DAMPER, ISOLATOR AND JOINT SYSTEM FOR SEISMIC PROTECTION OF TOLUCA VIADUCT FOR MEXICO CITY INTERCITY TRAIN

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Abstract

The Toluca–Mexico City Intercity Train will connect the metropolitan areas of Toluca with Mexico City. Once operational towards the mid of 2021, the train will provide service to over 300,000 passengers a day. The approximate total investment for the project is US$ 2.51 bn.

Considering stiffening and strengthening design of a bridge structure for seismic conditions up to 0.75 g PGA presents a major challenge for one of the longer Viaducts, namely Viaduct 2 with a total length of 3.8 km, within the first section of the project.

Conventional strengthening design of the structural members for proper seismic force transmission was not possible anymore. The significant required force reduction for the pier design in longitudinal bridge direction could be achieved with a seismic protection system consisting of an isolation and damping system only.

The viaduct comprises spans of 55 m to 64 m length and piers up to 65 m height. On each axis low friction spherical bearing isolators with up to 26 MN load capacity were placed.

It was crucial to minimize the number and displacements of the rail joints. The applied hydraulic dampers made it possible to block service train braking forces without significant longitudinal deck displacements and allow limited seismic displacements of +/- 650 mm in longitudinal direction for the MCE event with total damper forces up to 30,000 kN for each of the four 700 m to 850 m long viaduct sections.

The re-centering of the structure is granted through elastomeric isolators located at the so called fixed but elastic axes of each viaduct section.

The seismic isolation and damping system according to European Norm 15129 will reduce significantly the longitudinal forces by approx. factor three to five in combination with reasonable displacements of the decks. This helps to cut stresses in piers and decrease foundation size. The final goal of lesser total structural cost, as well as ensuring the safety of the structures and its functionality after seismic events was achieved and will be presented in this paper.

Keywords: Seismic protection, isolators, dampers, expansion joints

1. Introduction

Mexico City has got the urgent need to improve public transportation towards the west where the town Toluca is located in a distance of 70 km. Once operational towards the mid of 2021 the train will provide service to over 300,000 passengers a day. The approximate total investment for the project is US$ 2.51 bn. Therefore it was decided to establish this intercity train connection within which two rather long viaducts are located.

The Viaduct 2 is a structure of 3,865 meters length, which is divided in five continuous sections whose respective lengths are between 690 metres and 850 meters (Fig. 1).

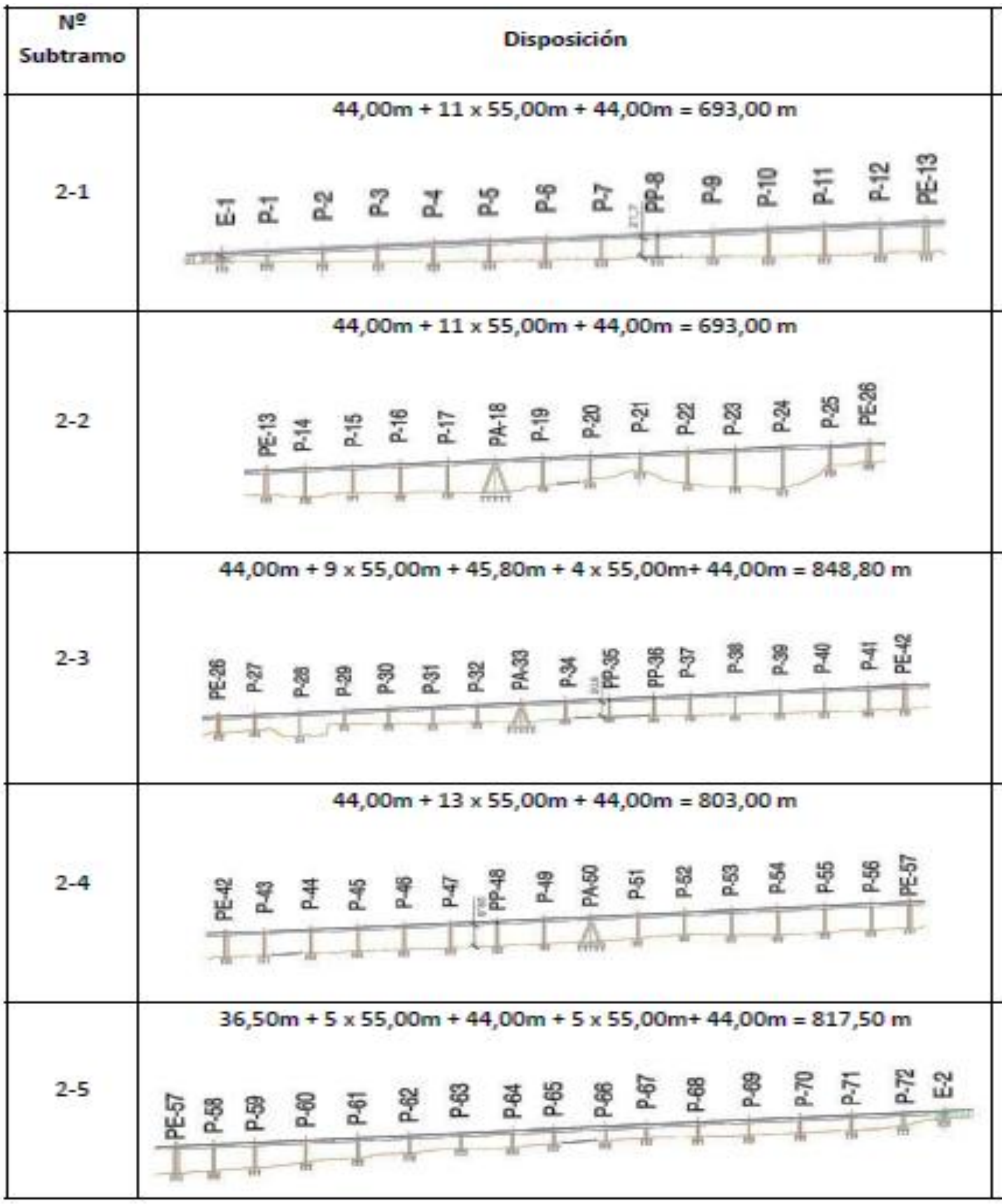


Fig. 1 – Side view on single five sections of Viaduct 2 [1]

The single deck sections will be built as a pre-stressed concrete box girder with a typical span of 52 m to 64 m and it will be cast with a mobile scaffolding system. The most remarkable aspect of the design of the viaduct is its anti-seismic conception, due to the high seismic risk of the region. On the final structural seismic design the applied bridge bearings, hydraulic dampers and railway expansion joints have special influence on the entire system performance, i.e. effectively reduce the longitudinally acting forces while still controlling and limiting the deck displacements.

2. General design remarks

2.1 Seismic spectrum

The seismic design spectrum was determined from a series of studies conducted by the National Autonomous University of Mexico (UNAM) in collaboration with IDEAM [1] (Fig. 2).

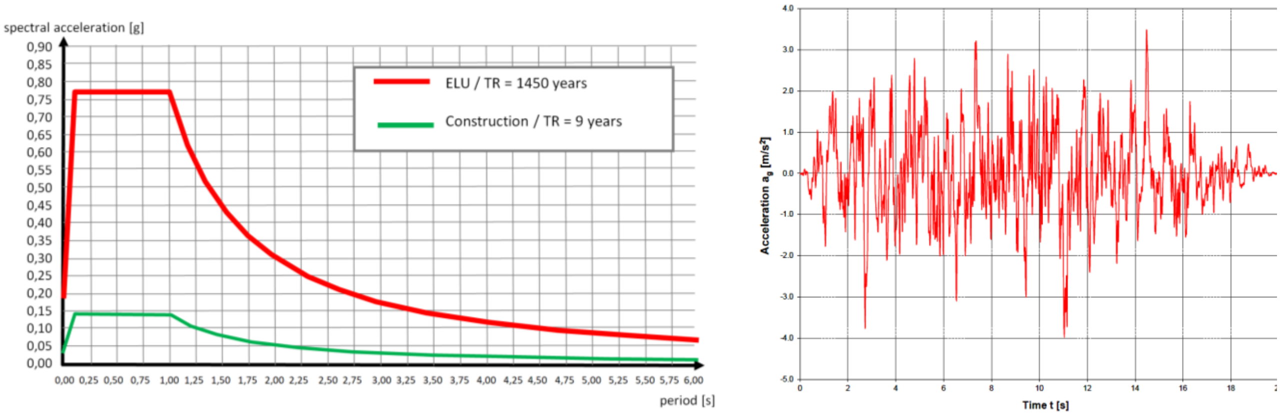


Fig. 2 – Response spectrum for 1475 years and 9 years return period and artificial accelerogram [2]

Considering the great importance of the structure a return period for the determination of the design spectrum of 1475 years – also declared to be the MCE event - has been considered. The design spectrum has a max. acceleration of 0.77 g when reaching the spectrum plateau at a period of 1 s. A seismic spectrum for the construction phase with return period of 9 years has also been defined (Fig. 2). For seismic structural calculation the European Standard EN1998-2:2005 was applied.

2.2 Deck design

The final design of the deck is a concrete box section with two railway tracks on top (Fig. 3).

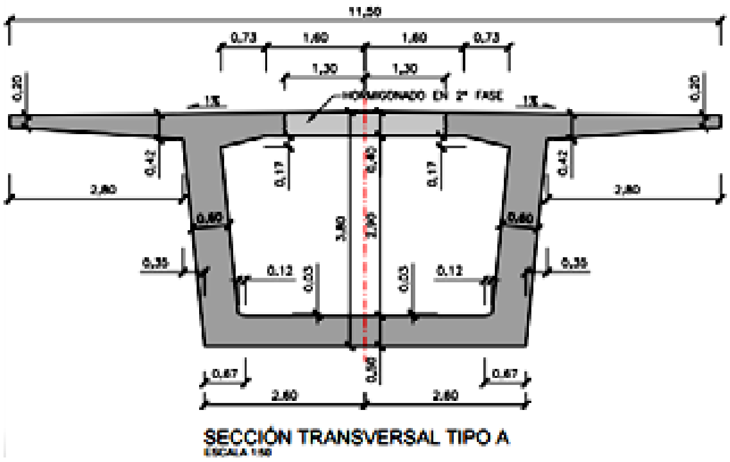


Fig. 3 – Section of concrete box deck [2]

The construction of the deck is done by self-supporting formwork which has been applied the first time ever in Mexico. This procedure allows independency of the terrain despite to very steep slopes within the terrain and numerous crossing streets underneath the viaduct. In addition the deck is resting on a significant height level above ground.

2.3 Pier design

The piers are up to max. 65 m and in average 30 m tall. The typical top view section is shown in Figure 4.

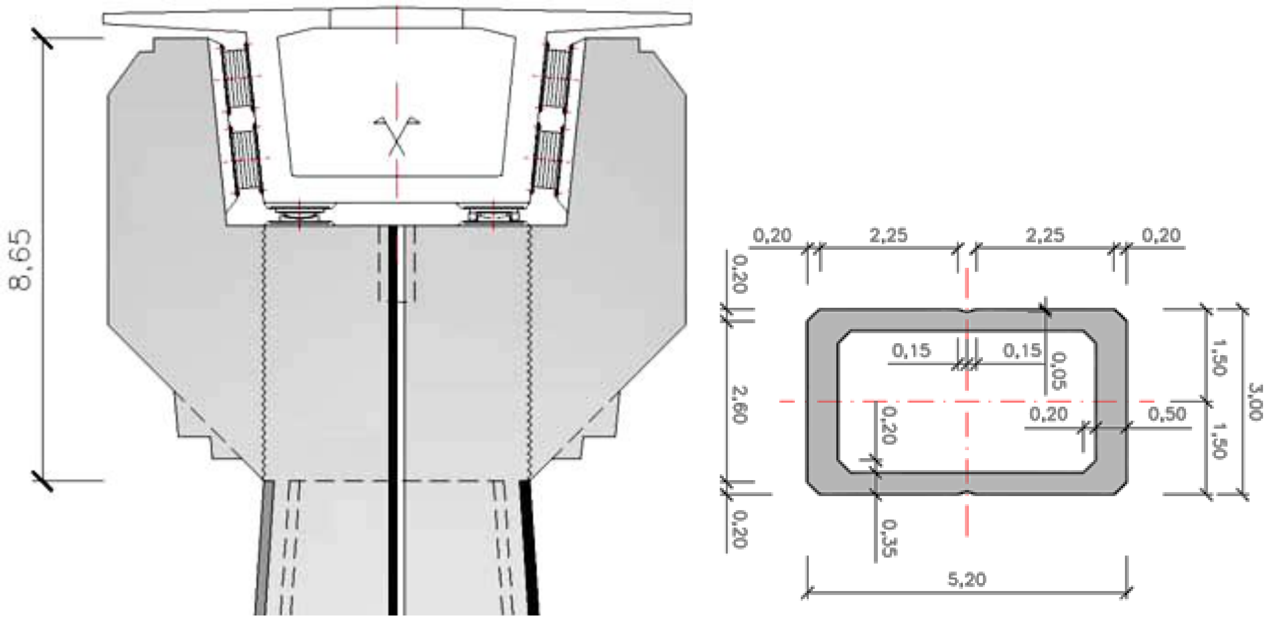


Fig. 4 – Typical longitudinal view and lower footprint of piers [2]

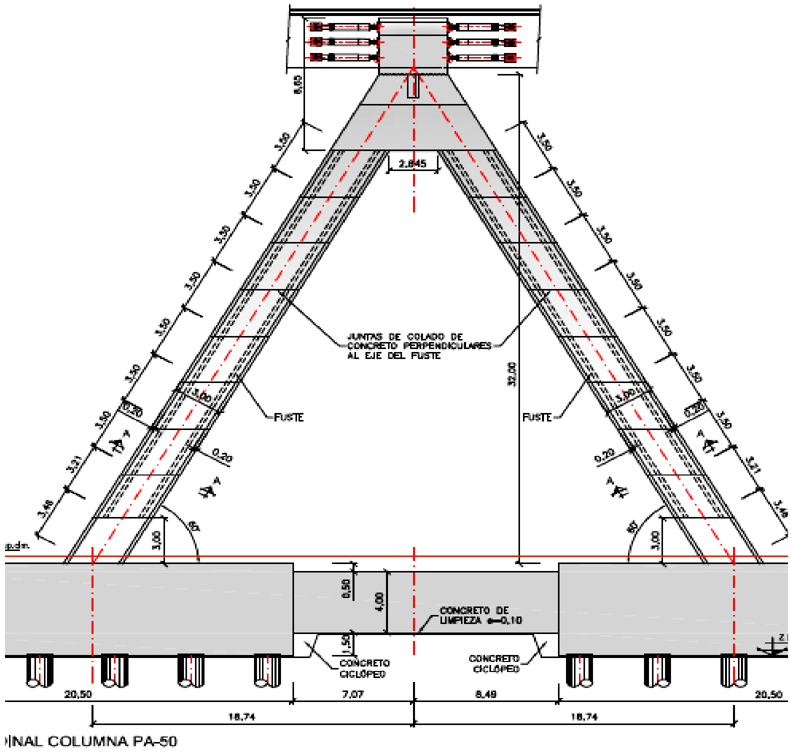


Fig. 5 – Lateral view on typical delta-pier [2]

The pier caps get fitted after deck construction with additional lateral concrete guide buffers (Topes) shown in Figure 13. On the intermediate sections V2-2, V2-3 and V2-4 one max. 40 m tall delta-shaped pier is marking the strong fixed central axis (see chapter 3.2) transmitting the main part of the longitudinal forces (Fig. 5).

3. Bearing, damper and expansion joint system

In general the bearing, damper and expansion joint system under and within the bridge deck offers specific functions for service and for seismic load cases in longitudinal and lateral direction. The system is able to provide thermal flexibility, lateral guiding, lock-up for service impacts and certain movements combined with energy dissipation for the earthquake to achieve a long isolation period with significantly decreased accelerations entering into the deck and piers. Therefore continued functionality will be ensured even after the maximum seismic events and EN15129 for Anti-seismic Devices was considered.

3.1 General performance of the deck in relation to the ground

To achieve a significant reduction of forces by factor three to five acting due to seismic impacts on the deck, piers and foundations, the deck was decided to be longitudinally isolated allowing up to +/-300 mm displacements between deck and pier caps or abutments respectively.

The displacement control will be provided by viscous dampers and the system re-centring from elastic rubber springs (see chapter 3.2). Any other isolator systems with sliding pendulum bearings or even lead rubber bearings create on all axes the re-centering and damping forces. For this specific project the re-centering and damping forces were desired because of partly bad ground conditions to be concentrated at certain locations and not shared to all single piers. The damper and re-centering forces were shifted to the specifically selected axes, which are the abutments and the delta piers (Fig. 5), able and especially designed to transmit the longitudinal forces. The regular piers - due to bad soil conditions – were not able to transmit longitudinally more than 1-2% sliding friction forces acting in the foreseen spherical sliding bearings.

The designers and the Mexican SCT (Secretaria De Communicaciones Y Transportes) specified to guide the viaduct deck in lateral direction while not allowing significant isolation movements. Thus the deck was decided to be laterally guided and more or less rigid. This was achieved by guided spherical bearings, which in addition provide the required vertical load capacity (see chapter 3.3) for service and max. vertical seismic effects.

3.2 Longitudinal system function

For the purposes of the longitudinal earthquake, each of the five continuous deck sections of Viaduct 2 behaves independently. It is typical for this railway viaduct that for each section a fixed axis was selected to transmit braking and rheological forces. The other axes and piers are then not transmitting these forces anymore, which results in savings for the piers and foundations. These fixed axes also resist the forces due to earthquake load cases. For the first and last section of the viaduct - hereinafter referred to as V2-1 and V2-5 - the fixed axes have been placed in the abutments E-1 and E-2 while in the intermediate sections V2-2, V2-3 and V2-4 the fixed axes have been placed on delta-shaped piers corresponding to supports PA-18, PA-33 and PA-50 (Fig. 1). These delta piers have been positioned as much as possible in the center of the viaduct section but in some cases with a slight off-set depending on the characteristics of the topography and the crossing streets.

The longitudinal deck fixation for service braking and acceleration forces from the trains is provided by special viscous dampers on these relevant fixed axes (Fig. 6). These six to eight nos. dampers (Fig. 7) lock-up immediately for deck velocities of 1-2 mm/s and limit max. deck displacements to typically 5-10 mm required for service movements within railway bridges.

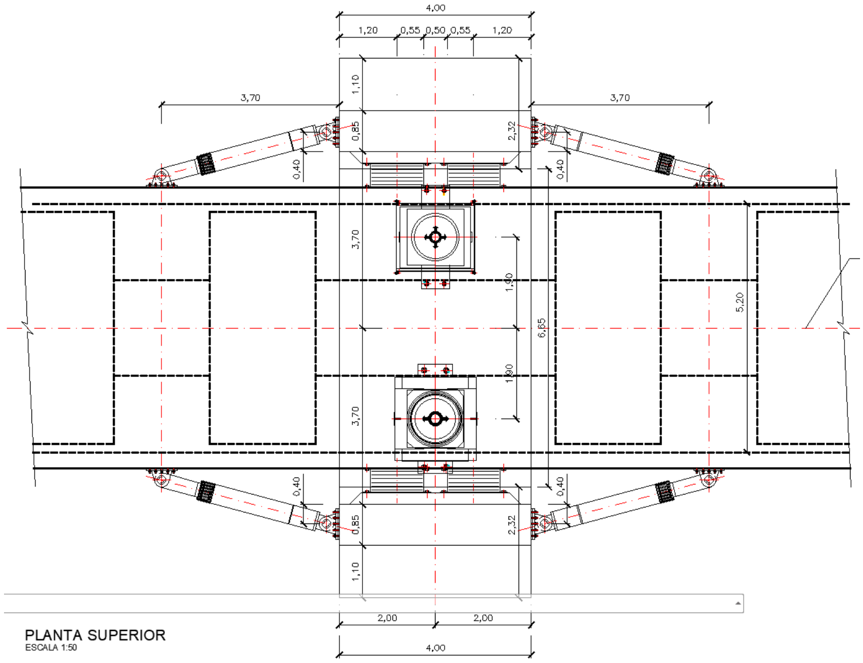


Fig. 6 – Top view on fixed delta pier axis with spherical bearing in centre, re-centring spring rubber bearings in parallel and viscous dampers [1]

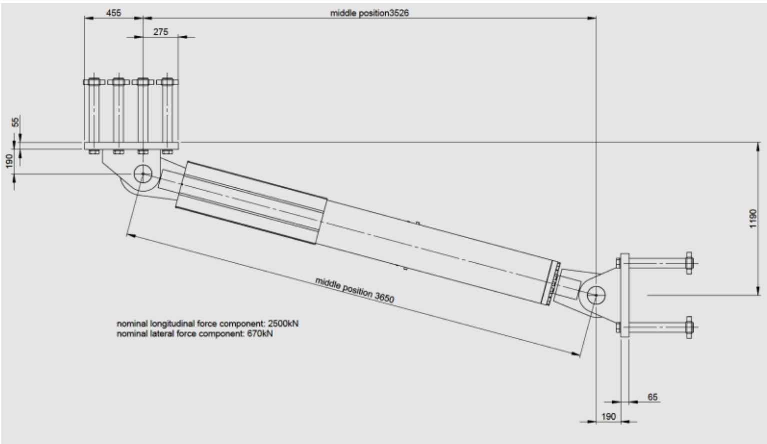


Fig. 7 – Viscous dampers with support brackets and concrete anchors at both ends to be bolted towards concrete

The specific lock-up behavior will retain the deck strictly in position for service braking or acceleration actions due to the small damping exponent alpha of 0.04, as already 80 % of nominal damper force (F_{AMORT}) level is achieved for 2 mm/s velocity:

$$F_{AMORT} = C\, v^{\alpha} \tag{1}$$

with F_{AMORT} = damper force

C = damping constant

v = velocity

α = damping exponent = 0.04

The max. seismic longitudinal displacements will be effectively limited by energy dissipation with the same viscous dampers to approximately +/- 266-294 mm and related velocities of 610 mm/s (Fig. 8).

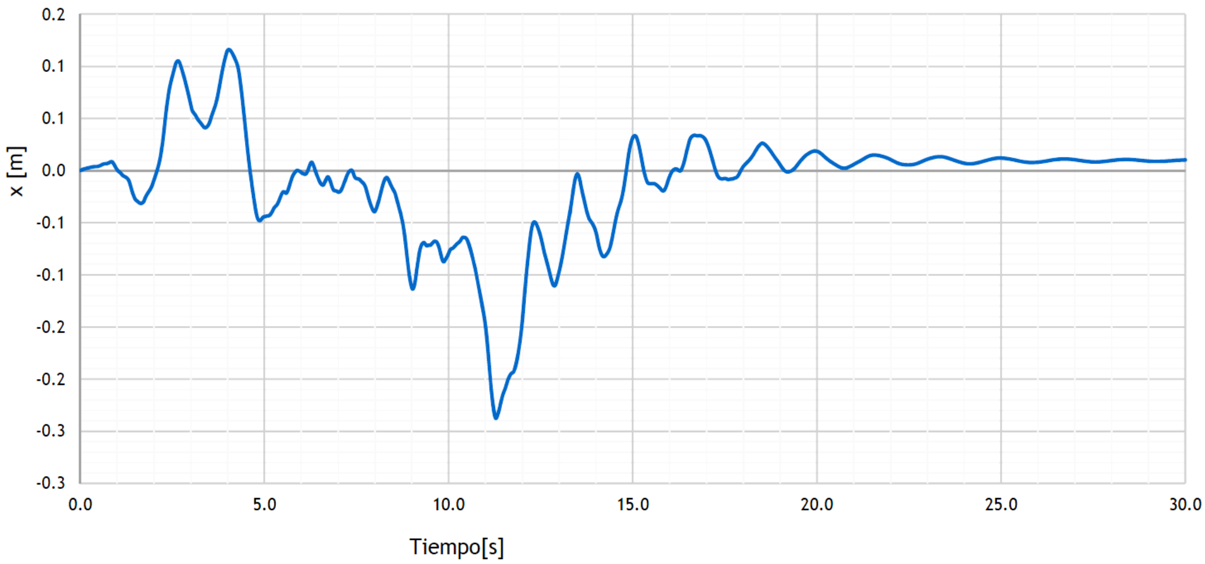
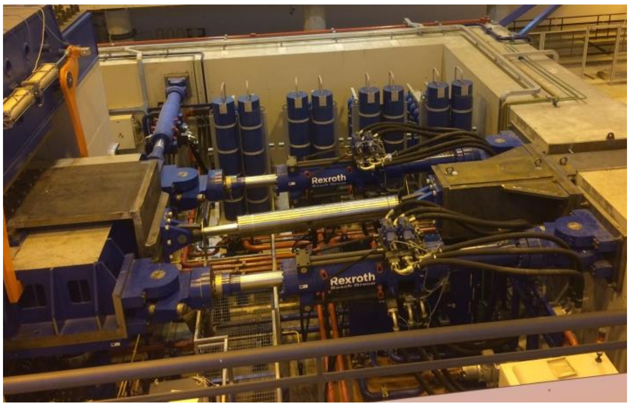


Fig. 8 – Time history displacement-time-plot for seismic movement of section V2-1 [6]

The compression stiffness of the inner fluid of the damper is in the range of max. 3 % of the displacement capacity. In case 500 mm displacement capacity in mid position is considered the elastic movement of the damper will be max. 15 mm until the maximum design force level gets activated. Thus the stiffness for a 3,000 kN damper is:

$$K_{AMORT} = 3{,}000 \text{ kN} / 15 \text{ mm} = 200 \text{ kN/mm} \tag{2}$$

These devices provide a high grade of energy dissipation when the defined nominal threshold force for fixation and positioning of the deck will be exceeded. The performance was tested full scale at the testing institute in Messina/Italy according to EN15129 (Fig. 9).



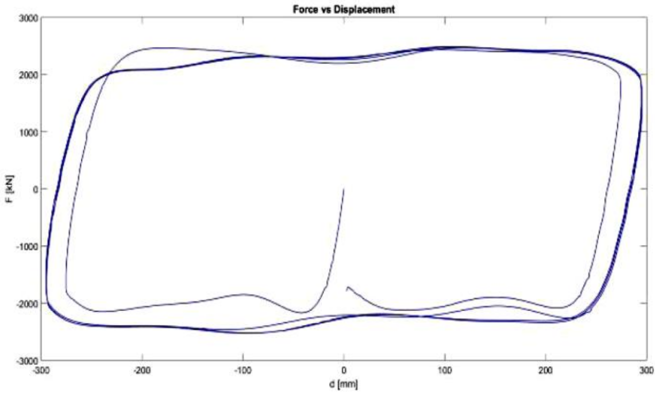


Fig. 9 – Viscous damper in test rig in Messina and force-displacement-plot of test with 610 mm/s [3]

For reliability the factor of 1.5 recommended by EN1998 was applied on the displacement of the dampers calculated for MCE event, i.e. the seismic design displacement was considered to be +/- 450 mm. The damper forces are always in relation to the deck relative displacements what is shown in Fig. 10. The total dampers forces of 6-8 nos. single units were chosen to be in the range of 24,000 kN to 30,000 kN (blue marked area in Fig. 10), as these forces provided the best reduction of displacements (250-300 mm) and accelerations in combination with still economical viscous damper sizes and amounts.

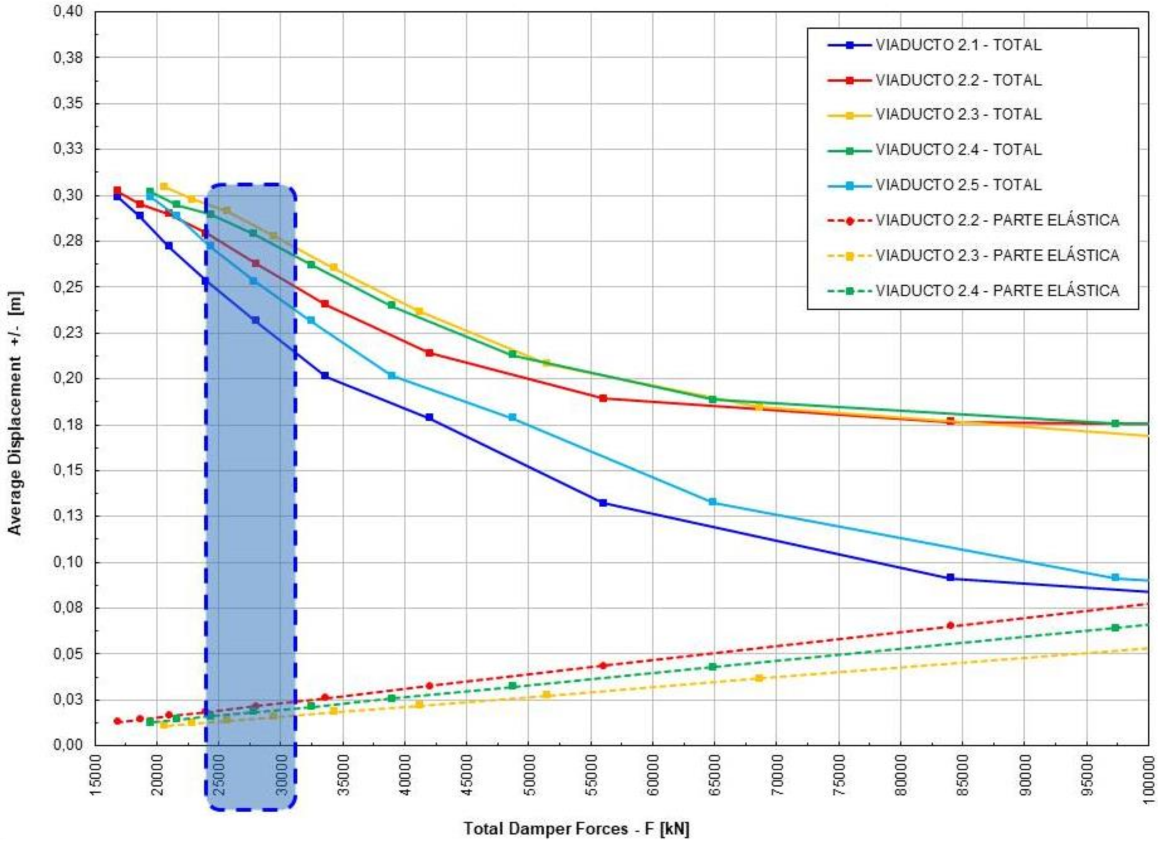


Fig. 10 – Plot showing longitudinal deck displacement relative to piers related to damper forces [1]

The re-centering of the system (Fig. 11 & 12) will be provided only on the fixed axes of each section with additional springs.

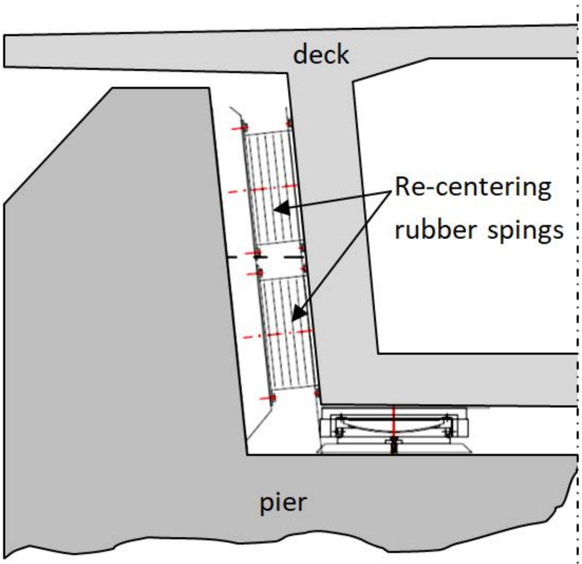


Fig. 11 – Arrangement of re-centering rubber springs on fixed axis between deck an pier top concrete buffers; sample on top of delta pier [6]

These springs are realized by a set of 6-8 nos. vertically arranged shear deforming rubber spring isolators with up to 1,150 x 1,150 mm footprint and 300 mm to 500 mm height. These springs accommodate up to 500 mm by shear deformation while pushing back the deck during and after the earthquake in mid position.

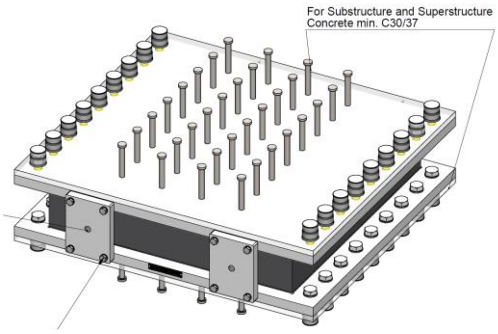


Fig. 12 – Shear deforming rubber springs [5]

The stiffness of each specifically designed set of springs on the fixed axes is 25,000 kN/m to 32,000 kN/m providing approximately 12,000 kN max. re-centering forces to each of the single deck sections shown in Fig. 1. During the construction phase the deck structure cannot be connected to the viscous dampers as the construction method is not enabling this. The longitudinal earthquake movements are controlled exclusively by the elastic re-centering rubber spring isolators. This is acceptable as the 9 year return period will be applied for the earthquake and not the 1475 year spectrum.

The deck is set onto two longitudinally spherical sliding bearings per axis (Fig. 13) to mitigate seismic accelerations.

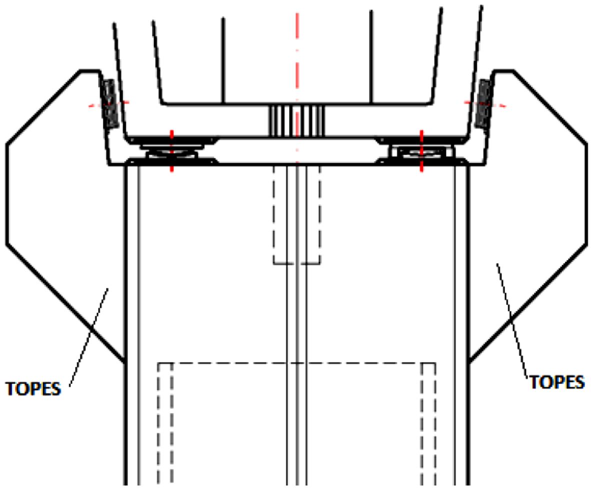


Fig. 13 – Typical pier section with view in longitudinal direction [2] and positioned spherical bearing [5]

The capacity of each bearing is 15,000 kN dead load and 29,000 kN max. load considering the vertical seismic impacts. When sliding the bearing induces very low dynamic friction of 0.3-1 % and 1-2 % static friction. Together with the re-centering spring isolators and the viscous dampers the deck period has been shifted towards 3 s while the total longitudinal base shear is in the range of 10 % only. This design philosophy and to concentrate the damper and re-centering forces to one fixed axis only, reduces significantly the longitudinal forces acting on the remaining piers. Consequently this allows a very slender and economical structural design.

The spherical bearing type is fitted with a highly wearing and stress resistant sliding liner called MSM® granting at least 50,000 m of accumulated sliding path with a minimum of 50 year service life time. Compared to regular PTFE (Teflon®) equipped pot bearings, their sizes are 30 % to 40 % smaller and allow a more economic and slender pier design. In addition the applied spherical bearings enable free and unrestrained horizontal rotation capability of up to +/- 0.02 rad.

The time history analysis was carried out with the below model considering the system performance parameters in Fig. 14.

This model is considering:

K_{CLOMNA}	=	pier/substructure stiffness
K_{FLUIDO}	=	fluid stiffness within viscous damper
C_{AMORT}	=	damping constant of viscous damper
α	=	damping exponent
$K_{RECENTRADO}$	=	re-centering stiffness of rubber spring isolators
M_{TBLERO}	=	mass of deck

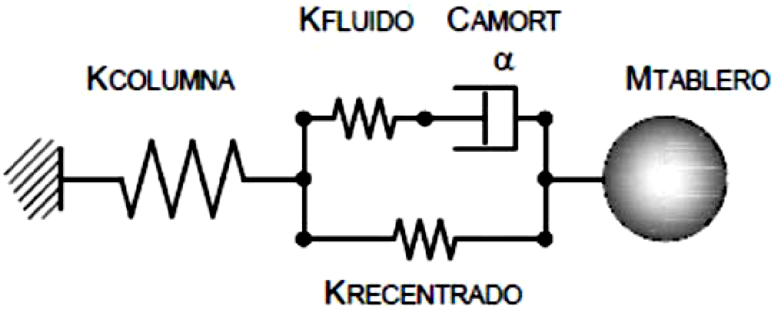


Fig. 14 – Model of deck with viscous dampers and springs for dynamic analysis [5]

The low sliding friction of less than 1 % within the sliding spherical bearings was not considered on the safe side for energy dissipation at all, even if this friction occurs.

Between the single deck sections from V2-1 to V2-5 and at the abutments specific railway expansions joints called guided *Cross Ties* were applied. These must bridge and compensate creep, shrinkage, thermal and seismic movements of max. 900 mm without damages to the structure and the rails (Fig. 15).

Fig. 15 – *Cross Tie* joint between single sections allowing longitudinal displacements with lateral, torsional and vertical off-set

With the guided *Cross Tie* a bridging system was developed which ensures that the spacing between the sleepers will not exceed the permissible value while being free of constraints. This system can accommodate any structural rotations and even slight vertical deflections (Fig. 16) which can be fully compensated by the joint. The *Cross Tie* is watertight and fulfills the requirements of the German Railway Authority EBA.

The firm, monolithic anchoring to the structure avoids up-lift, is suitable for up to 250 kN wheel loads and operates well for train velocities up to 350 kM/h.

The proper function, stability and durability for at least 50 years of service life span was dynamically tested at the Institute LSL and the University Munich with full train load on top (Fig. 17).

Fig. 16 – *Cross Tie* enables longitudinal displacements combined with lateral, torsional and vertical off-set

Fig. 17 – Dynamic full scale test of *Cross Tie* expansion joint

3.3 Lateral system function

The general design philosophy has been to fix the deck in lateral direction and not to allow any seismic or service movements greater than 5-10 mm.

One of the two sliding bearings on each pier has got a lateral restrainer guide system to lock lateral displacements while accepting longitudinal ones (Fig. 18).

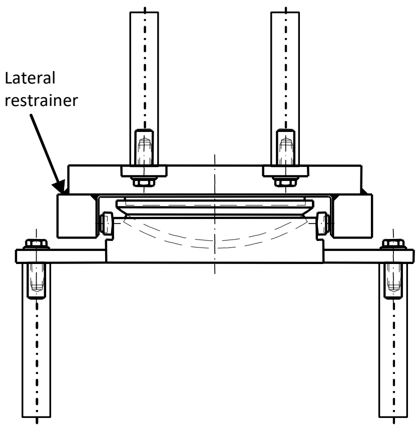


Fig. 18 – Spherical bearing guided with lateral guide restrainer; view in longitudinal direction [4]

The lateral restrainer has been designed to resist the 9 year return period earthquake during construction phase with up to 5,100 kN in lateral direction per pier. After the deck will be finished the lateral concrete buffers (= Topes in Fig. 13) will be added. Between these concrete buffers and the deck some sliding rubber bearings will be placed to avoid concrete sliding on concrete. These buffers transmit up to 18,000 kN corresponding to the MCE earthquake for 1475 year return period. Thus in case these forces occur the lateral guide restrainer of the spherical bearings will slightly start to yield by 5-10 mm until the external concrete buffers get activated. After this event the bearing restrainers have to be refurbished.

4. Conclusions

Long railway bridges in seismic zones like the Viaduct 2 of Toluca-Mexico City Intercity Train require careful investigations on displacements, forces and vertical loads acting within the deck/pier/abutment system. The key to success is to create a technical solution working for service and for seismic load cases with reasonable and acceptable economic impact.

It has been shown for this project with significant earthquake hazard that it is possible with a combination of available bearings, springs, viscous dampers and expansion joints to decrease service and seismic displacement combination to max. +/-450 mm. The forces onto the piers were significantly reduced by up to factor three to five in longitudinal direction and at the deck section ends any occurring movements were entirely compensated to avoid derailing of the train due to seismic motions.

After the MCE earthquake with declared 1450 year return period the bridge is still ready to be overpassed and continued functionality is ensured.

The proposed system has a service life time of at least 50 years, what was proven by European Technical Approvals for materials and long term dynamic fatigue testing.

5. References

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