Seismic Protection of the Basarab Overpass in Bucharest

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SUMMARY:
The paper describe the application of seismic protection to the Basarab overpass situated into the town of Bucharest.
The link is mainly composed by a steel arch bridge of 122 m length and a stay cable bridge of 360 m length and 42.5 m width, beside the access and connecting viaducts.
Because of the very particular seismic response spectrum, most of the viaducts are completely isolated and it represents up to now the state-of-the-art for the design and use of seismic devices. The viaducts are isolated using Lead Rubber Bearings up to 11000 kN vertical load, pot and spherical bearings up to 65000 kN coupled to viscous dampers up to 3750 kN and hysteretic devices up to 1750 kN of reaction force.
Particular attention has been done to the expansion joint system that has to allow movements in both directions due to the complex layout of the bearings.

Keywords: Seismic Isolation, Lead Rubber Bearings, Viscous and Hysteretic Dampers

1. INTRODUCTION

The Basarab overpass, situated near the "Gara de Nord" railway station in Bucharest, allows to speed up in a very efficient way the road condition of that area, that was previously very penalized by the presence of the railway and by the Dambovita river. Other possible solutions were proposed, like the construction of a new railway station close to the existing one in order to leave space for a new road gaining ground from the existing railroad. The overpass solution prevailed and the beauty and the effectiveness of this job convince on the fact that it was a suitable choice.

Figure 1. Overview of the Basarab Overpass

The new link, an investment of about 120 million euros, consists of several structures. From south, an access approach called SP1-PS1 of about 160 m raises up to the road level where a steel arch bridge of 122 m length crosses the river Dambovita and then carry on with a viaduct (PS2-PS4) of 790 m to reach the railroad in front of the “Gara de Nord” station. It is bypassed with a stay cable bridge of 360 m length and 42.5 m width. The towers of the stay cable bridge raise to a height of 80 m that are visible from many parts of the town.

The Basarab overpass hence has an overall length of about 1.5 km and is completely built with seismic isolation criteria. In addition to the technical and road condition aspects, the structure is appreciable also by the aesthetic point of view being placed inside the town, the three types of structure composing it, are joined in an absolute harmonic way.

The structure, completely realized by the joint venture contractor Astaldi-FCC with work starting in 2006 and the bridge opening to traffic in June 2011, was designed for the final stage by three important Spanish and Italian designers. The arch bridge and southern approach structure SP1-PS1 was designed by Fhecor Ingenieros Consultores from Madrid; the connecting viaduct PS2-PS4 by Italian consultant C&T Engineering from Treviso and the cable-stayed bridge by Carlos Fernandez Casado, also from Madrid.

2. THE SEISMIC ACTION

The Bucharest response spectrum, that defines the seismic action, is very particular due to its shape characterized by a wide constant branch with the maximum acceleration up to a period greater than 1.5 seconds. The figure 2 shows a comparison between the response spectra of Bucharest given by the 1992 seismic Rumanian standard P100-92, the one given by the most recent 2006 version of the same Rumanian standard and the response spectrum for the same type of ground and the same base acceleration given by the European standard (Eurocode 8).
This leads to high accelerations that are possible to reduce only applying the seismic isolation techniques, moving the natural frequency of the structure up to 3 seconds and dissipating a lot of energy.

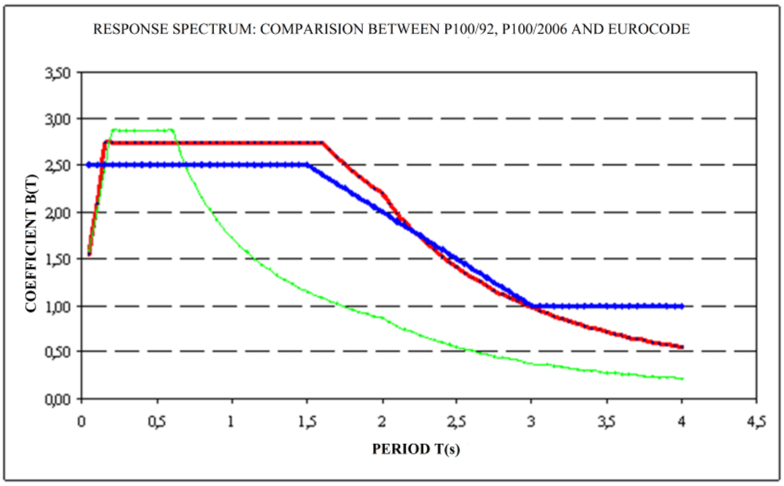


Figure 2. Comparison between response spectra of Bucharest given by P100-92 (bleu), P100_1/2006 (red) and Eurocode 8 (green)

With a such response spectrum appears the problem to obtain limited acceleration, and hence limited forces on the top of the piers, having at the same time displacements not too big. The solution adopted in the Basarab overpass consisted of coupling devices able to increase the natural frequency of the structure until an acceptable level of acceleration was reached and devices able to increase the energy dissipation, in order to reduce the ordinate of the response spectrum. The devices applied on the viaduct were “isolators” and “dissipation devices”.

The “isolation device” indeed is an apparatus that allow the application of vertical and horizontal loads, movements and rotations during service conditions (practically the isolators also behave as a structural bearing). In case of earthquake it allows to uncouple the structure movements by those of the ground permitting very high movements and carrying to a consistent reduction of the applied seismic forces. This is possible thanks to the changing of period of vibration that is obtained forcing the structure to move according to the “isolated frequency” instead of the “natural frequency”. In order to limit the value of such movements, some dissipation systems are used. They can be integrated into the isolator or can be alone increasing the overall dissipation of the structure. The dissipation device installed alone does not cover the characteristic of carrying the vertical load, hence it has to be installed in parallel to classical bearings or other isolators.

3. THE ISOLATION SYSTEM

The high loads due to the earthquake strength characterized by a such hard response spectrum and the heavy presence of underground service lines, carried to change the initial “not isolated” design into a new design that used the isolation criteria. In Romania was not the first time that isolation was applied, indeed another bridge, the Olt-Hoghiz river bridge applied isolation with pot bearings coupled with hysteretic dampers to obtain a multi-directional hysteretic device supplied by Alga (2001), but for sure the application of the isolation on the Basarab overpass is relevant for importance of the viaduct and for the great variety of isolator types applied.

The initial design of the whole viaduct, during the tender stage, was commissioned to the Italian consultant C&T Engineering, while after the design of the structure was divided among the three designers above mentioned.

The strategy of the seismic isolation was applied in different ways in the various parts that form the Basarab complex. The viaduct, indeed, is divided into five sections, each of them has bearings and isolators of different type.

3.1. Stay Cable Bridge

The stay cable bridge connecting the pier PS4 to the abutment SP2 is isolated only in longitudinal direction. The figure 3 shows the layout of the bearings and isolation system applied.

In transversal direction the seismic action is rigidly transmitted from the steel deck to the substructure through shear keys. They are composed by a very rigid steel frame hanging from the deck and laterally restrained by concrete blocks connected to the piers. Between the steel frame and the concrete blocks, sliding pot bearings are interposed. They are vertically installed and have sliding surface in PTFE in order to allow the longitudinal movements of the deck. This type of bearings was proposed as an alternative to the initially thinking of installing spherical bearings because the horizontal load to transfer from the deck to the pier was very high, up to 65000 kN, and it was not possible to transfer it using a single bearing with the allowable space. Dividing the force on more than one spherical bearing, in case of rotation in the plane, can cause an overload of some bearings with respect to the others. Pot bearings allow to avoid such a risk, the rotation element being made by an elastomeric disc confined into a steel pot plate. On the two ramps the vertically installed pot bearings are replaced by laminated elastomeric bearings with sliding plate even in PTFE.

The deck is installed on a series of free sliding pot and spherical bearings which near the intersection with the ramps also work as anti-lifting devices, thanks to a structural system that allow to the bearings to resist to traction forces even if they work only in compression. Indeed, a special structure hanging from the deck is interposed between two spherical bearings, both working in compression, connected to the pier. One spherical bearing is able to carry only the downwards vertical load and the other one only the upwards vertical load. This system have the characteristic to maintain the two bearings always in contact, allowing also to the bearing to carry the uplift force also in service conditions even if rotations of the deck are present. In order to obtain this, a system for the vertical adjustment was needed. Alga designed and supplied a wedge system coupled to the bearings that allows to simply act on a threaded locking ring for adjusting vertically the position of the two bearings, ensuring that they are perfectly in contact and allowing easily any future replacement or maintenance on them. The figure 4 shows the described structural system. Moreover, also the two continuous decks of the access ramps on the side of Calea Grivitei due to their geometry and slope produce uplifting loads on the abutments in service conditions. For this reasons, also in these positions pot bearings able to resist to uplift forces were installed. Here, unlike near the towers, the bearings have the anti-lifting system inside itself allowing equally rotations with tensile forces during service conditions.

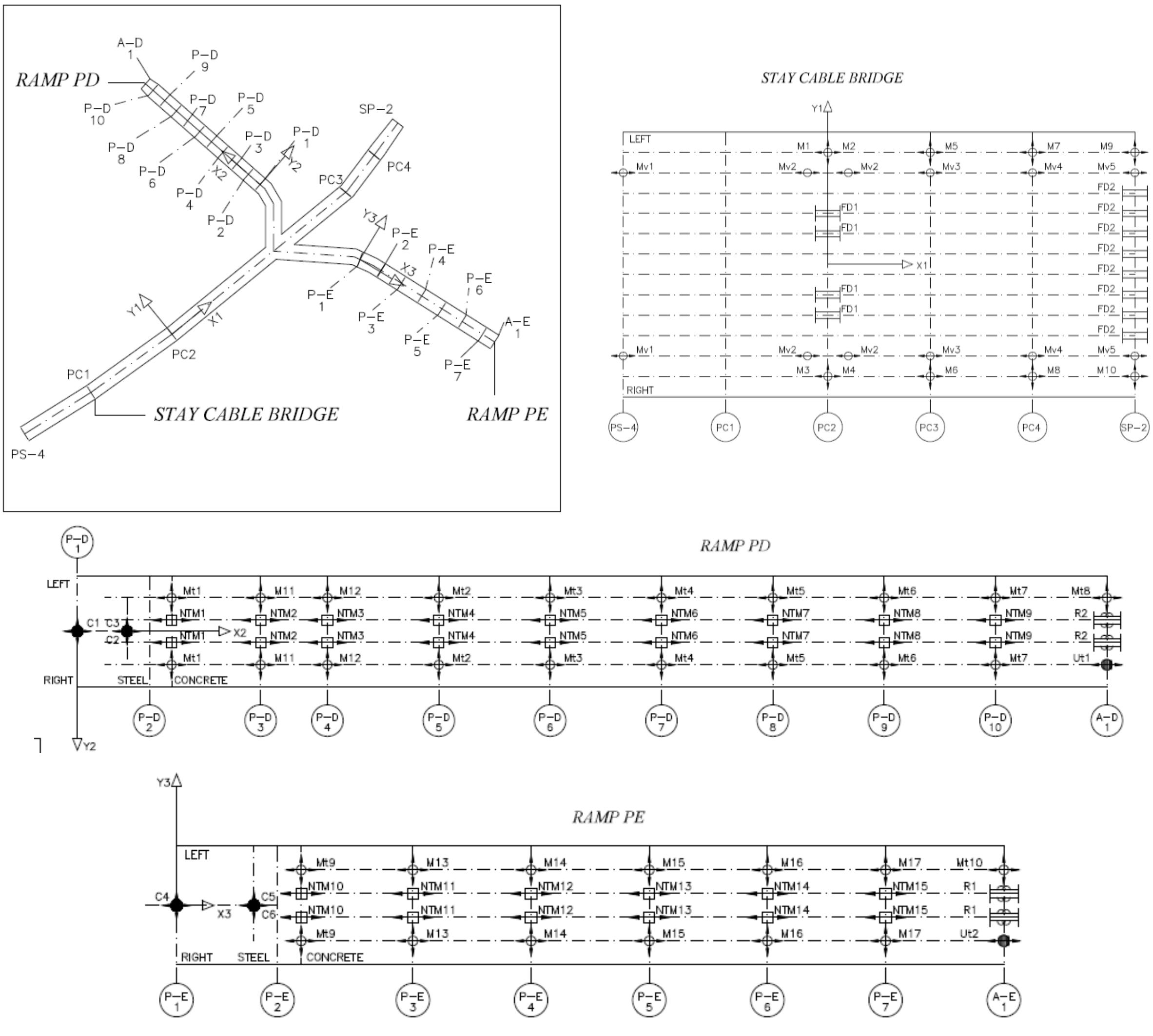


Figure 3. Bearing layout stay cable bridge

The longitudinal restraint is made by a series of fluid-dynamic devices of two different types. The first one is installed on the tower and consists of a viscous dissipator with non-linear-velocity-dependent device provided with a mechanical fuse. It behaves as a rigid fixed point in all the service conditions and it breaks at a pre-determined value of force, above which it is free to move dissipating in this way the energy transmitted by the earthquake. The overall force of 10000 kN is carried by four viscous dampers, 2500 kN each with 500 mm of total displacement. The second type is installed on the abutment SP2 and, unlike the ones installed on the tower, it always freely allows service movements of the deck, like for example thermal expansion, while in seismic condition it is able to dissipate energy exactly like the previous type. The overall force transmitted to the abutment by the 8 installed devices of 3750 kN each with 550 mm of total displacement is of 30000 kN. The fluid-dynamic dissipation system indeed transfers a global force of 40000 kN.

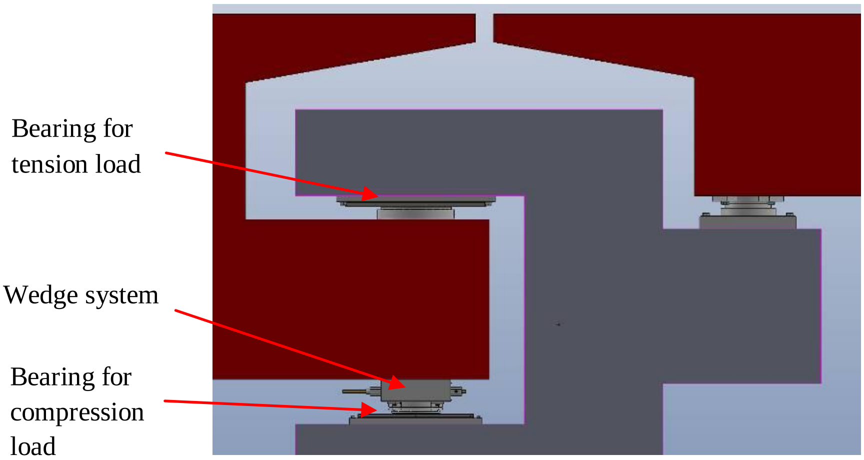


Figure 4. Spherical bearings coupled to carry both compressive and tensile vertical load

The non-linear law that characterize such kind of dampers has the expression of Eqn. 3.1, where F is the reaction force of the device, v is the velocity of movement during seismic conditions, C and α are coefficients that define the behavior of the device.

$$F = C \cdot v^{\alpha} \qquad (3.1)$$

These coefficients are conveniently chosen according to the response expected by the device, response that of course affect considerably the behavior the structure where it is installed. Indeed there are situations where it is better a coefficient α very small, for example α=0.02, in order to get the response of the structure practically independent from the velocity, simulating in this way the behavior of a hysteretic damper. In any case, using a viscous damper it is accepted that some delays in the response, due to the fluid compressibility, can occur. Otherwise it is preferred to limit the reaction forces for low values of the applied velocity and in this case is possible to adopt greater values of the α coefficient, like 0.2-0.3-0.4, like shown in the figure 5. Of course in order to maintain constant the force level into the device, the C coefficient has to be chosen conveniently. Both the types of viscous dampers installed on the stay cable bridge have the same coefficient α=0.2.

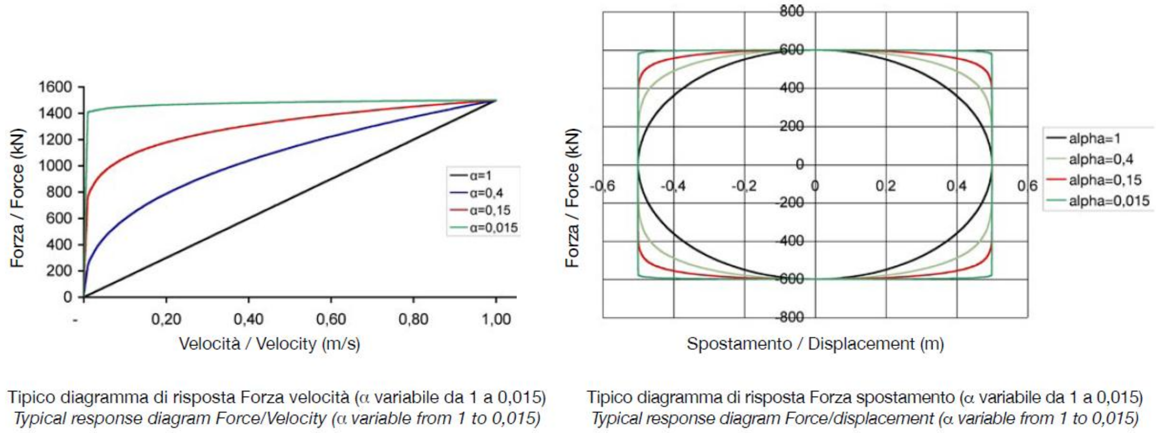
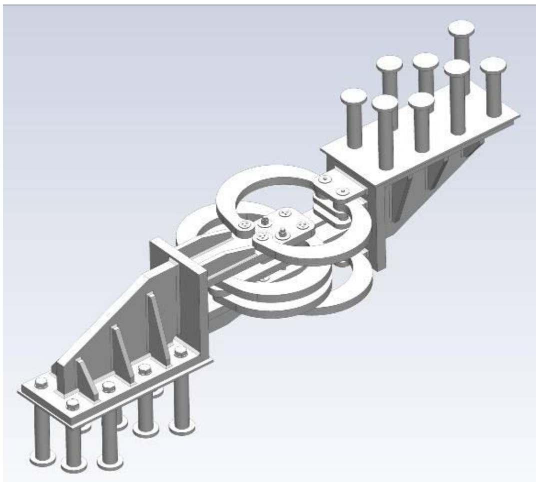


Figure 5. Comparison between device responses with different values of the coefficient α with α variable between 0.015 and 1: force-velocity and force-displacement diagrams

The two access ramps to the stay cable bridge were been designed according the same philosophy of the main bridge. Indeed the transversal forces are transmitted rigidly from the deck to the piers by means of shear keys hanging from the deck and allowing displacements by means of the interposition of sliding elastomeric bearings. The longitudinal forces are carried by two dissipators installed on the abutments, being also in this case the deck installed on free sliding pot bearings. The dissipators installed on the ramps are of a different type with respect to the ones installed on the stay cable bridge. Indeed in this case, even because of the limited space available, Alga proposed an alternative solution to the one originally forecast by the designer that consisted in viscous dampers. The proposed alternative solution, at the end accepted and installed on the bridge, suggested the use of hysteretic devices with non-linear-displacement-dependent behavior. The C-shaped steel elements that provide the hysteretic behavior, remain elastic under service conditions, being in this way the fixed point of the bridge. In seismic conditions they exceed the designed yielding threshold and plasticize dissipating the energy generated by the earthquake. The figure 6 shows the hysteretic device and its typical force-displacement behavior.



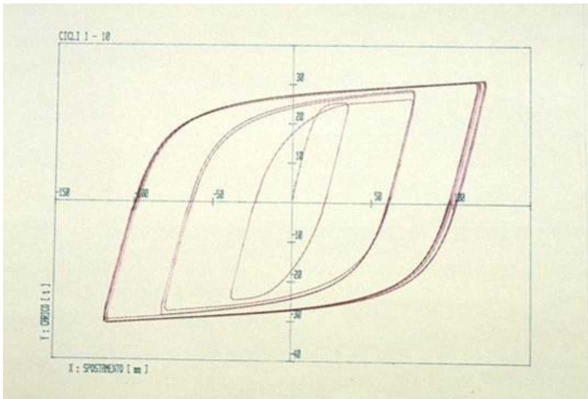


Figure 6. Hysteretic device installed on the ramps abutments and typical force-displacement loop

The stay cable bridge, beside being particular for the very complex bearings and dissipators layout, has also the peculiarity to accommodate above it the Basarab tramway station connected to the ground by means of an escalator system. A bearing system allows to the escalators to be fixed on the ground by means of fixed bearings while elastomeric sliding bearings support them at the level of the station. The maximum longitudinal displacement of the structure is 550 mm, so also these bearings allow the same movement forecast for the bearings supporting the deck. This expedient is very important because it allows to prevent damages to the non-structural parts in case of earthquake guaranteeing the serviceability of the structure on the whole.

3.2. Arch Bridge

The arch bridge (SP2-SP3) over the river Dambovita is a steel arch bridge of 122 m. The bridge is isolated in both longitudinal and transversal directions and it is supported by four lead-rubber bearings.

This kind of isolators, unlike the classical high damping rubber bearings (HDRB) contains one or more lead cores, that thanks to its characteristics to have a low yielding point but high ductility, allows to dissipate a lot of energy. On the other hand, the presence of the rubber, with the developed stiffness due to its elasticity, allows good re-centering capability to the device. The lead has the characteristic to re-crystallize at ambient temperature, so that it is able to efficiently sustain various earthquakes, without needs of replacement, because of the plasticization of the lead core due to the deformation. The lead-rubber bearings are therefore characterized by a bi-linear behaviour with first branch given by the stiffness of the lead core and second branch given by the stiffness of the rubber that start from the yielding of the lead core.

The lead-rubber bearings for the arch bridge have diameter of 1100 mm and are able to carry a vertical load up to 12600 kN in static condition and to allow a seismic movement of 270 mm being subjected to a vertical load of 14000 kN giving an energy dissipated per cycle of about 2225 kNm with a damping of 40 %.
Alga designed and supplied the isolators for the arch bridge according to the technical specification prepared by the designer and to the standard EN 1337 and prEN15129, even the latter at the time of the supply was not yet approved.

3.3. Access approach from South and connecting viaduct

The access approach from South connects the abutment SP1 and the transition pier PS1, that also is the abutment of the arch bridge. On the other hand, the connecting viaduct links the arch bridge from the transition pier PS2 (also abutment of the arch bridge) to the stay cable bridge at the transition pier PS4 (abutment of the stay cable bridge). Both the access approach SP1-PS1 and the connecting viaduct PS2-PS4 are supported by Lead-Rubber isolators.

The figure 7 shows the bearing layout and the isolation system for the more complex viaduct PS3-PS4 here described.

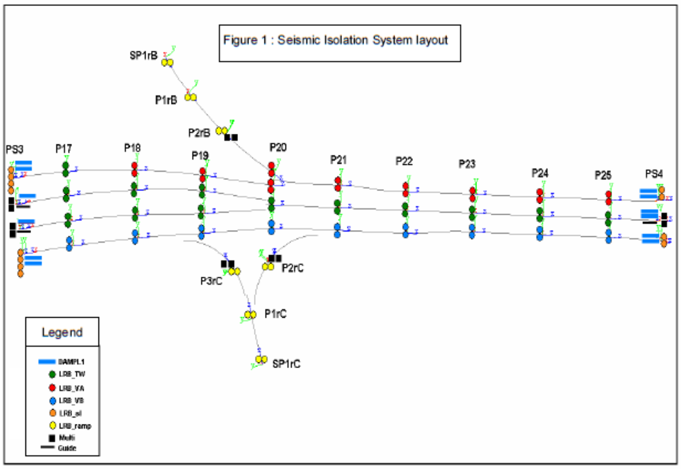


Figure 7. Bearing and isolation system for the link PS3-PS4

The lead-rubber isolators installed on the viaduct between SP1 and PS1 and between PS3 and PS4, unlike the ones installed on the arch bridge are provided by a particular system allowing the irreversible movements to take place without imposing any restoring forces. Indeed, a very important aspect to take into account is the construction procedure with the following cast-in-situ and post-tensioning operations, that should be subjected to restoring force as low as possible. In order to accommodate this requirement of the designer, Alga designed and supplied the lead-rubber isolators with a lower guided sliding plate, so that the irreversible longitudinal movement are able to take place but carrying the transversal forces. The figure 8 shows this LRB isolator with lower sliding plate. At the end of the construction phases a very simple and effective mechanical fixing system locks the isolator in the final position and starting from that moment, it can work with that undeformed condition.

On the viaduct PS3-PS4, in order to increase the energy dissipation in longitudinal direction, viscous dampers able to allow reversible movements, like the ones applied on the stay cable bridge, are installed on the abutment PS3 and PS4. On each abutments are installed 6 devices of 700 kN, giving a total force to each abutment of 4200 kN. For these devices, the designer requirement was a α

coefficient less than 0.02 in order to have a higher energy dissipation capacity and a behaviour less influenced by the velocity of the earthquake. Alga designed and supplied viscous dampers with coefficient α less than 0.02. The figure 9 shows the devices installed on PS3 and PS4.

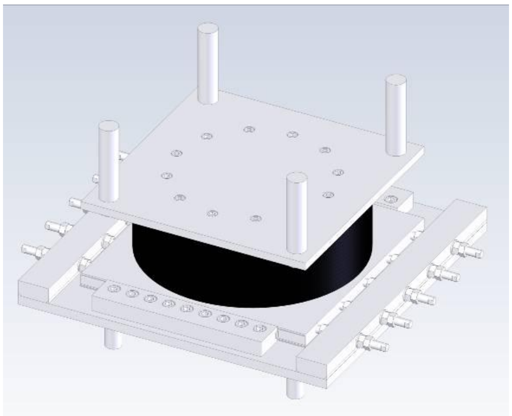


Figure 8. LRB with guided sliding plate able to allow only irreversible movements

Figure 9. Viscous dampers installed on the abutments PS3 and PS4

On the two ramps of the viaduct PS3-PS4 in order to increase the energy dissipation in transversal direction, the lead rubber bearings are coupled with hysteretic C-shaped elements with similar behaviour of the ones installed on the ramps of the stay cable bridge. The C-shaped elements are coupled in such a way that do not interfere with the longitudinal movement of the deck, but they activate dissipating energy only under transversal movement. The figure 10 shows the described device.

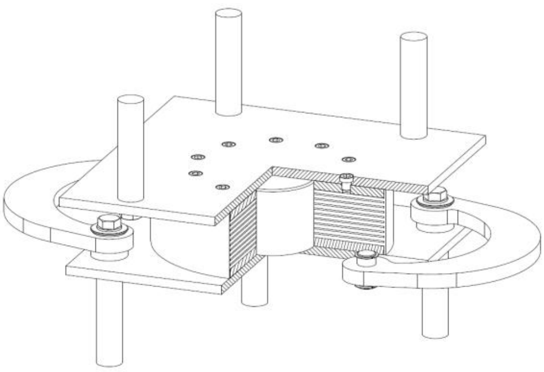


Figure 10. LRB coupled with transversal hysteretic C-shaped elements for the ramps of PS3-PS4

4. PERFORMED TESTS

The seismic devices on the viaduct were subjected to laboratory performance tests before the installation. Tests were performed at the Eucentre laboratory in Pavia and at the AlgaLab in Montebello della Battaglia (PV).

At Eucentre, European Centre in Training and Research in Earthquake Engineering, were performed tests on the viscous dampers FD 3750/550 installed on the stay cable bridge. The test protocol is based on the European standard on seismic devices prEN 15129, although it was not yet mandatory at the time of installation. Among the test performed, the most relevant are the Constitutive Law test and the Damping Efficiency test. The first one consists of three fully reversed cycles of axial displacement for five different velocities up to the maximum design velocity, that in this case was chosen by the designer in 600 mm/s. The aim of this test is to verify the damper's characteristic force-velocity curve, i.e. the parameters C and α. The second one consists of five fully reversed cycles of axial displacement at the frequency established by the designer with the aim to check the reaction stability and the energy dissipated. The figure 11 shows the viscous damper during the tests.

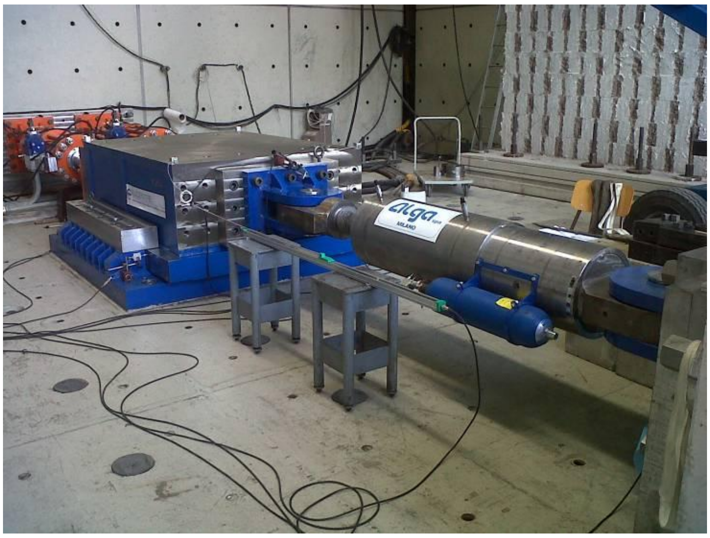


Figure 11. Viscous damper FD 3750/550 during the tests

The viscous dampers of 700 kN capacity were tested at AlgaLab with the witnessing of the Politecnico of Milano, and also for these devices the tests were performed according to prEN 15129, performing among the others the Constitutive Law test and the Damping Efficiency test.

At AlgaLab also the Lead Rubber Bearings installed on the PS3-PS4 viaduct were tested. Tests were performed according to prEN 15129 performing tests on the horizontal behavior in seismic condition, with the aim to check the displacement capacity, the horizontal effective stiffness and the energy dissipated.

5. EXPANSION JOINTS LAYOUT

The complex bearing layout of the viaduct requires particular attention also in the layout of the expansion joints. Indeed, the philosophy shared by the designers considers that they have to guarantee both longitudinal and transversal movements during the service life in order to accommodate thermal and irreversible movements, while during the earthquake some damages are allowed. In any case the expansion joints are designed to cover the gap even in case of earthquake with the aim to guarantee the viability of the emergency vehicles immediately after the seismic event.

The expansion joints installed on the Basarab viaduct are of two different types. The first one is made by reinforced rubber that allows both longitudinal and transversal movements. The second one is a steel modular joint with a fuse box to allow the come out of the joint during the earthquake, for displacements bigger than the service ones.

6. CONCLUSIONS

The Basarab Overpass in Bucharest collects bearings and seismic devices of different types. Here we find pot and spherical bearings up to 65.000 kN of vertical capacity and different systems to carry traction forces during service condition. The seismic devices here installed are of various type and size. There are Lead Rubber Bearings up to 12.600 kN vertical capacity and ±270 mm of seismic displacement together with a locking system able to allow the irreversible movements and Lead Rubber Bearings coupled with hysteretic C-shaped elements to increase the energy dissipation. Also we find hysteretic devices up to 1750 kN of longitudinal capacity and ±100 mm of seismic movement in both longitudinal and transversal directions. Finally we find viscous dampers with different load capacity up to 3750 kN and 550 mm of longitudinal movement and different non-linear-velocity-dependent laws with coefficient α varying from 0.015 and 0.2. Moreover, the viscous dampers installed on the tower are provided by fuse restraints to carry rigidly loads in service conditions.

The Basarab overpass, in addition to be the most important construction up to now in Romania, is the state-of-the-art for the design and use of seismic devices due to the wide range, for type and quantity of seismic devices installed.

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