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SEISMIC ISOLATION SYSTEM FOR RAILWAY VIADUCTS IN VENEZUELA

F. Tomaselli[1], M.G. Castellano[2], and P.Baldo[3]

ABSTRACT

The paper presents the special seismic isolation system already installed or under installation in the viaducts of the Caracas-Tuy Medio, Puerto Cabello-La Encrucijada and Caracas-Guarenas-Guatire Venezuelan Railway lines. Unlike the previous two, the latter is a metropolitan light train line without ballast between deck and rails. These lines are located in Venezuela´s north-central region, affected by the interaction of the Caribbean and South American tectonic Plates.

The isolation system comprises combined devices including a bearing equipped with steel hysteretic dissipating elements; the latter work only during well-determined seismic events, thanks to mechanical fuse restraints that impede displacements in desired directions during service and up to a pre-established horizontal force threshold. Under such conditions, the devices behave like normal bearings, realizing a scheme of statically determinate spans with a fixed point at one end and a mobile one at the opposite end. When the aforesaid threshold is exceeded, the fuses shear off and thus do not constitute a restraint to displacements in the directions previously blocked. Thus, the steel hysteretic elements are activated to dissipate seismic energy and control bridge deck movement as well as horizontal forces transmitted to the piers.

The different behavior of the bearing system under service and seismic actions is particularly useful in railway viaducts, in which horizontal displacements in service should be reduced as much as possible. The fuse's threshold is usually selected slightly higher than the horizontal force due to braking of trains and/or small earthquakes.

The steel hysteretic dampers are made of special austenitic stainless steel that guarantee a stable hysteretic behavior for many cycles. The fuses can be substituted after a big earthquake without need of uplift the deck.

Both the dissipating elements and the sacrificial elements have been subjected to experimental verification.

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Introduction

The government of Venezuela, through its Autonomous State Railways Institute (IAFE), is constructing a railway system for the central region to link the capital, Caracas, with the port of Puerto Cabello on the Caribbean. This is probably the biggest railway development project in the South American Continent. The initiative issued from the need to link the main cities of the central and central-occidental regions through a people-freight transport medium other than public highways that can prove safe and efficient. In fact, the usage of the existing highway network far exceeds its capacity to support such volume of traffic. Inevitably, traffic congestion leads to an obviously progressing increase in travel time as well as costs. As a

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reflection of this, the project aimed to create greater development of the areas touched by the line and decentralize urbanization demands to decongest in part the greater Caracas urban area.

The Caracas-Puerto Cabello line crosses a prevalently mountainous area, covered by tropical vegetation comprising the farthest extension of the Andes chain, characterized by deep ravines through which run water torrents whose flow is extremely variable (quebradas). The railway line is thus a continuing alternation of tunnels and viaducts. The Caracas - Tuy Medio tract is already completed, and comprises 14.9 km of tunnels and 7.8 km of viaducts respectively, throughout the 40 km extension of railway line. The tract La Encrucijada-Puerto Cabello is under construction, and will have a length of 108 km, with 24 viaducts.

The Caracas Electric Train is located in Caracas. The entire train alignment comprises sections CGO1 to CGO6 for a total length of about 31 km. Sections CGO1 to CGO3 will mainly consist of tunnels structures, while sections CGO4 to CGO6 will consist of viaducts only. The latter have an approximate length of 14 km, and will consist of elevated structures with approximately 40-meter long spans founded on about 1.5-meter diameter drilled shafts with lengths varying between 25 to 35 m.

These lines are located in Venezuela´s north central region, whose seismicity is influenced by the interaction of the Caribbean and South American tectonic Plates. The site region is characterized by high rates of seismicity and relatively frequent moderate to large earthquakes. Active tectonism in the region is very complex and is driven by "escape" tectonics along a distributed 600-km-wide Caribbean-South American (CA-SA) plate boundary to the west and at the site is characterized by a dominantly strike-slip CA-SA plate boundary, which continues eastward through the island of Trinidad. The largest earthquakes in the area are the 1900 Ms 7.6, 1766 Mw 7.6, and 1997 Mw 6.9 events [1].

The bridges and viaducts are all provided with FIP seismic isolators. About 3,000 isolators were installed on the railway from Caracas to Puerto Cabello, while more than 1,000 will be installed at the end of the works of metropolitan light electric train line.

Design criteria

The selection of the seismic isolation system was based upon the functions that it should comply with to guarantee the proper operation of the trains under normal and emergency conditions, as well as under exceptional conditions which might be produced by a severe earthquake. To accomplish this, the following basic principles were established:

- To provide an isostatic deck-substructure link condition due to the presence of geological faults across the viaducts' course;
- To avoid "floating" deck conditions by means of restricting movements in the horizontal plane during normal and emergency train operations, basically for reasons directly related to the support of the railway;
- To provide an isotropic deck-substructure link condition in the horizontal plane under normal, emergency and exceptional operational conditions;
- To avoid the occurrence of structural damage under the conditions imposed by the "Verification Earthquake" (earthquake with average return period of 50 years);
- To protect the decks from component failures and losing support under the conditions imposed by the "Design Earthquake" (earthquake with 7.5% probability of exceeding the same during the expected service life of 70 years, which is equivalent to an average return period of 900 years).

The study of the restraint system for both service and seismic conditions led to the choices described in the following [1, 2].

Normal Service Conditions

Under these conditions, the bearings are capable of restraining the bridge deck in every direction whilst allowing thermal and rheological excursions and rotations produced by elastic deformation through the effects of traffic. From this, it being a case of isostatic railway viaducts, arises the need for the decks to be rigidly restrained for thrusts induced by operational loads and/or wind so as to impede deck movements that might damage the rails and thus the line itself. The restraint system provided for the adoption of bearings with different characteristics, each of them capable of specifically individual functions. For the bridge decks with 2 couples of bearings, said restraint system called for the following types of bearings (Fig. 1):

- a fixed device + a transverse guided one on the fixed end;
- a longitudinal guided device + a free one on the mobile end.

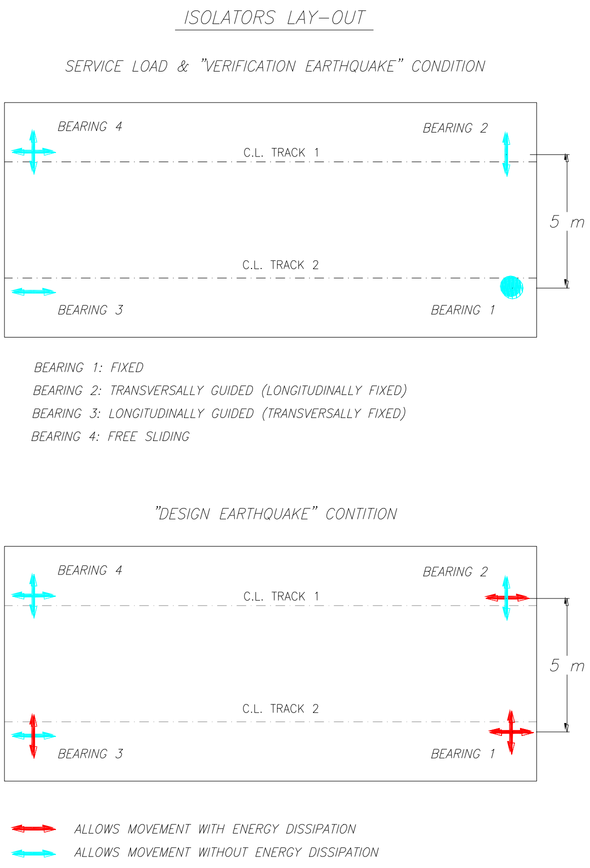

Figure 1. Typical isolators lay-out.

Seismic Conditions

The bridge deck bearing arrangement provides for all bearings to become free with a limited stroke, thus permitting the structure to move in all plane directions and ensuring a high level of seismic energy dissipation. The control of maximum displacements and horizontal forces transmitted to the understructure is achieved through the use of special steel dissipating pin elements that will be described later.

Design of the Isolators

Each isolator comprises three main components, the pot bearing, the steel hysteretic dissipating elements and the sacrificial elements or fuses (Figs. 2 and 3). The bearing serves to transmit vertical loads and allow rotation and horizontal displacements. The sacrificial elements transmit the horizontal load to the substructure, up to a pre-established force threshold. After the fuse breakway, the steel hysteretic dissipating elements dissipate energy and control the horizontal actions generated by the earthquake.

Steel hysteretic dissipating elements can have different shapes. The tapered pin shape was selected for this applications. The adoption of axially symmetric dissipating tapered pins guarantees multidirectionality and isotropic behavior in the horizontal plane with reduced dimensions in plan. The required yield and maximum force of the isolator are obtained by setting the proper number of dissipating elements working in parallel. The isolator is thus characterized by the modularity of the dissipating components, which makes it easily adaptable to different structural requirements. This modularity also gives the advantage of redundancy: i.e., any defect in one or more elements does not put a seismic device out of service.

The seismic isolation trough combination of bearings with steel hysteretic dissipating elements, also known in the past as the Italian technology of seismic isolation, has seen many successful applications since the eighties in viaducts, bridges, and other structures in Italy and all over the world. Some of the outstanding applications are the Mortaiolo Bridge in Italy [3], the retrofit of the Marquam bridge, Oregon, USA, the Bangabandhu Bridge in Bangladesh [4], the retrofit of the Granville bridge, Vancouver, Canada and the retrofit of the Chirag I offshore platform in Azerbaijan [5].

Rather than describing a traditional pot bearing, our description here below will concentrate only on the special components of the isolator.

Figure 2. Isolators in workshop (left during assembling phase – right as assembled) (type positions 2 and 3 of figure 1)

Sacrificial elements

Sacrificial elements (Fig. 4) are designed to transmit horizontal service loads (i.e. wind, braking actions, etc.) to the substructure without significant displacement (that is particularly important in railway viaducts) and to fail during a design earthquake, thus allowing the steel hysteretic dampers to work. Said elements are mechanical fuses that work elastically until the breakpoint threshold is reached. When the fuses shear off, the fixed and guided bearings become free, and keep the bridge deck restrained through the dissipating elements incorporated in the isolators themselves. Sacrificial elements are the only pieces to be replaced after a big earthquake; this replacement can be carried out without need of uplift the deck. This operation is made particularly easy by the presence of the eccentric rings. The isolators positions no. 1, 2 and 3 in Fig. 1 are equipped with four or eight sacrificial elements.

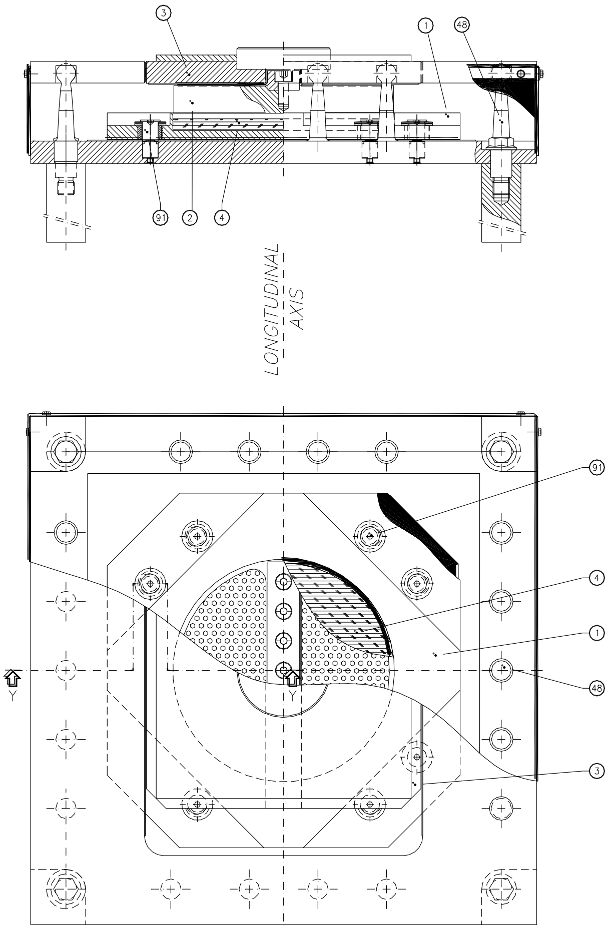

Figure 3. Guided seismic isolation device arrangement: 1) Pot element; 2) Intermediate element; 3) Sliding plate; 4) Elastomeric disc; 48) Steel dissipating pin; 91) Sacrificial element (fuse)

Figure 4. Installation of a sacrificial element.

Tapered pin steel hysteretic dissipating elements

The tapered pins are characterized by high dissipating efficiency and stable hysteretic behaviour, thanks to their special shape and to the use of a special austenitic steel with high physical-chemical characteristics, inalterable in time, and large ductility.

The constitutive model of the dissipation element is represented by a bilinear force-displacement curve. Figure 5 shows the idealized force-displacement hysteresis loop associated to the maximum design displacement, represented by M (d_{max}, F_{max}). The intersection of line r_1 with the Force axis corresponds to the so called characteristic strength F_d. The yield force is denoted as F_y, Elastic stiffness K_o and Post-elastic stiffness K_d.

The dimensions of the dissipating elements depend on the bilinear curve that should be obtained, so there are different sizes of tapered pins.

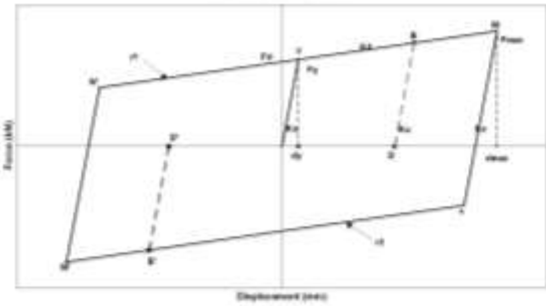

Figure 5. Force vs Displacement model curve

To check the experimental vs. theoretical behaviour, the tapered pin were subjected to low-cycle fatigue tests at constant displacement (equal to the design displacement) in FIP Industriale laboratories (Fig.6). The number of cycles that produces failure, when the specimen is subjected to maximum displacement, is over 15. Due to the fact that an intensive earthquake in an isolated structure usually corresponds to only 3÷4 cycles at the design displacement, plus others at much lower displacement, it will not be necessary to substitute the tapered pins because their life should be longer than the life of the viaducts they have to protect.

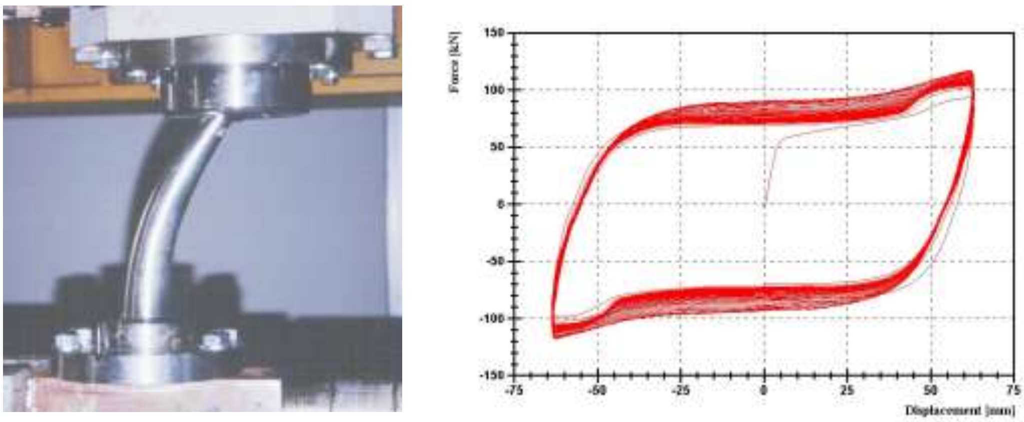

Figure 6. A tapered pin dissipating element during tests at FIP Industriale laboratory and its Force vs Displacement experimental curve

Shaking table tests

Test facilities and experimental model

The experimental program described here was carried out on the shaking table of the CESI S.p.A. (formerly ISMES) laboratories in Bergamo, Italy. The table measures 4m × 4m in plan. It can be controlled in 6 degrees of freedom, but the tests described here were carried out in only one horizontal direction, so as to simplify the evaluation of results. The test structure was meant to be a model of the deck of two typical viaducts of the Caracas-Tuy Medio Railway.

The scope of the tests was to study the dynamic behavior of the steel hysteretic dampers and fuse system and not that of the deck itself. Thus, the model structure is extremely stiff and comprises a series of steel and r.c. masses supported by a steel frame. It is considerable that the model isolation system consisted of a full scale steel hysteretic dissipating element, identical to those used in the isolators installed in the viaducts. It is the modularity of the isolation system described above that allowed not having to scale down the damper, as it is usually necessary with shaking table tests. Using full scale elements permitted to avoid scaling the time and all other quantities. Consequently, the tests results are more reliable and representative of the actual situation, when compared to tests performed on scaled-down models.

The model mass thus represents the portion of the deck mass that is seismically protected by a single dissipating element in the isolated viaduct, i.e. the mass value given by the ratio of the total deck mass to the number of dissipating elements. Two different mass values were used for the model, i.e. 38765 kg and 27760 kg, for models representing viaducts No. VI19 and No. V5-4 respectively. For example, the dampers installed in a typical span of viaduct No. VI19, having a length of 40 m and a mass of about 1240 t, comprise 32 tapered pin elements for each direction (i.e. longitudinal and transversal).

The dissipating element is installed at the centre of one side of the steel frame. It is characterized by a nominal yielding force of 43 kN, yielding displacement of 5 mm, a maximum design displacement equal to 65 mm, a maximum force equal to 57 kN and post-elastic stiffness 0.027 times the elastic stiffness.

The model rests on 4 free sliding bearings. There are also 2 guiding devices, aimed at avoiding displacements orthogonal to the direction of the test. The model isolation system, as well as the actual one, also comprises a sacrificial restraint designed to fail at 127 kN. This value was obtained dividing by 32 (i.e. the total number of tapered pins) the total design failure force (4050 kN) of the sacrificial restraints installed in the reference span of viaduct No. VI19. Further details are given in [6, 7].

Experimental program

Two main series of tests were carried out. The first series was carried out on the model with a mass equal to 38765 kg. The model was subjected to a set of 4 different artificial earthquake inputs generated to match the design acceleration spectrum (AST type) characterized by a PGA of 0.41g (Fig.7, at left), according to AASHTO specifications.

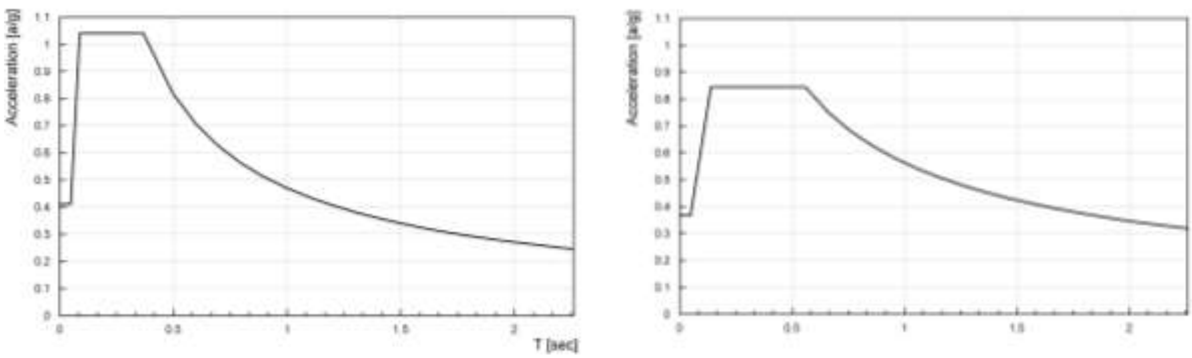

Figure 7 - Design acceleration spectrum type AST (left) and type IMP (right).

The second series of tests was carried out on a model with a mass equal to 27760 kg. The model was subjected to a set of 4 different artificial earthquake inputs generated to match the design acceleration spectrum (IMP type) and characterized by a PGA of 0.37g (Fig.7, at right). Said spectrum differs from the previous one not only in the PGA but in the shape as well, which corresponds to a different type of soil. At any rate, it is associated with the same average return period (900 years).

All the tests in the series were conducted on the same type of tapered pin. The pin was substituted after the completion of the first series, before the start of the second series.

Experimental results

Test #1 was carried out on the model comprising the sacrificial restraint. The time history plot of the deck accelerations measured during Test #1 (Fig. 8) clearly shows the difference between the two phases of the test, before and after the failure of the sacrificial restraint that occurs at circa 3.5 seconds. The first phase is characterized by much higher accelerations (up to 0.51 g) and frequencies than the second phase when the dissipating element is activated. It is also evident how the acceleration peaks remain almost constant (about 0.12 g) during the second phase, owing to the elasto-plastic behavior of the dissipating element.

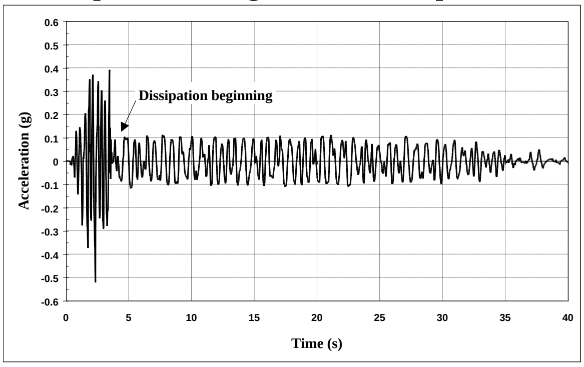

Figure 8. Time history of deck acceleration. Test with sacrificial restraint.

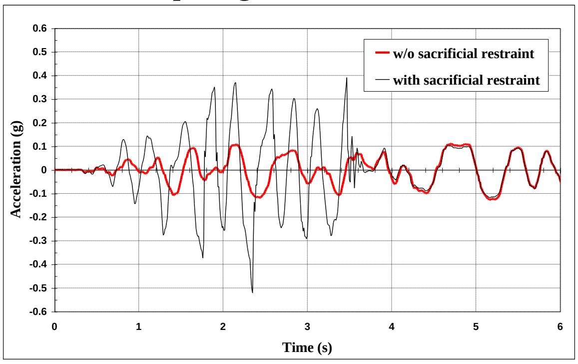

Figure 9. Time history of deck acceleration. Comparison of tests #1 and #2

Fig.9 shows a comparison between the first 6 seconds of the deck acceleration time histories measured during tests #1 and #2. The latter was carried out with the same input (AST4) as test #1, but without the sacrificial restraint. After the failure of the sacrificial restraint, the acceleration response was identical for the two tests. This shows how the dissipating element works properly immediately after the failure of the sacrificial restraint.

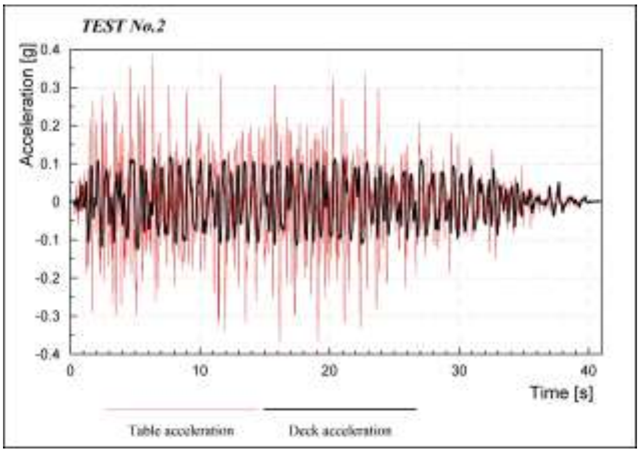

Figure 10. Time histories of table and deck accelerations. Test #2

An impressive reduction of acceleration above the isolation system was observed during each test. The acceleration reduction due to the isolation system falls within a range of 51÷72%. It can also be observed comparing the time history plots of table and deck accelerations (Fig.10).

Test results show that a steel hysteretic damper can withstand at least 8 maximum expected earthquakes. In effect, the first tapered pin was subjected to 8 consecutive tests with inputs type AST without any damage.

The second damper was subjected to 12 tests with inputs type IMP, and the damage started only during the 12th test. This, together with the results of countless low cycle fatigue tests, confirms the fact that there is usually no need to substitute steel hysteretic dampers after the occurrence of an earthquake with the design intensity (in this case associated to a 900-year return period) and energy content.

The recorded responses during the test sequence performed on the same dissipating element indicated stable hysteretical behavior.

Project specifications limited residual final maximum displacement to about 10 mm; test results show that this strict requirement was respected. A typical time history plot of the damper displacement is shown in fig. 11, relating to test #7.

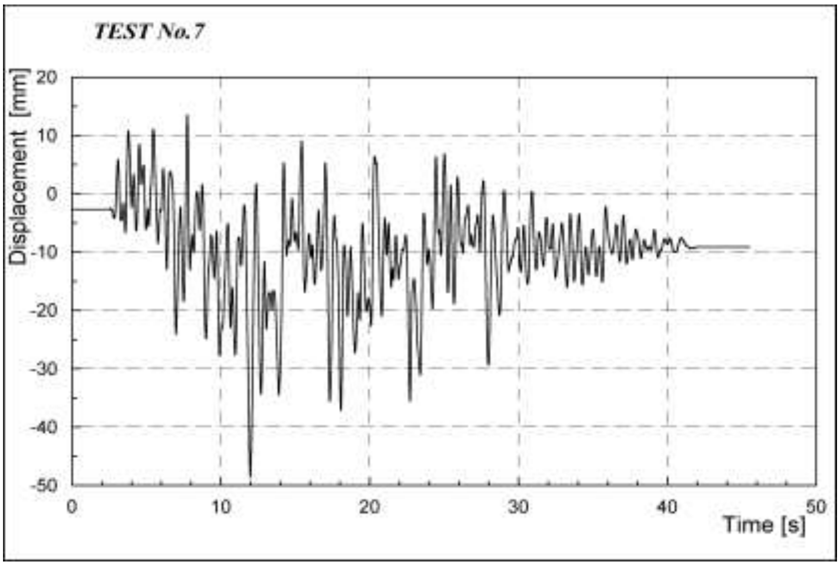

Figure 11. Time history of displacement of the tapered pin. Test # 7.

Conclusions

By means of incorporating seismic isolation with high energy dissipation capacity between the deck and the substructure, it is possible to control the maximum horizontal forces induced by earthquake as well as displacements, and protect structural elements against the damaging effects of an earthquake. The cost associated with the substitution of sacrificial elements or even energy dissipation elements (if needed) is much lower than those originated by damage and/or collapse of the structure.

The special concern about seismic isolation of railway bridges or viaducts, related to the need of avoiding displacements during operation, can easily be solved by special design of the isolation system, in particular through the use of properly designed sacrificial restraints.

A full scale portion of an actual bridge deck was tested on a shaking table, owing to the modularity of the steel hysteretic dampers selected that comprise a number of dissipating elements working in parallel. The experimental model reproduces the portion of the deck mass corresponding to one dissipating element and is seismically isolated through a full scale tapered pin acting as dissipating element, and sliding bearings. As far as these authors know, this was the first time that the behavior of a seismic isolation system with a sacrificial restraint was dynamically tested on a shaking table. Test results validate the use of sacrificial restraints in combination with steel hysteretic dampers. In effect, after failure of the sacrificial restraint, the damper behaves exactly as it would have without a sacrificial restraint. Test results show that the steel hysteretic damper tested can withstand at least 8 maximum expected earthquakes without failure. Results also show a significant reduction in superstructure accelerations due to the isolation system. During the different tests, the peak acceleration on the deck ranged from one third to one half of that on the shaking table.

The seismic isolation system here described was widely applied in railway bridges in Venezuela, realizing one of the world's biggest seismically isolated projects.

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