding bearings to create a seismic isolation system. This combination is often used in a single device or isolator, comprising (Fig. 3): 1) a free-sliding (or uni-directional, if so required by the bearing system) bearing (pot, spherical or elastomeric) that serves to transmit vertical loads and allow rotations and horizontal movements; 2) a series of steel dissipating elements to control horizontal actions and dissipate energy (these elements are arranged around the bearing to ease inspection). A large amount of experimental data on the behaviour of isolators of this type can be found in [HITEC Ed., 1998].

When necessary, shock transmission units (STUs) are also combined with steel hysteretic dampers to handle significant thermal movements. STUs are inserted between the moving portion of the structure and the steel dissipating elements, in series with the latter. The resulting devices allow slow movements under service conditions without activating the dissipating elements, while under earthquake excitations the STUs lock, transmitting the force to the steel dissipating elements.

Sometimes, sacrificial restrainers are also used. These are designed to resist service loads and fail during a design earthquake, thus allowing the steel hysteretic dampers to work properly [Castellano et al., 2001].

The aforesaid combination of steel hysteretic dampers and sliding bearings has become known as “the Italian approach to seismic isolation” because it was developed by Italian manufacturers of seismic devices and was applied in hundreds of bridges - first in Italy and then all over the world, since the 1980s.

Figure 1: Typical force vs displacement experimental curve of tapered pin shaped (left) and crescent moon shaped (right) steel hysteretic damper



鋼遲滯阻尼器

這些裝置的建造是使用高延展性剛材做成的各種形狀金屬元件，他們大部份是以撓曲降伏為基礎。即便世界第一座鋼遲滯阻尼器使用在紐西蘭的South Rangitikei 高架橋[Skinner et al, 1993]，被發現最大量開發與應用是在義大利。FIP Industriale開發的各形式鋼遲滯散熱元件當中，最廣泛使用的是(圖2): 1) 新月元件; 2) 錐形插鞘或是雙錐形插鞘元件; 3) X形或蝴蝶形元件(類似ADAS元件主要應用在美國結構建築斜撐，在義大利經常使用在橋梁橋台)。

一旦依照設定位移選定元件的形狀與正確尺寸後，鋼散熱元件依據安裝地點組成所需要的功能(單向或多向)。鋼遲滯阻尼器所需要的最大荷載、彈性剛度與後彈性剛度是透過平行方向安裝散熱元件的標準數量所決定。這提供了贅餘的優點: 即在一個或多個元件失效時，地震裝置仍可繼續使用。

橋梁鋼遲滯阻尼器經常與滑動支承座組合成隔震系統。這種組合常使用在單一裝置或隔震裝置，包括(圖3): 1) 一個自由滑動(或單向，支承座系統要求) 支承座(鍋，球形或彈性)傳遞垂直載重並允許旋轉與水平移動; 2) 一個鋼散熱元件系列控制水平行動與散發能量(這些元件組合在支承座周圍以緩解檢驗)。這款隔震裝置行為的大量實驗數據可在[HITEC Ed., 1998] 中找到。

當有必要，衝擊傳遞單元(STUs)也可與鋼遲滯阻尼器組合控制重要的熱位移。STUs 插入在結構物的移動部位與鋼散熱元件之間，並與後者串連。這種裝置在正常狀態下允許緩慢位移而不啟動散熱元件，但當地震發生時，會觸發STUs 鎖住並傳遞地震力至散熱元件。

有時犧牲限位裝置也被採用。平時設計成承受外力荷載且當地震發生時會失敗，於是促成鋼遲滯阻尼器正常作用[Castellano et al., 2001]。

鋼遲滯阻尼器的上述組合與滑動支承座成為眾所周知的“義大利式的隔震法”，因為這些地震裝置從80年代起由義大利製造商開發，一開始應用在義大利的幾百座橋梁上，然後延伸至全世界。

圖1: 典型外力vs.位移實驗曲線錐形插鞘形狀(左)與新月形狀(右)鋼遲滯阻尼器

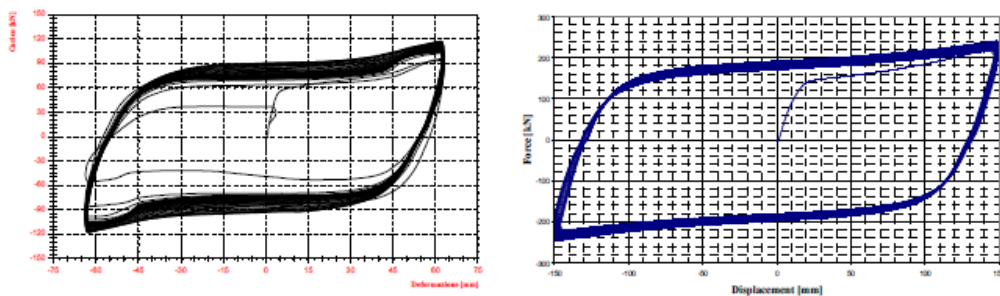
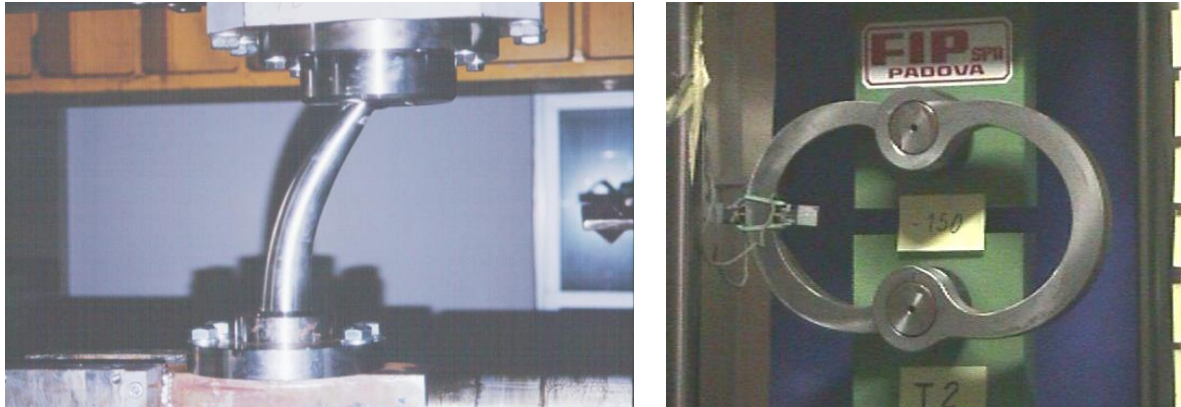


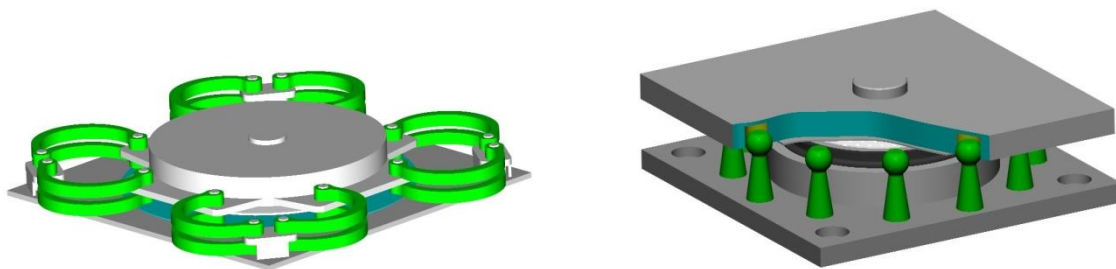
Figure 2: Tapered pin (left) and crescent moon (right) elements under testing



Intrinsically, crescent moon steel hysteretic elements exhibit uni-directional behavior (Fig. 2 right), but can be arranged in different ways to create dampers with multidirectional behavior. An outstanding application of this type of dampers to retrofit bridges is the one in the approaches of the Granville Bridge in Vancouver, Canada, where 157 dampers were installed both in longitudinal and transverse directions, with horizontal forces ranging from 130 to 220 kN and design displacements of ± 152 mm. Isolators with this type of steel hysteretic elements were also used in the retrofit of an offshore oil platform [Infanti et al. 1997].

Tapered pin steel hysteretic dissipating elements can be of two types: single, i.e. a cantilever type element (Fig. 2 left) or double, equivalent to two single pins in series. Their main advantage resides in their intrinsic multi-directional behavior (in the horizontal direction, of course). Shaking table tests have been carried out on a full-scale tapered pin element to fully validate its seismic behaviour [Castellano et al., 2001]. A main example of application of double tapered pin steel hysteretic dampers is the Bangabandhu (Jamuna) Bridge in Bangladesh [Castellano and Cestarollo, 1999]. Isolators equipped with double tapered pin type elements were used in the retrofit of the Marquam Bridge, Oregon – USA (see chapter 8 below). More than 4000 isolators with tapered pin elements have been recently installed in the new viaducts of the Caracas-Tuy Medio Railway [Pérez et al., 2001 a, Pérez et al., 2001 b] and installed or under installation in the viaducts of the Puerto Cabello-La Encrucijada and Caracas-Guarenas-Guatire Venezuelan Railway lines.

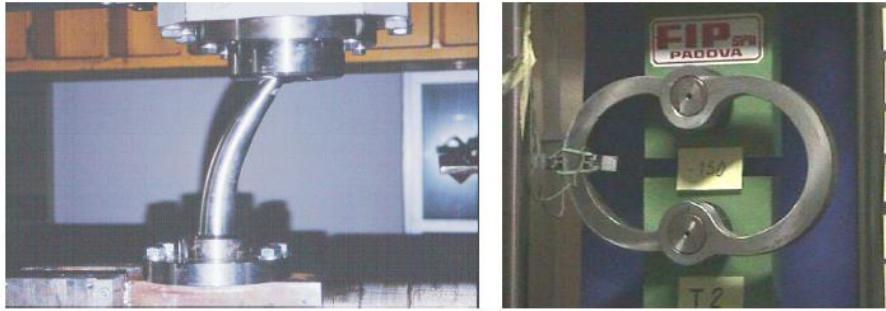
Figure 3: Sketches of a sliding isolator with crescent moon (left) and tapered pin (right) dissipating elements.



Fluid Viscous Dampers

Fluid viscous dampers are axial devices whose force is proportional to velocity, whether linear or not. The hydraulic circuit connecting the two chambers in which the cylinder is divided by a piston head, as well as the fluid and the geometric design of the dampers, are different depending on the manufacturer [Soong & Dargush, 1997]. The hydraulic circuit usually consists of

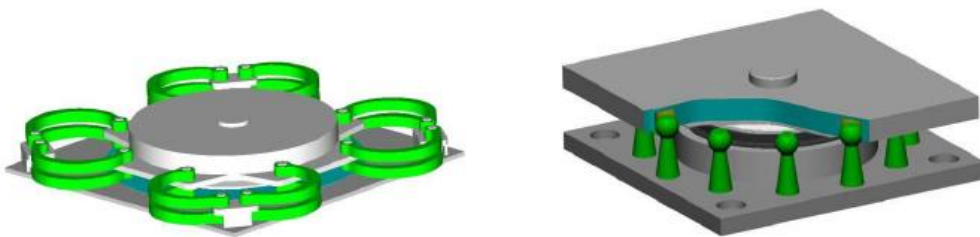
圖2: 測試中的錐形插鞘形狀(左)與新月形狀(右)元件



本質上，新月鋼遲滯元件表現出單向行為(圖2右)，但可安排以不同的方式與多向行為創建阻尼器。這種類型的阻尼器最典型的成功案例是加拿大溫哥華Granville橋的補強工程，有157個阻尼器同時安裝在縱向與橫向，水平力範圍從130到220KN以及 ± 152 mm的設計位移。這種類型的鋼遲滯元件的隔震裝置也被用作海上石油平台的補強[Infanti et al. 1997]。

錐形插鞘鋼遲滯散熱元件有2種型態：單一，即懸臂型元件(圖2左)或是雙層構造，等同於兩個單一系列插鞘。它們主要優點在於內在的多方向行為(當然是水平方向)。振動台試驗已進行了一個全面的錐形插鞘元件，充分驗證其耐震行為[Castellano et al., 2001]。應用雙錐形插鞘鋼遲滯阻尼器的一個主要例子是孟加拉的Bangabandhu(Jamuna)橋[Castellano and Cestarollo, 1999]。配有雙錐形插鞘類型元件的隔震裝置使用在補強美國俄勒岡州的Marquam橋(請看以下第8章)。超過4000個錐形插鞘元件隔震裝置最近已安裝在Caracas-TuyMedio鐵路的新高架橋[Pérez et al., 2001 a, Pérez et al., 2001 b] 以及已安裝或正在安裝中的委內瑞拉鐵路線Puerto Cabello-La Encrucijada與Caracas-Guarenas-Guatire的高架橋。

圖3: 新月(左)與錐形插鞘(右)散熱元件的滑動隔震裝置草圖。



流體粘性阻尼器

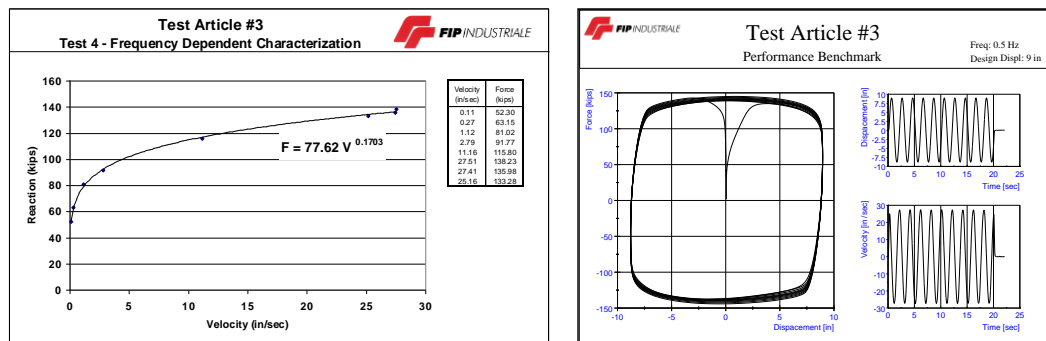
流體粘性阻尼器不論是否線性，是一種外力正比於速度的軸向的設備。液壓迴路連接兩個腔室，其中氣缸被活塞頭分割，以及流體和阻尼器的幾何設計因製造商而不同[Soong & Dargush, 1997]。液壓迴路通常包含活塞頭部孔或洩壓閥。

orifices in the piston head or relief valves. Consequently, the force vs. velocity relationship $F = C \cdot v^\alpha$ of fluid viscous dampers also varies with the manufacturer, the exponent α usually ranging from 0.1 to 1. In the last few years, viscous dampers manufactured by FIP Industriale have undergone major testing programs [Boeing Ed., 2000; Infanti & Castellano, 2001; Benzoni & Seible, 2002; Infanti et al., 2003 b] which entitled the company to be entered in the Pre-qualified Damper Manufacturers List for the Golden Gate Bridge Retrofit project as well as to enter the CALTRANS (California Department of Transportation) List of Pre-qualified Damper Manufacturers. FIP's last generation of fluid viscous dampers have orifices in the piston head, and commonly have an exponent $\alpha \approx 0.15$ (Fig. 4, left). Thus, their reaction is almost constant within a wide velocity range. This permits the devices to already initiate damping reaction at low velocities. Said effect maximizes the reduction of displacements owing to the high efficiency of the hysteretic loop (Fig. 4, right). In other words, a device characterized by a larger α exponent at an equal level of maximum load transmitted to the structure permits greater displacement.

Fluid viscous dampers in bridges are used together with a suitable bearing system composed by sliders (e.g. pot sliding bearings or others) or elastomeric bearings. They can be used both in longitudinal and transversal direction.

On June 6, 2008 the Rion-Antirion Bridge in Greece – protected by VDs - has been struck by a 6.3M earthquake having its epicenter at 36km from the bridge location. The main bridge and its approaches, protected by almost 200 dampers of different load capacities and strokes, survived the seismic event with no damages.

Figure 4: Force vs. velocity experimental relationship (left) and typical hysteretic loop of a FIP's fluid viscous damper under sinusoidal excitation (right).



Elastomeric Isolators

Elastomeric isolators are reinforced rubber bearings made of alternating layers of steel laminates and hot-vulcanized rubber. Usually, they are circular in shape but can be fabricated in square or rectangular section as well.

These devices are characterized by low horizontal stiffness, high vertical stiffness and a moderate damping capacity (10-15% in terms of equivalent viscous damping) provided by particular rubber compounds used for the purpose from which they take the name (High Damping Rubber Bearings or HDRBs). These characteristics permit, respectively, to increase the fundamental period (the increase of the fundamental period) of vibration of the bridge, to resist to vertical loads without appreciable settling, and to limit horizontal displacements in seismically isolated structures.

In the same family, we can include the Lead Rubber Bearings (LRB) which are reinforced rubber bearings equipped with a cylindrical central lead ore. The energy dissipation provided by the lead core, through its yielding, allows to achieve an equivalent viscous damping coefficient up to about 30% so about twice that of high damping elastomeric isolators.

Thanks to such high damping capacity, by means of LRBs it is possible to reduce the horizontal displacement, in comparison with that of an isolation system with the same equivalent stiffness but lower energy dissipation capacity.

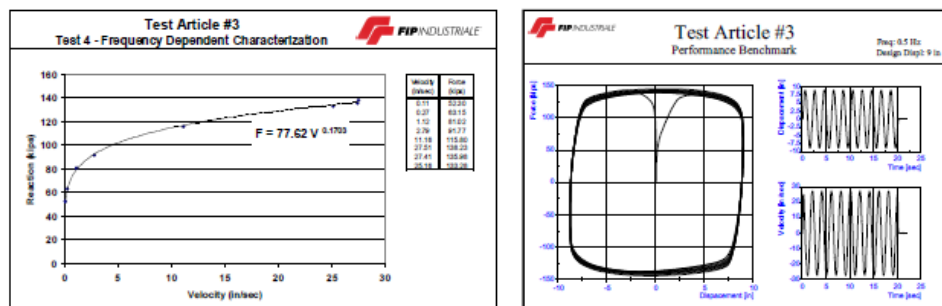
For the above mentioned reason LRBs are commonly preferred to HDRBs for retrofit purposes.

The elastomeric isolators, owing to their limited vertical load and moderate damping capacity, are commonly suitable for small to medium span bridges, or bridges whose decks are made up of many pre-cast girders. Anyway, viscous dampers can be installed in parallel to them in order to increase the energy dissipation capacity of the isolation system and thus reduce displacements if required [Infanti et al. 2003].

因此，流體粘性阻尼器的力量對應速度的關係 $F = C \cdot v^\alpha$ 也是隨製造商而不同，指數 α 通常的範圍從0.1到1。過去幾年，FIP Industriale粘性阻尼器製造商已進行重大的測試程序[Boeing Ed., 2000; Infanti&Castellano, 2001; Benzoni&Seible, 2002; Infanti et al., 2003 b] 讓該公司列於金門大橋補強計畫與CALTRANS (加州交通部門)資格預審合格的阻尼器製造商名單中。FIP最後一代的流體粘性阻尼器具有活塞頭孔，且指數通常是 $\alpha \approx 0.15$ (圖4左)。因此，他們的反應在很寬的速度範圍內幾乎不變。這允許設備在低速就可啟動阻尼反應。由於遲滯迴路的高效率可最大化降低位移(圖4右)。換言之，一個具有較大 α 指數的裝置，在傳遞結構的最大負荷相同等級，允許較大的位移。

橋梁流體粘性阻尼器可與含滑塊的支承座系統一起使用(例如，鍋滑動支承座或其他)，或是彈性支承座。縱向與橫向都可使用。在2008年6月6日，希臘的Rion-Antirion橋-用VDs保護- 受到6.3M地震的襲擊，震央位置距離橋梁36公里處。主橋及其方法，因受到近200個不同承載力與行程的阻尼器保護，地震後倖存下來沒有損害。

圖4: 力vs.速度的實驗關係(左)和正弦激勵下FIP液體粘性阻尼器的典型遲滯迴圈(右)。



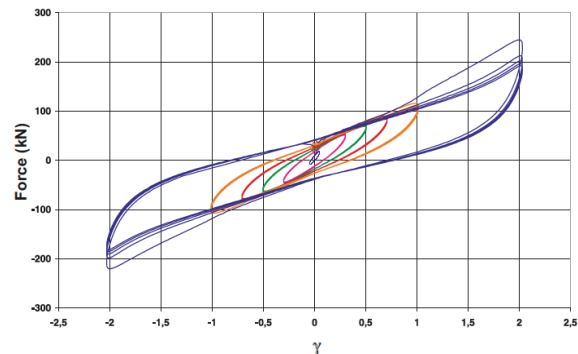
彈性隔震裝置

彈性隔震裝置是強化橡膠支承座，由交替層的鋼層壓板和熱硫化橡膠製成。通常，它們是圓形的，但也可以製成方形或矩形的截面。

這些裝置的特徵在於低的水平剛度，高的垂直剛度和適度的阻尼容量(10-15%等效粘性阻尼組成)，依據不同名字的特殊橡膠合成物而命名(高阻尼橡膠支承座或HDRBs)。這些特性分別允許提高橋梁振動的基本週期(基本週期的提高)，抵抗垂直承載而沒有明顯的沉陷，並限制隔震結構的水平位移。

在同一個家族，我們可以包含鉛芯橡膠支承座(LRB)，含有一個圓柱形中央鉛礦石的強化橡膠支承座。由鉛芯提供的能量耗散，通過其降伏，允許實現一個等效粘性阻尼係數高達約30%，是高阻尼彈性隔震裝置的兩倍。由於這樣的高阻尼能力，透過LRBS的方法，在與該隔震系統具有相同的等效剛度，但較低的能量耗散能力作比較，可以減少水平方向的位移。基於上述原因，LRBS通常優先選擇HDRBs用於補強用途。彈性隔震裝置，由於其有限的垂直荷載和適中的阻尼容量，通常適用於小到中等跨度橋梁，或橋梁的橋面板是由許多預力梁組成。無論如何，粘滯阻尼器可以平行安裝，以增加隔震系統的能量耗散能力並依需要減少位移[Infanti et al. 2003]。

Figure 5: Elastomeric Isolator under testing (right) and typical HDRB hysteresis loop.



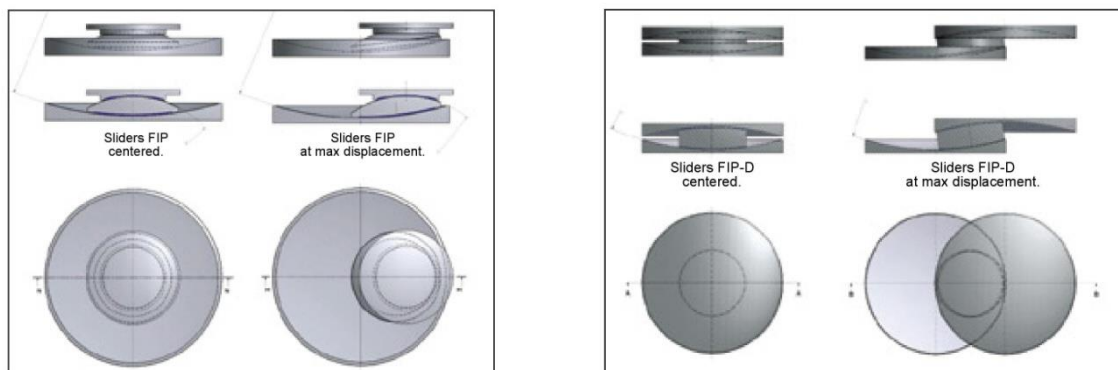
Curved Surface Sliders

Curved Surface Sliders (CSS), also known as friction pendulum isolators, are manufactured and used in USA and around the World since 1985.

The application of CSS in bridges in Italy started on 2010 whilst in buildings the year before.

There are two variants of curved surface sliders, which may be simple (CSS) or double concave curved surface units (DCCSS), whose functional patterns are shown in Figure 6 (respectively right and left) both in centered position and at their maximum displaced configuration. CSS has a main sliding surface (at the bottom in Fig. 6) providing energy dissipation through friction and restoring force, and a secondary sliding interface aimed at accommodating rotations of the structure. DCCSS comprises two facing primary sliding surfaces with the same radius of curvature, both contributing to the accommodation of horizontal displacements. The primary difference between said variants is the dimension in plan; in fact, in DCCSS, each of the two sliding surfaces has dimensions that can deal with a movement of half the design displacement demand. For this reason the space in plan required to accommodate the isolator is considerably reduced. Thus, this configuration is the most used for retrofit purposes. Another geometrical interesting characteristic for retrofit purposes is that such units require for a very limited headroom in order to be installed.

Figure 6: CSS configuration (left) and DCCSS configuration (right).



In both variants the sliding surfaces consist on one side of an appropriate high-strength thermo-plastic material and on the other side of mirror-polished stainless steel.

The functional law for both variants can be traced to the law of the simple pendulum, where the period of oscillation does not depend upon the mass but on the length of the pendulum.

Analogously, the period of the structure isolated with these isolation units does not depend on the mass of the structure itself, but mainly on the radius R of the curved sliding surface (or the equivalent radius for DCCSS), according to the formula:

圖5: 測試中的彈性隔震裝置(右)和典型HDRB遲滯迴圈。



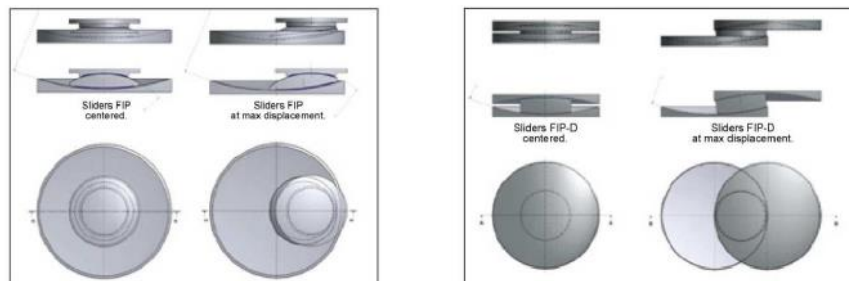
曲面滑塊

曲面滑塊(CSS), 也稱為摩擦鐘擺隔震器, 自1985年以來在美國和世界各地製造和使用。

CSS在意大利橋梁中的應用開始於2010年, 而前一年在建築物中。

曲面滑塊有2種變體, 可以是簡單的 (CSS) 或雙凹形曲面單元 (DCCSS), 功能模式如圖6所示, (分別是右和左) 同時在中心位置和他們的最大位移配置。CSS有一個主滑動面 (在圖6底部) 通過摩擦提供能量耗散和恢復力, 和一個次級滑動界面, 旨在容納結構的旋轉。DCCSS包括具相同曲率半徑的兩個相對的主滑動面, 有助於水平位移的駐紮。所述變體之間的主要區別在於平面尺寸; 事實上在DCCSS, 兩個中的任一個滑動表面的尺寸能夠處理一半的需求設計位移。為此, 所需的隔震裝置的平面空間被大大減小。因而, 這種配置最常用於改裝用途。用於補強用途的另一個有趣的幾何學特徵是, 這樣的設備需要一個非常有限的淨空, 以便進行安裝。

圖6: CSS 配置(左)和DCCSS 配置(右)。



在這兩個變體中, 滑動表面由在一個適當的高強度的熱塑性材料的一側, 與鏡面拋光不銹鋼的另一側。

這兩種方式的功能性定律可以追溯到單擺, 振盪的週期不依靠重量, 而是在擺的長度。

類似地, 這些分離單元的結構週期不依靠結構本身的重量, 但主要是在彎曲滑動表面的半徑R(或DCCSS相等半徑), 依據公式:

$$T = 2\pi \cdot \sqrt{\frac{1}{g \cdot (\frac{1}{R} + \frac{\mu}{x})}}$$

where x is the maximum displacement, g is the acceleration of gravity and μ is the coefficient of friction.

Figure 3 shows the theoretical bi-linear hysteresis response of a CSS or DCCSS. The system is nearly rigid until the friction force $F_0 = \mu_s W$ is overcome, being W the applied weight and μ_s the static coefficient of friction. The restoring force increases proportionally to the displacement, with stiffness $K = W/R$.

For retrofit purposes, the space availability issue is not secondary but not the only one to be considered.

Curved Sliders are commonly providing for isolation periods in the order of 3 seconds (2.5 to 4s in the most of the cases), so the associated seismic displacement – depending upon the considered seismicity level – may be important. In order to reduce such seismic movements, few simple strategies are normally applied.

The first is to reduce the radius of curvature R on its own thus providing for oscillation periods in the order of 2.5s. The second relies on the friction coefficient choice: an high value - in the order of 5 to 6% - can provide a good equivalent viscous damping. By adjusting properly the radius R and the friction coefficient μ , high damping levels in the order of 30% can be achieved. The following formula provides the estimation of the damping parameter:

$$\beta = \frac{2}{\pi} \cdot \left(\frac{1}{1 + \frac{x}{\mu R}} \right)$$

The last verification should take into consideration that any lateral isolator movement is corresponded by a vertical movement z according to the following formula:

$$z = [1 - \cos(\sin(x/R))] \cdot R$$

So, the expansion joints and any other bridge detail shall allow for this free vertical displacement.

It is worth noting that Curved Sliders can be even proposed as part of a seismic protection system where viscous dampers are used in order to increase drastically the structural damping and so to reduce to the minimum the seismic displacement.

BRIDGE RETROFIT IN ITALY

Table 1 lists the retrofitted structures where seismic isolation and/or energy dissipation devices manufactured by FIP Industriale have been used. The applications are listed in chronological order from most recent to latest. More than 2300 FIP's seismic devices have already been installed in bridges and viaducts retrofitted with the seismic isolation approach.

In Italy, the first bridge retrofits via seismic isolation were carried out in 1986 - with lead rubber bearings, similarly to the first bridge retrofits in New Zealand and USA carried out during those years [Skinner et al., 1993]. A few years later, the use of viscous dampers and steel hysteretic dampers - combined with sliding bearings – were started.

A bridge retrofit scheme used very often in Italy is that based on the change of static scheme from isostatic to statically indeterminate. In effect, the use of statically determinate viaducts is frequently seen in Italy although it is known that the earthquake response of this type of structure is poor. The change from a simply supported to a statically indeterminate scheme is usually achieved through the connection of decks via a new continuous slab. The total number of expansion joints is thus reduced, remaining only those at the abutments - or a lesser number every few spans. Existing bearings are substituted with an isolation system of high energy dissipation capability - i.e. comprising viscous dampers and/or steel hysteretic dampers - to limit as much as possible seismic movements. It is worth noting that the space available for movements in existing bridges (especially longitudinal movements) is always quite limited. Thus, the limitation of displacements through a high damping seismic isolation system in said bridges is more important than in new bridges, because it affects not only the cost but also the technical feasibility of the intervention. When piers are endowed with sufficient capacity to withstand horizontal forces, the isolators or dampers are located in all piers. In this manner, all piers are called to withstand seismic forces - i.e. the force distribution typical of a statically indeterminate scheme is achieved. Conversely, when piers or foundations are not of sufficient capacity to withstand horizontal longitudinal forces, the dampers are located only at the abutments. In the transversal direction, piers usually have sufficient capacity. Thus, transverse isolation is sometimes not necessary.

Whenever possible, the design maximum force of the isolation system is selected to be of lower entity than the capacity of the piers and foundations. In this fashion, there is no need to reinforce the substructure. The high energy dissipation offered by both

$$T = 2\pi \cdot \sqrt{\frac{1}{g \cdot (\frac{1}{R} + \frac{\mu}{x})}}$$

其中x是最大位移，g是重力加速度與μ是摩擦係數。

圖3示出了一個CSS或DCCSS的理論雙線性遲滯響應。該系統幾乎是剛性的，直到摩擦力 $F_0 = \mu_s W$ 被克服，W代表外加重量和 μ_s 代表靜摩擦係數。恢復力依位移比例提高，具有剛度 $K = W/R$ 。

為達補強目標，空間的可用性問題不是次要但也不是唯一要考慮的。彎曲的滑塊通常提供隔震期間為3秒左右的規模(大部份是2.5至4秒)，因此相關的地震位移 - 取決於地震規模 - 可能是重要的。為了減少這樣的地震移動，一些簡單的策略通常適用。

第一是降低其本身從而提供振盪週期2.5秒的曲率半徑R。第二是依賴於摩擦係數的選擇：一個高數值 - 在5至6%左右 - 可以提供一個良好的等效粘性阻尼。經由調整適當的半徑R和摩擦係數μ，在30%的數量級高阻尼水準是可以實現的。以下公式提供了阻尼參數的估計：

$$\beta = \frac{2}{\pi} \cdot \left(\frac{1}{1 + \frac{x}{\mu R}} \right)$$

最後的驗證應該考慮任何橫向隔震移動是由一個垂直移動z，根據下列公式相對應：

$$z = [1 - \cos(\text{asin}(x/R))] \cdot R$$

因此，伸縮縫及任何其他橋梁細節應允許這種自由的垂直位移。

值得一提的是曲形滑塊甚至可作為耐震保護系統的一部分，其中使用粘滯阻尼器，以大幅增加結構阻尼，將地震位移減至最小。

義大利橋梁的補強

表1列出了補強結構，其中由FIP Industriale製造的隔震和/或耗能裝置已被使用。該應用程序從最新到最後依時間順序排列。超過2300FIP的耐震裝置已經使用隔震方法安裝在橋梁和高架橋。

在義大利，1986年進行了經由隔震的第一座橋的補強 - 使用鉛芯橡膠支承座，類似這些年裡在紐西蘭和美國進行的的第一座橋的補強[Skinner et al., 1993]。幾年後，開始採用粘滯阻尼器和鋼遲滯阻尼器 - 結合滑動支承座。

經常使用在義大利的橋梁補強方案是基於靜態計畫從均衡到靜不定的變化。實際上，靜定高架橋的使用常見於義大利，即使已知這類型結構的地震反應較差。從簡支撐改變為靜不定方案，通常是使用一個新的連續板將橋面板連接而成。伸縮縫的總數量減少了，只剩下那些在橋台的 - 或每隔幾跨度使用較少數目。高耗能隔震系統取代現有軸承 - 即包括粘滯阻尼器和/或鋼的遲滯阻尼器 - 盡可能限制地震移動。值得一提的是，現有橋梁可移動（特別是縱向移動）的空間始終是相當有限的。因此，位移通過高阻尼隔震系統在上述橋梁的限制比新的橋梁更為重要，因為它不僅影響成本，而且干預技術的可行性。當橋墩被賦予足夠的能力來承受水平力，隔震裝置或阻尼器須位於所有橋墩。在這種方式下，所有的橋墩被稱為承受地震力 - 即實現典型的靜不定方案的動力分配。相反的，當橋墩或基礎不具足夠的能力承受水平縱向力時，阻尼器僅位於橋台。在橫向上，橋墩通常有足夠的能力。因此，橫向隔震通常是不需要的。

只要有可能，隔震系統的最大設計力被選為比橋墩和基礎承載能力更低的數據。以這種方式，沒有必要加強次結構。由鋼遲滯和非線性粘滯阻尼器提供的高耗能大大助於實現這一目標。

steel hysteretic and non-linear viscous dampers considerably helps to achieve this objective.

Table 1: List of bridges and viaducts retrofitted with seismic isolation & energy dissipation techniques using seismic devices manufactured by FIP Industriale.

Bridge Name & Location	Country	Year	Type and Number of Seismic Devices
Castelrotto	Italy	2014	48 HDRB
Balzaccia	Italy	2014	84 CSS
Macchione	Italy	2014	19 SHD
San Michele	Italy	2013	128 HDRB
Corfinio	Italy	2013	30 (HD+VD) + 8 HD+ 8 VD
Resia	Italy	2012	24 HDRB
Strada vicinale Falce	Italy	2012	4 HDRB
Torre del Lago	Italy	2011	304 HDRB
Opere 753, 787, 829, 812A	Italy	2010	22 HDRB
Acque basse modenesi e Fossa raso	Italy	2010	98 HDRB
delle Zuane	Italy	2009	16 HDRB
San Paolo	Italy	2009	4 VD
Ponte degli Alpini	Italy	2009	4HDRB + 18 (HD+VD) + 2 STU
Jinju Grand Bridge	Korea	2008	16 VD
South Wonju	Korea	2008	4 VD
Jinju JCT	Korea	2008	4 VD
Bridge	Korea	2007	2 VD
Sa Chun	Korea	2006	4 VD
D'Antico, NA-Canosa	Italy	2006	22 SHD
Irminio	Italy	2006	34 VD
Piazza Molise, CB	Italy	2006	14 RB
Bi-Ryong, Kyonggi	Korea	2004	8 VD
Piave river, Eraclea	Italy	2004	4 SHD
3 viaducts on SS 115	Italy	2004	114 VD
Isap, Attiki-Odos	Greece	2004	144 VD
Vara I, A12	Italy	2004	132 RB + 40 STU
Adige, SS 20, Zevio	Italy	2004	4 VD + 8 HD
Chun Chun	Korea	2003	24 VD
Su Jik	Korea	2003	17 VD
Dong Yun	Korea	2003	20 VD
Back Won	Korea	2003	28 VD
Adige, SP19, Albaredo	Italy	2002	11 HD
Val di Leto, Cosenza	Italy	2002	18 VD
Pardazzo 1	Italy	2002	126 RB
E-Po	Korea	2002	10 VD
Kang Dong	Korea	2002	27 VD
Sa Chun	Korea	2002	6 SHD + 36 (SHD+STU)
Viaducts on SS 647	Italy	2001	148 (HD+VD) + 40 VD
Ok Yeo	Korea	2001	10 VD
Chun Su	Korea	2001	12 VD

表1:使用FIP Industriale製造的耐震裝置隔震和消能技術去補強橋梁和高架橋的清單。

橋梁名稱與位置	國家	年	地震裝置的型態與數量
Castelrotto	義大利	2014	48 HDRB
Balzaccia	義大利	2014	84 CSS
Macchione	義大利	2014	19 SHD
San Michele	義大利	2013	128 HDRB
Corfinio	義大利	2013	30 (HD+VD)+8 HD+8VD
Resia	義大利	2012	24 HDRB
Strada Vicinale Falce	義大利	2012	4 HDRB
Torre Del Lago	義大利	2011	304 HDRB
Opera 753, 787, 829, 812A	義大利	2010	22 HDRB
Acque Basse Modenesi E Fossa Raso	義大利	2010	98 HDRB
Delle Zuane	義大利	2009	16 HDRB
San Paolo	義大利	2009	4VD
Ponte Degli Alpine	義大利	2009	4HDRB+18 (HD+VD)+2STU
Jinju Grand Bridge	韓國	2008	16VD
South Wonju	韓國	2008	4VD
Jinju JCT	韓國	2008	4VD
Bridge	韓國	2007	2VD
Sa Chun	韓國	2006	4VD
D' Antico, Na-Canosa	義大利	2006	22SHD
Irminio	義大利	2006	34VD
Piazza Molise, CB	義大利	2006	14RB
Bi-Ryong, Kyonggi	韓國	2004	8VD
Piave River, Eraclea	義大利	2004	4SHD
3 Viaducts On SS 115	義大利	2004	114VD
Isap, Attiki-Odos	希臘	2004	144VD
Vara I, A12	義大利	2004	132RB+40STU
Adige, SS 20, Zevio	義大利	2004	4VD+8HD
Chun Chun	韓國	2003	24 VD
Su Jik	韓國	2003	17VD
Dong Yun	韓國	2003	20VD
Back Won	韓國	2003	28VD
Adige, SP19, Albaredo	義大利	2002	11HD
Val Di Leto, Cosenza	義大利	2002	18VD
Prdazzo 1	義大利	2002	126RB
E-Po	韓國	2002	10VD
Kang Dong	韓國	2002	27VD
Sa Chun	韓國	2002	6SHD+36 (SHD+STU)
Viaducts On SS 647	義大利	2001	148 (HD+VD)+40VD
Ok Yeo	韓國	2001	10VD
Chun Su	韓國	2001	12VD

Table 1 (continued)

Bridge Name & Location	Country	Year	Type and Number of Seismic Devices
Vallone della Difesa	Italy	2001	7 VD
Seo Hae	Korea	2000	54 VD
Castellare, A1 BO-FI	Italy	1998	10 SHD
Granville, Vancouver	Canada	1995	157 HD
Hood River	USA	1995	12 HD + 6 VD
Poplar Street	USA	1994	12 SHD + 18 (SHD+VD)
Marquam Int.	USA	1994	8 SHD + 4 STU
Pecorone	Italy	1992	25 SHD
Marmo, SS Basentana	Italy	1991	51 HD
Carito, A3 SA-RC	Italy	1991	12 HD
Aoglio, A1 BO-FI	Italy	1991	32 HD
Galdo I, A3 SA-RC	Italy	1991	4 VD + 4 STU
Galdo II, A3 SA-RC	Italy	1990	4 VD + 4 STU
8 viaducts on A1	Italy	1990	580 LRB
Portimao	Portugal	1990	1 VD
Viaducts on A3 SA-RC	Italy	1989	52 VD
Vallonalto 1 & 2, NA-BA	Italy	1986	98 LRB
Carafone	Italy	1986	44 LRB

Legend - HD: Hysteretic Damper; LRB: Lead Rubber Bearing; RB: Rubber Bearing; SHD: Slider with Hysteretic Damper; STU: Shock Transmission Unit; VD: Viscous damper; CSS: Curved Surface Sliders; HDRB: High Damping Rubber Bearing.

Table 1 provides an important information that requires for a clarification. During the last five years, the most of the bridge retrofits in Italy were performed using High Damping Rubber Bearings. Such technology is commonly characterized by a moderate level of equivalent viscous damping (10 to 15%). This time the designer choice is easily explained by the fact that the most of the named bridges are located in low to moderate seismicity regions where HDRBs were sufficient to improve to the required level the structural safety.

It is worth noting that shock transmission units (STU) are often used in Italy - as well as in other countries - in the seismic retrofit of bridges. These devices, under a dynamic condition such an earthquake or an impulsive load, act as very stiff temporary connections [Infanti et al., 2006 a].

The typical retrofit scheme exploiting STUs is the change from a statically determinate scheme in service to a statically indeterminate scheme under seismic actions. Of course, this retrofit scheme is less effective than seismic isolation in terms of improving the seismic performance of the structure. However, sometimes it could suffice when the substructure capacity is relatively high and/or the site seismicity level is low. Furthermore, sometimes there is not enough space to allow the seismic movements associated with seismic isolation. In such cases, the use of STUs can be helpful, even though pier reinforcement is often necessary. This retrofit scheme, despite using seismic devices, is a measure strengthening the structure, and is not based on the seismic isolation and/or energy dissipation approach. Consequently, it is beyond the scope of this paper; the structures retrofitted with STU are thus not listed in Table 1.

ISAP RAILWAY BRIDGE, GREECE

The Isap Railway Bridge (Athens, Greece) comprises 3 bridge portions: two one-span independent bridges towards the city of Athens and one central bridge composed of sixteen statically independent spans at the station area [Infanti et al., 2006 a]. The central bridge as well as the two independent bridges comprise 18 statically independent sections made of pre-stressed concrete. Each section has a length of 21 m and a width of 7.60 m kept constant throughout the length of the bridge.

The initial design dates back to 1957 when the specified seismic level was 0.06g at SLS (0.11g at ULS) but new Greek anti-seismic regulations now specify 0.46g at ULS - which is a value 4 times greater.

The new seismic action in the transverse direction creates considerable moments and shears to the structure, which it was not

橋梁名稱與位置	國家	年	地震裝置的型態與數量
Vallonedelladifesa	義大利	2001	7VD
Seohae	韓國	2000	54VD
Castellare, A1 BO-FI	義大利	1998	10SHD
Granville, Vancouver	加拿大	1995	157HD
Hood River	美國	1995	12HD+6VD
Poplar Street	美國	1994	12SHD+18 (SHD+VD)
Marquam Int.	美國	1994	8SHD+4STU
Pecorone	義大利	1992	25SHD
Marmo, SS Basentana	義大利	1991	51HD
Carito, A3 SA-RC	義大利	1991	12HD
Aglio, A1 BO-FI	義大利	1991	32HD
Galdo I, A3 SA-RC	義大利	1991	4VD+4STU
Galdo II, A3 SA-RC	義大利	1990	4VD+4STU
8 viaducts on A1	義大利	1990	580 LRB
Portimao	葡萄牙	1990	1VD
Viaducts on A3 SA-RC	義大利	1989	52VD
Vallonalto 1&2, NA-BA	義大利	1986	98LRB
Carafone	義大利	1986	44LRB

說明 - HD: 遲滯阻尼器; LRB: 鉛芯橡膠支承座; RB: 橡膠支承座; SHD: 滑塊與遲滯阻尼器; STU: 震動傳輸單元; VD: 粘滯阻尼器; CSS: 曲面滑塊; HDRB: 高阻尼橡膠支承座。

表1提供了需要澄清的一個重要信息。在過去的五年中，義大利的橋梁補強案最多採用高阻尼橡膠支承座。這種技術通常歸納為中等水平的等效粘性阻尼（10~15%）。此時的設計者的選擇是很容易被解釋，事實上大部分被指名的橋均位於低到中等地震地區，HDRBs已足以提高到所要求的結構安全。

值得一提的是震動傳輸單元（STU）在義大利通常被使用 - 以及在其他國家-進行橋梁的耐震補強。這些設備，在動態的條件下，例如地震或衝擊負荷，扮演非常剛性的臨時連接 [Infanti et al., 2006 a]。

典型利用STUs的補強方案是從既有橋梁的靜定方案改變為地震作用下的靜不定方案。當然，這個補強方案比起隔震在改善結構的耐震性效果較差。但是，有時也可能是足夠的，當次要結構的承载力相對較高和/或現場地震規模較低。此外，有時沒有足夠的空間，讓地震移動與隔震相關聯。在這種情況下，儘管橋墩加固往往是必要的，使用STUs是有益的。雖然使用地震設備，此補強方案是一種結構加強的衡量，且不是基於隔震和/或能量消耗的方法。因此，它已超出了本論文的範圍;加裝STU的結構不列在表1中。

希臘的ISAP鐵路橋梁

ISAP鐵路橋（希臘雅典）包括三個橋梁單元：兩個單跨獨立橋面對雅典市和一個在車站區域擁有16個獨立靜定單元的中央橋[Infanti et al., 2006 a]。中央橋與兩個獨立橋共形成18個獨立的靜定的預力混凝土梁區段單元。在整個橋梁，每個部分都是21米長和7.60米寬。

最初的設計可以追溯到1957年，當時耐震程度為0.06g在SLS（0.11g在ULS），但希臘新耐震設計規範ULS規定為0.46g - 是4倍大。

adequately reinforced to withstand. The scope of the retrofit was to avoid damage and total collapse in the event of a strong earthquake.

Seismic Protection System Design

The implemented solution was planned to provide additional supports with a seismic protection system comprising 144 viscous dampers placed in the transverse direction only. Since the stiffness of the structure was considerably higher in the longitudinal direction, viscous dampers were not installed in this direction because they would have not been activated by very limited structural movements (see Figures 7 and 8).

The total dissipation load was selected in such a manner as to decrease seismic actions by up to 50% according to the AASHTO Interim 2000 specifications [AASHTO, 2000].

The viscous dampers of the Isap Railway Bridge are characterized by a reaction equal to 75 kN at the maximum design velocity of 400 mm/s, a velocity exponent equal to 0.15, and a design stroke of ± 55 mm.

FIP Industriale manufactured the viscous dampers and performed acceptance tests on one of them to verify its constitutive law and its dissipative capacity (tolerance on the theoretical values was equal to $\pm 15\%$); the damper was also subjected to an earthquake time-history [Infanti *et al.*, 2006 a].

The seismic retrofit of the Isap Railway Bridge was concluded in the year 2004.

Figure 7: Isap Bridge Retrofitted Configuration (Transverse Elevation)

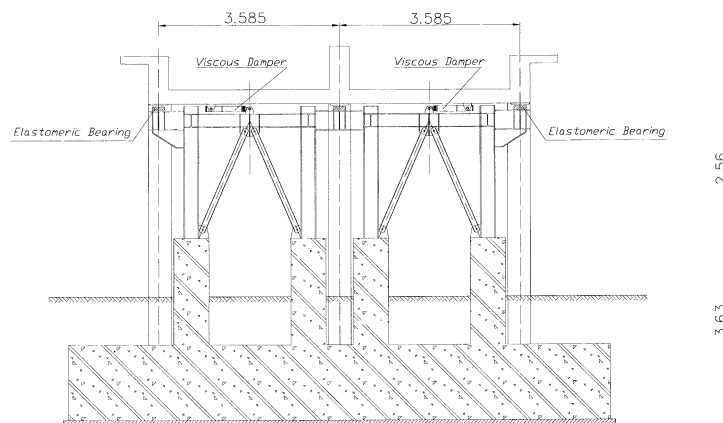


Figure 8: Isap Bridge Viscous Dampers as Installed



CARBOJ, SAN VINCENZO I AND SAN VINCENZO II VIADUCTS, ITALY

The Carboj, San Vincenzo I and San Vincenzo II Viaducts are located on the main road No. SS 115 in Sicily, Italy. They were

新地震作用在結構體橫向產生相當大的彎矩和剪力，它沒有充分加固承受。結構體補強的範圍就是要避免在強烈地震時破壞和全面崩塌。

地震保護系統設計

解決方案就是提供額外的支撐，在橫向上放置144個粘滯阻尼器的耐震保護系統。由於結構在縱向的剛度是相當高，粘滯阻尼器未安裝在這個方向的理由是他們不可能被非常有限的結構移動量所啟動(參考圖7與圖8)。根據AASHTO在2000年修訂版的規定，以這樣方式選定的總功耗負荷，可以減少地震作用達50% [AASHTO, 2000]。

在400 mm/s的最大設計速度下，Isap鐵路橋的粘滯阻尼器的特點是等於75 kN的反應力，速度指數等於0.15，且設計衝程在 ± 55 mm。FIP Industriale生產的粘滯阻尼器和進行其中之一的驗收測試，可驗證其組合率及其耗散能力(容忍的理論值是 $\pm 15\%$)；阻尼器也受到地震歷時的影響 [Infantiet al., 2006 a]。

Isap鐵路橋的耐震補強工程於2004年完成。

圖7: Isap橋梁補強配置 (橫面圖)

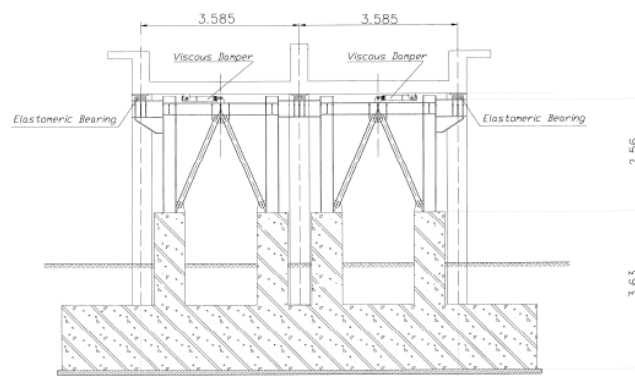


圖8: 安裝Isap橋梁的粘滯阻尼器



義大利CARBOJ, SAN VINCENZO I AND SAN VINCENZO II高架橋

Carboj, San Vincenzo I and San Vincenzo II高架橋位於義大利西西里主幹道編號SS115。

built in the early 1970s. The longest of the three is the Carboj viaduct; it comprises a series of 37 spans simply supported upon two terminal abutments and 36 intermediate piers 54 m apart from each other with a total length of about 2 km (Figure 9). These decks were originally restrained following a conventional bearing layout using pot bearings of the fixed type, transversely unidirectional at one end of the bridge deck and longitudinally unidirectional and free-sliding at the other end. The need to provide a structural retrofit such as to furnish an adequate level of resistance to horizontal actions in the presence of both normal service loads as well as seismic action led to the conception of a rather different bearing system, based on the use of a seismic protection system with high energy dissipation capacity capable of limiting horizontal loads transmitted to the substructure. The new design earthquake is characterized by a 0.35g PGA.

FIP Industriale was involved in the following activities:

- Design of the seismic protection system;
- Manufacturing of the structural devices (dampers, bearings, expansion joints, as described in the following);
- Viaduct retrofit.

Seismic Protection System Design

In its retrofitted configuration, the Carboj Viaduct (as well as its neighbor S.Vincenzo I and II Viaducts) was divided into sections (segments) comprising 4 to 8 spans connected via the slab.

The seismic protection system comprises two types of viscous dampers, FIP's OP and OTP series, both installed in the longitudinal direction (Figure 10). OP series viscous dampers are devices equipped with relief valves designed to open at pressures (loads) higher than those induced by service load conditions. OTP series viscous dampers are devices that can accommodate longitudinal displacements induced by both thermal deformations (providing a very low reaction) as well as earthquake actions. Under service conditions, longitudinal horizontal loads (*i.e.*, wind, braking actions, etc.) at the fixed piers are resisted by OP series viscous dampers. OTP series viscous dampers are installed at all the sliding locations. Under seismic conditions, the behavior of OP and OTP series viscous dampers is the same: owing to their non-linear constitutive law, they dissipate a large amount of the energy transmitted by the earthquake.

Both OP and OTP dampers are installed between adjacent girders according to the configuration shown in Figure 11 (left). At expansion joint piers, OTP dampers are installed connecting the girders to the pier cap according to the configuration shown in Figure 11 (right).

At all locations, lateral service and seismic loads are withstood by longitudinally sliding elastomeric lateral bearings (DEM series) characterized by a load capacity up to 3500 kN (Figure 8).

Figure 9: Carboj Viaduct.



建造於1970年代早期。三座當中，Carboj高架橋最長；它包括一系列37個跨度，在兩個簡支撐橋台和由36根彼此距離54米的中間橋墩支撐，總長度約2公里長（圖9）。這些橋面板原本遵循傳統支承座設計，使用固定式盆式支承座，在橋面的一端橫向單向，在另一端縱向單向自由滑動。

為了提供足夠的阻力給地震水平作用力，並在正常工作載荷及地震作用下，因此創造出一種相當不同的軸承系統來進行結構補強。基於使用具有高耗能能力的地震防護系統，可限制水平荷載傳輸到下部結構。新規定的地震設計為0.35g PGA。

FIP Industriale參與下列活動：

- 地震保護系統設計；
- 結構裝置製造（如下所述的阻尼器、支承座、伸縮縫）；
- 高架橋補強。

地震保護系統設計

在補強結構中，Carboj高架橋（以及鄰近的S.Vincenzo I和II高架橋）被分成幾個部分（段），包括由厚板連接的4至8個跨度。

耐震保護系統包括兩種類型的粘滯阻尼器，FIP的OP和OTP系列，兩者都安裝在縱向（圖10）。OP系列粘滯阻尼器配有洩壓閥，當壓力（負載）高於外力負載時，設計成打開。OTP系列粘滯阻尼器是可容納熱變形（提供了一個非常低的反應力）以及地震力的縱向位移的裝置。在外力的狀態下，在固定橋墩的縱向水平荷載（即風、煞車動作等）是由OP系列粘滯阻尼器所阻擋。OTP系列粘滯阻尼器安裝在所有會滑動的位置。在地震狀況下，OP和OTP系列粘滯阻尼器的行為是一樣的：由於其非線性本構關係，它們消耗了大量的地震傳播的能量。

根據圖11（左）所示的結構中，OP和OTP阻尼器都是安裝在相鄰梁之間。在伸縮縫橋墩，根據圖11（右）所示的結構中，OTP阻尼器是安裝在連接梁到橋墩帽。

在所有位置，側向外力和地震荷載是由縱向滑動彈性側向軸承（DEM系列）承受，負載能力高達3500kN（圖8）頂住。

圖9: Carboj高架橋。



Retrofit Phases

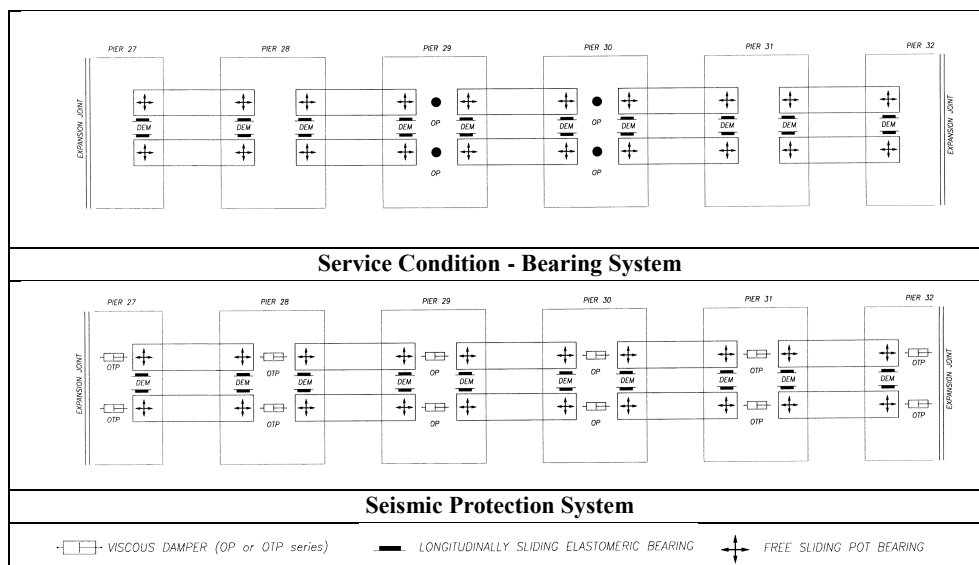
The retrofit was carried out implementing the following operations:

- Substitution of pre-existing bearings with free sliding pot bearings;
- Creation of slab links;
- Installation of longitudinal viscous dampers type OP at the fixed piers;
- Installation of longitudinal viscous dampers type OTP on those piers where deck thermal expansion/contraction is allowed;
- Installation of longitudinally sliding lateral bearings anchored to the existing pier tops;
- Installation of expansion joints.

In conclusion, the FIP Industriale supply for the aforesaid three viaducts was the following:

- N. 208 free-sliding Pot-Bearings VM 450 series – 4500 kN vertical load capacity, total displacement capacity ranging from 200 mm to 700 mm;
- N. 196 Lateral bearings DEM series - lateral load capacity ranging from 1500 kN to 3500 kN; total displacement capacity ranging from 200 mm to 700 mm;
- N. 32 viscous dampers OP series, with load capacity ranging from 500 to 1000 kN, and stroke values from ± 100 mm to ± 200 mm;
- N. 82 viscous dampers OTP series, with load capacity ranging from 250 to 1000 kN, stroke values from ± 100 mm to ± 350 mm;
- 130 m of RAN-P series Reinforced Rubber Expansion Joints characterized by total Displacement Capacity ranging from 300 mm to 900 mm.

Figure 10: Carboj Viaduct: Bearing and Seismic Protection System Schemes



補強階段

補強的進行是實施以下的操作：

- 以自由滑動的盆式軸承替代預先存在的軸承；
- 建造厚板連接；
- 安裝縱向粘滯阻尼器型的OP在固定端橋墩；
- 安裝縱向粘滯阻尼器型的OTP在允許橋面板伸縮端的橋墩；
- 安裝縱向滑動的側軸承固定在現有橋墩頂端；
- 安裝伸縮縫。

結論，FIP Industriale供應上述三座高架橋如下：

- N. 208自由滑動盆式軸承VM 450系列- 4500 kN垂直荷載能力，總位移能力範圍200 mm至700 mm；
- N. 196側軸承DEM系列- 側荷載能力範圍1500 kN至3500 kN；總位移能力範圍200 mm至700 mm；
- N. 32粘滯阻尼器OP系列，荷載能力範圍500 to 1000 kN，行程值範圍 ± 100 mm至 ± 200 mm；
- N. 82粘滯阻尼器OTP系列，荷載能力範圍250 to 1000 kN，行程值範圍 ± 100 mm至 ± 350 mm；
- 130 m of RAN-P系列增強橡膠伸縮接頭，其總位移量介於300至900 mm。

圖10: Carboj高架橋：軸承和地震保護系統方案

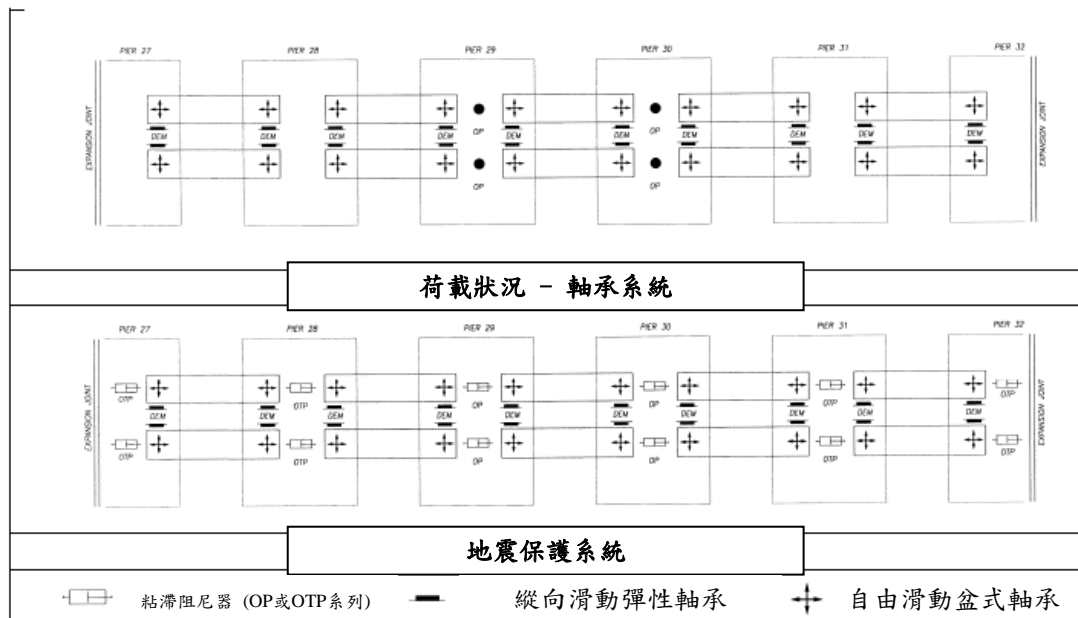


Figure 11: Carboj Viaduct: Viscous Dampers as installed in a standard pier (left) and under installation in an expansion joint pier.



SEO-HAE GRAND BRIDGE APPROACHES, KOREA

Until 1992, none of highway bridges in Korea were designed to withstand an earthquake. The Korean Bridge Design Standard Specifications adopted seismic design regulations in 1992 and thereafter enforced seismic design in practice.

The Seo-Hae Grand Bridge, situated 70 km southwest of Seoul, comprises 3 different types of bridges: a cable-stayed bridge (990 m), an FCM bridge (500 m), and approach bridges (5820 m) with r.c. deck produced with the Pre-cast Segmental Method (PSM). These bridges, designed in the late 1980s contemplating small intensity earthquakes, were revised during construction when the seismic design requirements surfaced in 1992. Fortunately, the cable-stayed and FCM bridges satisfied the requirements of the new specifications ($PGA=0.14\text{ g}$). However, 5 of the 16 PSM bridges comprising the approaches, for a total length of 2220 m, needed to be retrofitted. These bridges are located near both the abutments where their piers are short. The bridges have from 3 to 10 spans.

Seismic Protection System Design

Since the bridges were under construction, the use of anti-seismic devices was the only feasible way to provide the necessary capabilities to the bridges. Many types of seismic devices were reviewed. Amongst them, the viscous damper was selected as the most suitable, because of its reliability and ease of installation. 54 viscous dampers were placed between the superstructure and the pier as shown in Figure 12. Their design maximum force is 500 kN at a maximum design velocity of 240 mm/s and stroke ranges from $\pm 100\text{ mm}$ to $\pm 200\text{ mm}$. They were installed at every pier except the piers at the expansion joints and those with fixed bearings. A double effect was thus obtained: first, almost all the piers were called to withstand a longitudinal seismic force (force distribution) and second, the dampers dissipate a great portion of the energy introduced by ground motion. This retrofit solution was cost effective, because it did not require the substitution of existing bearings (fixed bearings at the central and tallest pier and guided or free sliding bearings at the other piers). The devices were anchored to the structure taking advantage of originally designed shear keys (Figure 13). In this manner, installation is made inside the box girder - restraining the upper end of the shear key and the deck bottom slab trough viscous dampers [Infanti, 2001]. In the transverse direction, the bridge was deemed to have sufficient capacity to withstand the new level of design accelerations due to a good distribution of seismic loads (achieved through the shear keys) as well as intrinsic pier strength.

A wide testing campaign was carried out at the FIP Industriale laboratory on three prototypes of the three types of devices proposed for application, that only differed in their design stroke. In particular, their behavior was checked not only at room temperature but at extreme design temperatures equal to -25°C and 40°C as well. Figure 14 shows the force vs velocity behavior at said extremes of temperature: device reaction is almost independent from the testing temperature. Other types of tests were also carried out: energy dissipation tests, endurance tests and friction tests [Infanti, 2001].

圖11: Carboj高架橋:粘滯阻尼器安裝在標準橋墩（左）和安裝在伸縮縫橋墩。



韓國SEO-HAE大橋方案

直到1992年，在韓國的公路橋梁橋梁設計納入地震力設計。直到1992年起，韓國的橋梁設計標準開始納入耐震設計規範及以後執行的耐震設計實務。

Seo-Hae大橋，位於首爾西南方70公里，包括3種不同類型的橋梁：一座斜張橋（990 m），一座FCM橋（500 m）和預鑄節塊（PSM）鑄成的RC橋面板的引橋（5820 m）。這些在1980年代後期設計的橋梁，僅考慮輕度地震的狀況；當耐震設計要求逐漸納入於1992年版設計規範時，需要在施工期間進行修正。所幸斜張橋和FCM橋梁滿足新規範（PGA為0.14 g）的相關要求。然而，16座包括此工法的PSM橋梁中的5座，總長度2220 m，則需要進行補強。這些橋梁都位於靠近橋墩很短的橋台，橋梁有3至10跨。

地震保護系統設計

對於正在建造中的橋梁，提升橋梁承載能力唯一可行的辦法，便是增加使用耐震構件，因此當時有許多類型的地震構件被提出來審查。在許多可行的建議方案中，粘性阻尼器被選定為最適合，如圖12所示連結橋墩。在最大設計速度240 mm/s和行程範圍為 ± 100 mm至 ± 200 mm，其設計最大的力為500 kN。除了伸縮縫和使用固定支承座的橋墩之外，都有安裝在每根橋墩。如此得到雙重功效：首先，幾乎所有的橋墩都承受縱向地震力（動力分配），第二，阻尼器消耗了大量由地面運動引起的能量。這種補強方案符合成本效益，因為它不要求替代現有軸承（固定軸承在中央和最高的橋墩，並在其餘的橋墩使用導引式或自由滑動軸承）。該設備被錨定在最初設計剪力鍵的結構上（圖13）。在這種方式下，在箱梁內安裝 - 抑制剪力鍵的上端和橋面板底板槽粘滯阻尼器[Infanti, 2001]。在橫向上，橋被視為有足夠的能力承受新等級的設計加速度，經由地震荷載的分配（透過剪力鍵實現）以及內在的橋墩強度。在FIP Industriale實驗室進行了廣泛的測試活動，三個應用類型設備的三個原型，只是不同的設計行程。尤其是，他們的行為不僅在室溫下而且在極端的设计溫度-25°C和40°C。圖14所示在上述溫度下的力與速度行為：裝置反應力幾乎與測試溫度無關。其他類型的測試也被執行：能量耗散試驗、耐性試驗和摩擦試驗[Infanti, 2001]。

Figure 12: Installation of Fluid Viscous Dampers in the Seo-Hae Grand Bridge Approaches.

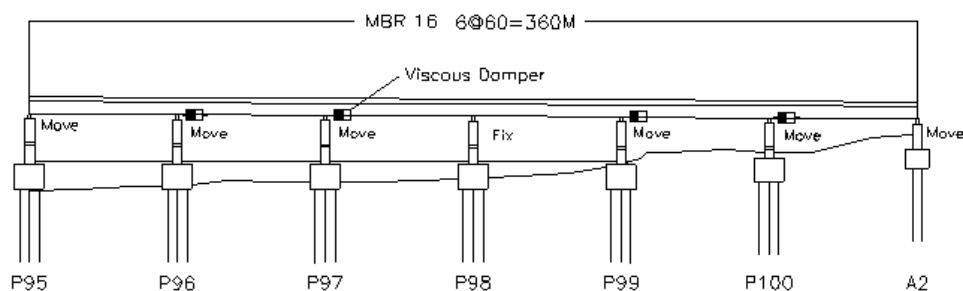
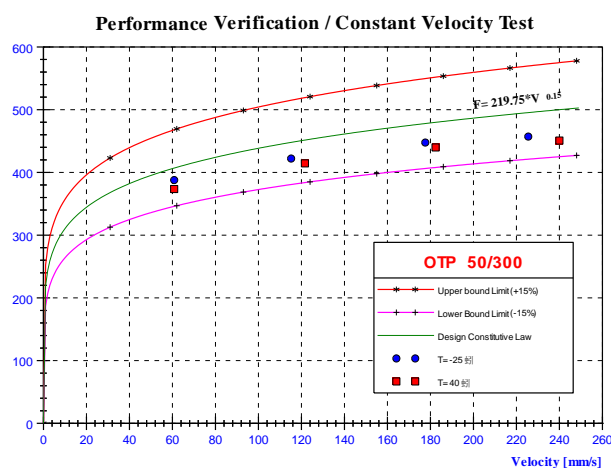


Figure 13: Viscous Damper as installed inside the box girder of the Seo-Hae Bridge Approaches.



Figure 14: Results of performance verification tests on a Seo-Hae Bridge fluid viscous damper prototype.



The Seo-Hae Grand Bridge Approaches project was the very first application of viscous dampers in the seismic protection of bridges in Korea. Subsequently the same retrofit scheme was applied to other bridges, such as the Ok-Yeo, Chun-Su, E-Po, and Kang-Dong bridges [Infanti *et al.*, 2004] and more recently the Buchun, An Nyang, Jinju bridges and several others.

圖12: Seo-Hae大橋方案液體粘滯阻尼器安裝。

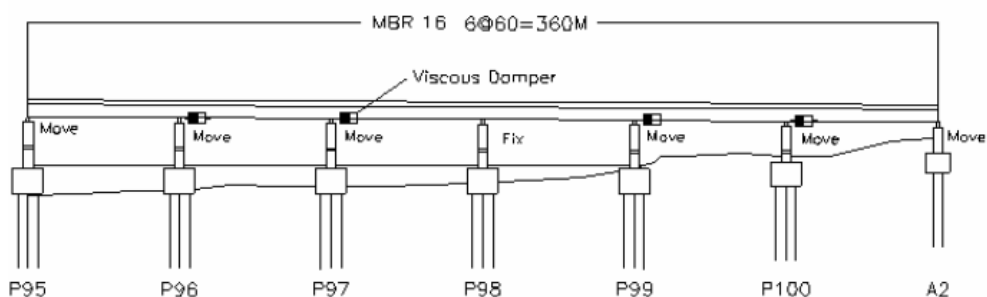
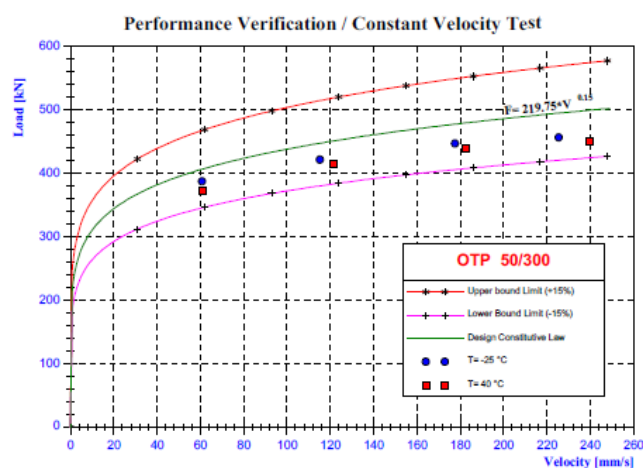


圖13:Seo-Hae大橋方案粘滯阻尼器由箱梁內部安裝。



圖14: Seo-Hae大橋液體粘滯阻尼器原型的性能驗證測試結果。.



Seo-Hae大橋方案計畫是韓國最早期使用粘滯阻尼器進行橋梁的地震保護。隨後，同樣的補強方案已應用到其他橋梁，如Ok-Yeo、Chun-Su、E-Po與Kang-Dong橋[Infantiet al., 2004] 以及最近的Buchun、An Nyang、Jinju橋和其他橋梁。

VIADUCTS ON SS 647 HIGHWAY, ITALY

The viaducts on the S.S. 647 highway, in Southern Italy, were built between the 1960s and 70s with simply supported decks. A change in seismic codes (the new design PGA for the area is 0.25 g, and the importance factor for said viaducts is 1.2), together with additional pier and deck problems (due to intense traffic and past lack of maintenance), imposed the retrofit of 20 of the 44 viaducts along this highway [Infanti et al, 2006 b]. The piers vary in height from 3.5 to 12 m (Figure 15).

FIP Industriale was involved in the following activities:

- Design of the seismic protection system;
- Manufacturing of the structural devices (dampers, bearings, expansion joints, as described in the following);
- Viaduct retrofit.

Seismic Protection System Design

During the first phase of the intervention, repair and strengthening of piers and pier tops were carried out, to both permit subsequent deck lifting operations as well as withstand earthquake loads. The static scheme was changed from isostatic to statically indeterminate by connecting the beams through the slab, and thus eliminating expansion joints at the piers - leaving expansion joints only at the abutments.

The new continuous decks count from 2 to 7 spans, with the fixed point in one of the central piers. Figure 16 shows the bearing system scheme under both service and seismic conditions for a typical multi-span viaduct; in particular, a 6-deck configuration (Carletto Viaduct) is shown.

On each pier, there are two seismic devices (MELOP or MELOTP series damping units, Figure 17) comprising within the same unit a non-linear fluid viscous damper in the longitudinal direction and steel hysteretic dissipating elements - crescent-moon shaped – in the transverse direction. On each abutment, there is a device of the same type used in the piers and one fluid viscous damper working in the longitudinal direction. Such a damping system - aimed to control horizontal forces - is combined to a free sliding pot-bearings scheme that serves to transmit vertical loads and permit horizontal displacement in all directions.

Under service conditions, the longitudinal loads at the fixed piers are resisted by units (MELOP series) whose dampers are equipped with relief valves designed to open at pressures (loads) higher than those induced under service load conditions. MELOTP series seismic devices are installed at all the sliding locations. At all locations, steel hysteretic dampers aligned transversally provide a very stiff restraint under normal service conditions.

Under seismic conditions, all the seismic devices behave according to their constitutive law, dissipating large amounts of energy transmitted by an earthquake.

A total number of 188 seismic devices were installed, together with 380 free sliding bearings and 440 m of expansion joints with 400 mm total displacement capacity. Functional tests on both viscous dampers and crescent moon shaped steel dampers were carried out at the FIP Industriale laboratory [Infanti et al, 2006 b].

Figure 15: Typical Details of a SS647 Viaduct (before and after retrofit).



義大利SS 647高速公路高架橋

義大利南部的S.S.647高速公路高架橋是在1960與70年代使用簡支撐橋梁建造。在耐震規範的改變（該區的新設計PGA為0.25g，該高架橋重要係數是1.2），且有額外的橋墩和橋面的問題（由於激烈的流量和過去缺乏維護），沿著這條公路44座高架橋的20座需要實行補強 [Infanti et al, 2006 b]。橋墩高度變化從3.5m至12 m (圖15)。

FIP Industriale參與以下的活動：

- 地震保護系統設計；
- 結構裝置製造（如下所述的阻尼器、支承座、伸縮縫）；
- 高架橋補強。

地震保護系統設計

在介入的第一個階段，進行維修與加強橋墩和橋墩帽，允許後續橋面板上升作業，以及承受地震荷載。靜態方案是由均衡改變為靜不定連接橫梁與厚板，從而消除橋墩上的伸縮縫-只留伸縮縫在橋台。

新的連續板從2到7跨度計算，在中央橋墩之一的固定點。圖16顯示了一個典型的多跨度高架橋的性能和地震情況下的軸承系統方案；特別顯示出6個橋面板的結構（Carletto高架橋）。

每個橋墩有兩個地震設備（MELOP或MELOTP系列阻尼單元，圖17）在同一單元內包括縱向上的非線性粘滯流體阻尼器和橫向上的-新月形-鋼遲滯散熱元件。在每個橋台，有一個與橋墩使用的相同類型裝置和一個縱向流體粘滯阻尼器。這樣的阻尼系統，為了要控制水平力，結合到一個自由滑動盆式軸承方案，用於傳遞垂直載荷，並允許在各個方向有控制的水平位移。

在承載的狀況下，固定橋墩的縱向載荷是由單元（MELOP系列）去承受，其阻尼器都配有洩壓閥，設計成當壓力（負載）高於外力負載時打開。MELOTP系列耐震裝置被安裝在所有會滑動的位置。在所有地點，橫向對準的鋼遲滯阻尼器提供正常荷載狀況下的剛性限制。在地震狀況下，所有的地震設備根據其本構關係動作，消散由地震傳來的大量能量。

總共安裝188個耐震設備，連同380個自由滑動支承座和440m的伸縮縫與400mm的總位移量。在FIP Industriale實驗室進行粘滯阻尼器和新月型鋼阻尼器的功能測試[Infanti et al, 2006 b]。

圖15: SS647高架橋之典型內容(補強前和補強後)。



Figure 16: Bearing and Seismic Protection System Schemes of a typical SS 147 viaduct.

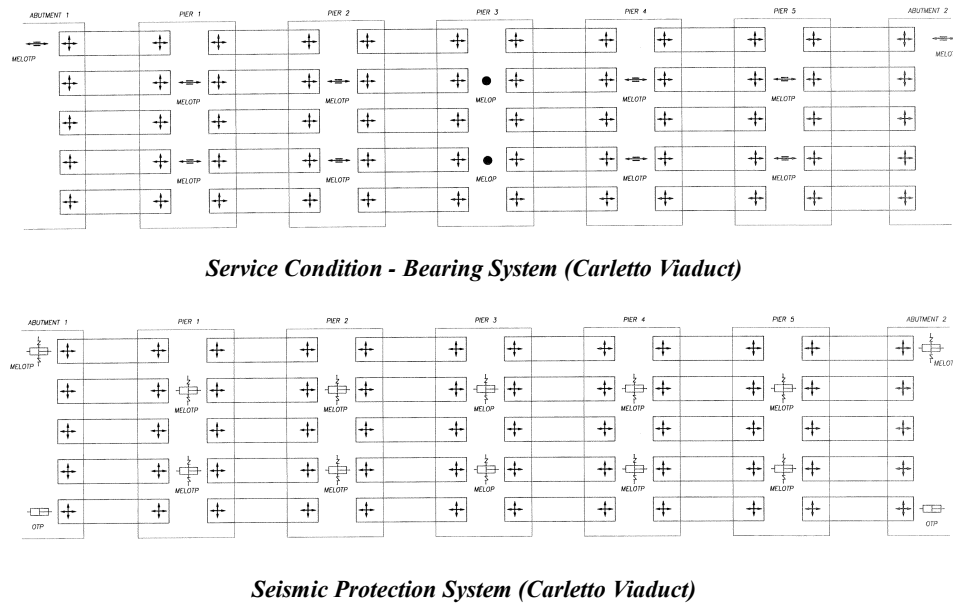


Figure 17: MELOTP Damping System as installed in a SS 147 viaduct.



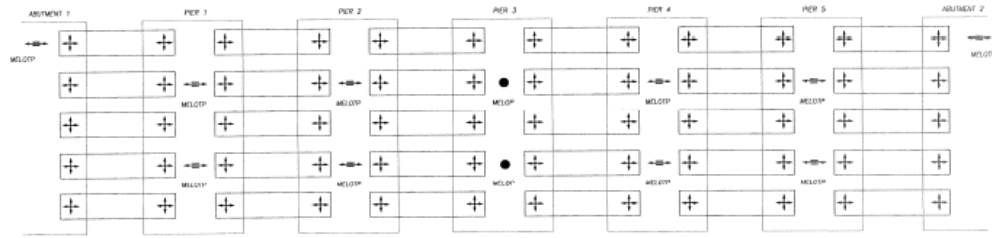
THE MARQUAM BRIDGE, OREGON, USA

The Marquam Bridge across the Willamette river in Portland (Oregon, USA) was built in the early 1960s. The deck comprises three spans steel trusses carrying two superimposed roadways with a total length of 318 m. The static arrangement is of typical “Gerber girder” construction, in which the two end-girders have a cantilever beam toward the deck centre, which supports the overhung 79 m long central truss (Figure 18 a). The two end spans measure 92 m and the central span has a total length of 134 m. The piers are r.c. frames.

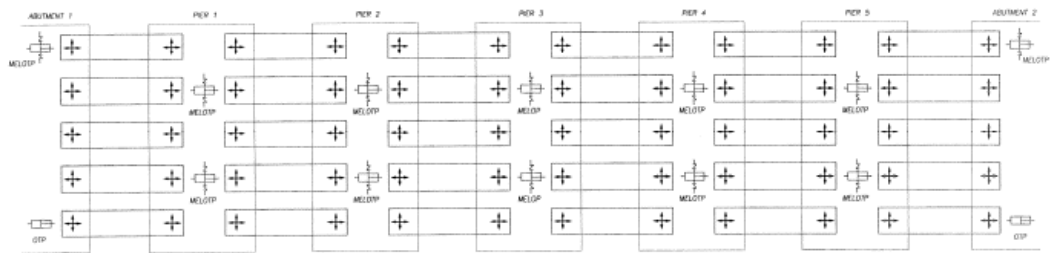
A seismic retrofit of the structure was undertaken in the early 1990s, on the occasion of some maintenance work. The retrofit project had the following objectives:

- to avoid any damage to the structure in the event of the design maximum expected earthquake ($PGA=0.29\text{ g}$);
- to avoid the need for strengthening existing structural elements (i.e. piers, trusses, foundations, etc.);
- to maintain the existing bearing system;

圖16: 一個典型SS 147高架橋的軸承及地震保護系統方案。



荷載狀況軸承系統 (Carletto 高架橋)



地震保護系統(Carletto 高架橋)

圖17: SS 147高架橋安裝的MELOTP阻尼系統。



美國俄勒岡州MARQUAM大橋

在波特蘭（俄勒岡州，美國）橫跨Willamette河的Marquam大橋始建於1960年代初。橋面板包含三跨鋼桁架，總長度為318 m，並通過兩個疊加的道路。靜態結構是典型的“Gerber梁”結構，兩個梁端有一根懸臂梁朝向橋面板中心，用於支持懸臂79 m長中央桁架（圖18a）。兩端跨度92 m以及中央跨度總長度134 m。橋墩是RC架構。

該結構的耐震加固於1990年代初在一些維修工作的場合進行。

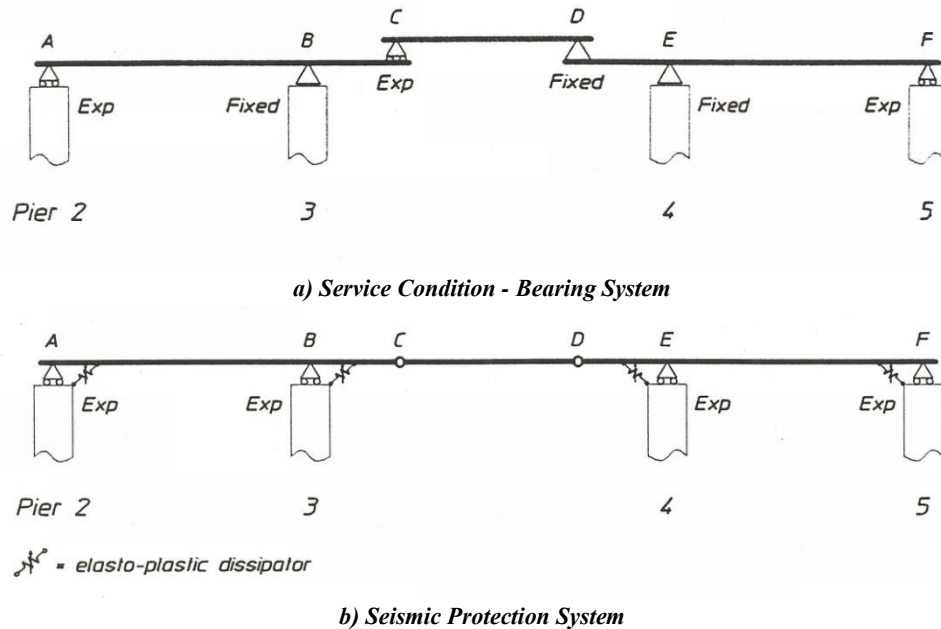
補強計畫有以下的目標:

- 避免在最大預期的設計地震($PGA=0.29g$)發生時造成任何結構的損害;
- 避免需要加強現有的結構元素(即如橋墩、桁架、基礎等等。);
- 維護現有的軸承系統;

- to limit relative displacements to values compatible with the existing gaps (longitudinal displacement not to exceed ± 127 mm).

Said objectives were fulfilled by the seismic protection system described in the following section. This was the first application of Italian seismic devices in the USA.

Figure 18: Bearing (a) and Seismic Protection System (b) Schemes of the Marquam Bridge.



Seismic Protection System Design

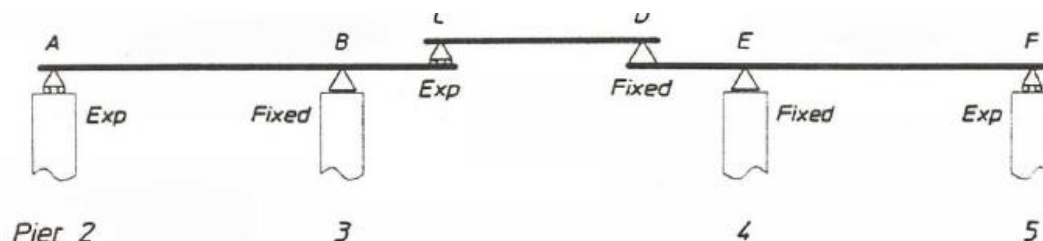
The 8 pre-existing vulnerable steel bearings - 4 rockers and 4 hinges - were replaced with 8 isolators comprising a free sliding pot bearing and a series of steel dissipating elements of the double tapered pin type (Figure 19). The 4 isolators installed at the expansion points (Piers 2 and 5, Figure 18) additionally comprise an STU (see chapter 2.1). Four shock transmission units were inserted at the expansion end of the suspended span. The seismic protection system scheme is shown in Figure 18 b: during an earthquake, the structure behaves as a multi-span continuous girder. Thanks to a proper selection of the maximum force of the dissipating elements and to their high energy dissipation capacity, all piers and foundations remain within their elastic limits and the displacements thereof are within specified limits. Under service conditions, the bearing scheme remains as it was before the retrofit. This objective was accomplished through the employment of sacrificial restrainers (shear keys) thus ensuring that normal service loads (including wind, braking actions, and even moderate earthquakes) do not stress dissipating elements and displace the isolators. Additionally, said restrainers impede displacements at the “fixed” piers (Piers 3 and 4, figure 18) as well as any transverse movements at the “mobile” piers (Piers 2 and 5).

The devices underwent rigorous tests simulating actual normal service actions and seismic attack conditions [Medeot, 1995]. Figure 19 (right) shows an isolator prototype undergoing a combined vertical-horizontal test.

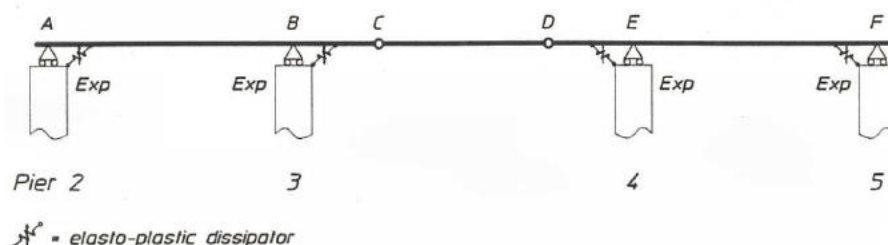
-限制相對位移值，以與現有的差距相容（縱向位移不超過 $\pm 127\text{ mm}$ ）。

上述目標可由以下段落的地震保護系統說明。這是義大利地震設備在美國的首次應用。

圖18: Marquam大橋方案的軸承(a)和地震保護系統 (b)。



a) 荷載狀況 - 軸承系統



b) 地震保護系統

地震保護系統設計

8個預先存在的脆弱鋼軸承 - 4個搖桿和4個鉸鏈-替換成個8隔震裝置，包含一個自由滑動的盆式軸承和一系列的雙錐形插鞘類型（圖19）的剛性消散元件。安裝在伸縮端（橋墩2和5，圖18）的4個隔震裝置還包含一個STU（參考2.1節）。四個震傳動遞裝置被插入在懸掛跨度的伸縮端。地震保護系統方案如圖18 b所示：在地震中，結構表現如同多跨度的連續梁。由於採用了適當選擇的消散元件最大耐力和它們的高能量耗散能力，所有橋墩和基礎保持在它們的彈性極限內，其位移也在指定範圍內。在荷載的狀況下，軸承的方案維持與補強前一樣。這一目標是透過採用犧牲限位裝置（剪力鍵）來達成，從而確保正常的工作荷載（包括風、煞車動作、甚至是溫和的地震）不會加壓消散元件和移位隔震裝置。此外，所述限位裝置阻礙“固定”橋墩的位移（橋墩3和4，圖18），以及“行動”橋墩的任何橫向移動（橋墩2和5）。

該設備進行了嚴格的測試，模擬實際正常荷載行為和地震襲擊的狀況[Medeot, 1995].圖19 (右)顯示了一個隔震裝置原型機正在進行聯合垂直-水平的測試。

Figure 19: Slider with steel hysteretic dissipating elements installed in the Marquam Bridge, Oregon, USA (left) and the prototype under testing in FIP Industriale's laboratory (right).



PONTE DEGLI ALPINI, ITALY

The “Ponte degli Alpini” Bridge, crossing the Ardo river, is one of the main traffic link to the Belluno municipality in Northern Italy.

It was opened to traffic in 1971 and is characterized by 8 simply supported decks for a total length of 294m. The piers vary in height from 11 to 42 m (Figure 20, left). The original design considered the use of standard elastomeric bearings.

A change in seismic codes (the new design PGA for the area is 0.25g, and the importance factor for said bridge is 1.3 due to its strategic importance for emergency management providing therefore a 0.325g design acceleration), together with additional pier, foundation and deck problems imposed the necessity of retrofit.

FIP Industriale was involved in the following activities:

- Design of the seismic protection system;
- Manufacturing of the structural devices (dampers, bearings, expansion joints, as described in the following);
- Viaduct retrofit.

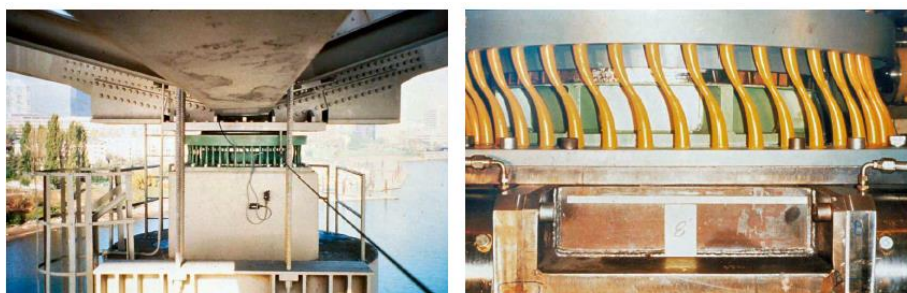
Seismic Protection System Design

During the first phase of the intervention, the strengthening of piers and their foundation was carried out, both permitting subsequent deck lifting operations for bearings substitution. The static scheme was changed from simply supported to statically indeterminate by connecting the beams through the slab in order to remove the most of the expansion joints at the piers – leaving those at three locations only (at the abutments and in the middle).

Figure 20: Ponte degli Alpini before (left) and after the retrofit (right)



圖19: 滑塊與鋼遲滯散熱元件安裝在美國俄勒岡州的Marquam橋（左）和正在FIP Industriale實驗室中測試的原型機構（右）。



義大利的PONTE DEGLI ALPINI

橫跨Ardo河的“Ponte degli Alpini” 橋是義大利北部主要連接Belluno市的交通要道之一。

它於1971年建成通車，其特點是有8個簡支撐橋面板總長度為294 m。橋墩的高度變化從11到42 m（圖20，左）。最初的設計考慮使用標準的橡膠支承座。

在耐震規範的改變（該區的新設計PGA為0.25g，而該橋的重要係數是1.3由於它的緊急管理的策略重要性，因此提供0.325 g的設計加速度），與其他額外的橋墩、基礎和橋面板問題導致補強的必要性。

FIP Industriale參與下列活動：

- 地震保護系統設計；
- 結構裝置製造（如下所述的阻尼器、支承座、伸縮縫）；
- 高架橋補強。

地震保護系統設計

在導入的第一階段，進行加強橋墩與基礎，兩者皆允許軸承替換的後續橋面板上升作業。靜態方案是由簡支撐改變為靜不定連接橫梁與厚板，從而消除橋墩上的伸縮縫-只留在三個位置（在2個橋台和橋中央）。

圖20: Ponte degli Alpini補強前(左)和補強後(右)



The actual two continuous decks count respectively for 5 and 3 spans, with the fixed points located at the tall piers 2 and 3 and at pier 6.

On each pier and abutment, two combined seismic devices (MELOP or MELOTP series damping units, see Fig. 22) are located comprising within the same unit a non-linear fluid viscous damper in the longitudinal direction and steel hysteretic dissipating elements - crescent-moon shaped – in the transverse direction. Such a damping system - aimed at controlling the transmission of the horizontal forces - is combined with free sliding pot-bearings: a scheme capable of transferring vertical forces that permits controlled horizontal displacements in all directions.

It is worth noting that in order to reinforce and control the seismic actions at pier P1, where there was insufficient space for any basement modifications, chevron braces have been installed (see Fig. 21 left). The latter were equipped with High Damping Rubber Bearings, working as visco-elastic dampers in order to provide additional energy dissipation (see Fig. 21 right). This solution, commonly applied in buildings, was suitable for the reduction of the actions at the pier basement and the avoidance of its enlargement/reinforcement.

Another particular solution exploited in this project regards the expansion joints. In order to reduce the expansion/contraction movement at the middle joint (i.e.: in between the two decks) and wishing to avoid possible out-of-phase oscillations along the longitudinal deck axis during the seismic event, shock transmission units have been installed. These devices - anchored at their ends directly to the two adjacent decks - connect them temporarily only in case of dynamic events: In this way, the expansion joint and its gap need to be designed for service movements only.

Figure 21: Chevron braces at Pier 1 (left), HDRB as installed on a chevron brace top (right)



Figure 22: MELOP Damping System as installed (left), Shock Transmission connecting the decks during installation (right)



實際連續的兩個橋面板分別為5和3個跨度，固定點位於高橋墩2和高橋墩3以及橋墩6。

在每個橋墩與橋台，兩個組合的地震設備（MELOP或MELOTP系列阻尼裝置，參見圖22）位於同一單元內包括在縱向的非線性粘滯流體阻尼和在橫向的-新月亮形-鋼遲滯散熱元件。這樣的阻尼系統，為了要控制水平力，結合到一個自由滑動盆式軸承方案:用於傳遞垂直載荷，並允許在各個方向有控制的水平位移。

值得注意的是，為了加強和控制在橋墩P1的地震作用力，因沒有充分的空間供基礎修正，所以安裝了人字形支架（參見圖21左）。後者配備了高阻尼橡膠支承座，擔任粘彈性阻尼器，以提供額外的能量耗散（參見圖21右）。這解決方案常用在建築物中，是適合於減少在橋墩基礎的作用力，並避免其放大/加固。

另一個關於伸縮縫的特別解決方案在這個計畫中被採用。為了降低在中間連接點（即：在兩個橋面板之間）的膨脹/收縮移動，並希望避免在地震期間沿縱向橋面板軸線外凸的可能振盪，因此安裝了震動傳輸單元。這些設備 - 在它們的端部直接錨定到兩個相鄰的橋面板 - 僅在動態事件臨時連接它們：在這種方式中，伸縮縫與其間隙需要被設計為只供荷載的移動。

圖21:橋墩P1的人字形支架(左)，HDRB安裝在人字形支架頂端(右)



圖22: MELOP阻尼系統安裝(左)，安裝震動傳輸連接橋面板(右)



PRODUCTION CONTROL ACCORDING TO THE EUROPEAN CODE EN15129:2009

The aim of the European Code EN15129:2009 is to provide for simple and common rules for design, testing and production purposes. In order to allow the free trade within the European Union, such code was conceived as a performance based one and cannot specify brand products.

It covers all the known technologies at the time of its first issue but it was conceived trying to allow as much as possible the introduction of new technologies: the European approval dates 19 September 2009. Since then many countries outside the European Union – where is now mandatory - have started using it totally or partially as a reference code. Nowadays, we can find projects in the Mediterranean Area (Turkey, Israel, Algeria, Albania...) or even in the Far-East (Mainland China, ...) where, in lieu of a local specific regulation, EN15129:2009 has been considered as reference and applied.

Within the EU, this code is the main reference document describing all the activities that must be followed in order to provide the seismic products with the CE (European Conformity) mark required for a safe and legal installation.

Wishing to enter into the merit of the activities aimed at verifying the consistency of the design with the production quality, we can identify two main test phases: Type Testing (TT) and Factory Production Control Testing (FPCT). All such activities are performed on full-scale products.

Type Tests consist on a full test program which investigates all the main characteristic of the technology under testing.

E.g.: the lateral stiffness and damping of isolators or the force vs. velocity constitutive law of a viscous damper, etc.

TTs must be repeated every time a new product is too different from the Type Tested reference device: the code defines when the most critical and key parameters are exceeded and new units require for Type Testing.

Factory Production Control Tests consist on a limited number of tests aimed at verifying that the produced units behave as the prequalified reference device.

FPCTs shall be performed under the responsibility of the manufacturer on each production lot, the number of units under testing depending upon the technology under consideration.

Table 2: Used seismic devices classification according to EN15129:2009

EN 15129:2009 Clause Title	EN 15129:2009 Typologies	Typologies used for bridge retrofits	Factory Production Control Test
5. Rigid Connection Devices	Fuse Restraints		
	Temporary Connection Devices	STU: Shock Transmission Units	5%
6. Displacement Dependent Devices		HD: Hysteretic Damper	2%
7. Velocity Dependent Devices	Fluid Viscous Dampers Fluid Spring Dampers	VD: Viscous Damper	5%
8. Isolators	Elastomeric Isolators	HDRB: High Damping Rubber Brg.	20% + 1 unit
	Curved Surface Sliders	LRB: Lead Rubber Bearing	20% + 1 unit
	Flat Surface Sliders	CSS: Curved Surface Sliders	5%
9. Combination of Devices	Any combined device	SHD: Slider with Hysteretic Damper	2%
		HD+VD: Hysteretic + Viscous Dampers	2% & 5%

依據歐盟EN15129：2009的生產控制

歐盟EN15129：2009的目標是提供用於設計、測試和生產的簡單且常見的規則。為了確保歐盟內的自由貿易，這樣的規範被認為是一個基本表現之一，且不能針對特定品牌的產品。

它涵蓋了在其首次公布的時的所有已知的技術，但它的構思是試圖盡可能的引進新技術：歐洲批准日期為2009年9月19日。自那時以來，許多歐盟以外的國家 - 現在是強制性的 - 已經開始全部或部分使用它作為參考規範。如今，我們可以在地中海地區（土耳其、以色列、阿爾及利亞、阿爾巴尼亞...），甚至在遠東（中國大陸，...）發現以此規範代替本地具體規定的計畫，EN15129：2009已經被認定為參考和應用。

在歐盟內部，這個規範是主要的參考文件，說明所有須遵循的活動以提供具有安全與合法安裝的CE（歐洲整合）標誌的耐震產品。

為了要得到驗證與生產品質設計一致性活動的優點，我們可以驗證兩個主要的測試階段：類型試驗（TT）和工廠生產控制測試（FPCT）。所有這些活動都在真實產品中進行。

類型試驗包括一個完整的測試程序，調查測試技術的所有主要特徵。

例如：側向剛度和隔震裝置的阻尼或是外力vs.粘性阻尼器的速度本構關係等等。

TT必須在每一次新產品與類型試驗參考設備差異太大時重複進行：該規範定義何時最關鍵和主要的參數超出，以及新單元需要進行類型試驗。

工廠生產控制測試包括對有限的測試數量驗證其所生產的單元如同通過預認證的參考設備。

FPCTs應在製造商的責任下進行每個生產批次，測試單元的數量取決於所考慮的技術。

表2:依據EN15129:2009所採用的耐震裝置的分類

EN 15129:2009 條款名稱	EN 15129:2009 類型學	類型學 用於橋梁補強	工廠生產控制測試
5. 剛性連接裝置	保險絲制約 臨時連接設備	STU: 震動傳遞裝置	5%
6. 位移相關設備		HD: 遲滯阻尼器	2%
7. 速度相關設備	流體粘滯阻尼	VD: 粘滯阻尼器	5%
8. 隔震裝置	彈性隔震裝置 曲面滑塊 平坦表面滑塊	HDRB: 高阻尼橡膠支承座 LRB: 鉛芯橡膠支承座 CSS: 曲面滑塊	20%+1 單位 20%+1 單位 5%
9. 裝置的組合	任何組合的裝置	SHD: 滑塊與遲滯阻尼器 HD+VD 遲滯+粘滯阻尼器	2% 2%&5%

For sake of clarity, Fluid Viscous Dampers – whose production requires tight machining tolerances – requires for a 5% FPCT sampling, while Elastomeric Isolators - whose production requires rubber to steel vulcanization - requires for a 20% FPCT sampling. In other words, each known technology was investigated and the related test activity proposed accordingly in terms of sampling frequency and testing methodology considering for its most critical production aspects.

In EN15129:2009 all the seismic devices are classified within four main identified groups respectively described in Clauses 5 to 9 where the design rules and tests are defined: In Table 2 the seismic devices used for the above mentioned retrofit projects are identified by typology and correlated to the relevant Clause.

CONCLUSIONS

The almost 30-year experience of the Italian manufacturer FIP Industriale in the seismic retrofit of bridges and viaducts via seismic isolation and energy dissipation devices has demonstrated that said devices can be used in most cases to improve the seismic performance of existing structures at the level required by modern seismic codes - reducing to a minimum (or avoiding completely) the strengthening of piers and foundations.

The few examples described above show how different devices can be used – and combined – to solve specific problems presented by a particular structure.

The use of the European Code EN15129:2009, the world-wide most updated and advanced code relevant to anti-seismic devices, has allowed the structural designers to specify for high standard quality levels and helped the manufacturers to provide for a constant and outstanding control of their products.

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為清楚起見，流體粘滯阻尼-該生產需要嚴格的加工容差-需要按5%FPCT採樣，彈性隔震裝置-該生產需要橡膠硫化鋼-需要按20%FPCT採樣。換句話說，每一個已知的技術都被進行調查，且相關的測試活動提出包括採樣頻率和檢測其最關鍵的生產面工法。

在規範EN15129:2009中，所有的耐震設備被分類成四個主要鑑定群組，分別說明於定義設計規則和測試的條款5至條款9：在表2，上述補強項目的耐震裝置是由類型學鑑定並關聯至相關的條款。

結論

在橋梁和高架橋使用隔震和消能裝置的耐震補強有近30年經驗的義大利製造商FIP Industriale，證明上述裝置可以在大多數情況下被用來改善現有結構，達到現代耐震規範所要求的水平的耐震強度-讓橋墩和基礎的加強減少到最低限度（或完全避免）。

上述的幾個案例示出不同的設備如何使用 - 和組合-以解決特定的結構的具體問題。

使用全球相關的耐震裝置中最新與最先進的規範-歐盟EN15129:2009，可讓結構設計人員指定高標準的品質水平，並幫助製造商提供一套控制產品穩定與優良的作業標準。

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