Seismic isolation of continuous bridges through curved surface sliders combined with shock transmission units

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SUMMARY:
This paper presents a combined anti-seismic device able to diversify its performance in case of service or seismic input, to be used in long continuous bridges to reduce the horizontal forces transmitted to the substructure under service conditions while at the same time to benefit by the advantages of seismic isolation. The proposed device is based on the combination of Curved Surface Sliders (CSS), flat sliding surfaces and Shock Transmission Units (STU). In particular, the flat sliding components, characterised by a very low friction coefficient, are activated only during service conditions, while any seismic motion will benefit from the curved surface isolator. The STUs provide the dynamic connection between flat and curved components of the isolator: under an earthquake the STUs become stiff and the CSS is activated, thus dissipating energy and ensuring the re-centring effect according to its force vs. displacement curve.

Keywords: seismic isolation, bridge, curved surface slider, friction isolation pendulum

1. INTRODUCTION

The design and construction of continuous bridge decks of significant length and located in high seismicity areas raised in recent years difficulties never experienced before. For instance, due to the extensive length of the deck (e.g. greater than 500 m), the bridge can experience during service life large permanent deformations induced by creep and shrinkage as well as transient thermal deformations in the order of hundreds of millimeters. These service displacements can be of the same order of magnitude of the movements induced by earthquake in seismic isolation devices, i.e. hundreds of millimeters, and this could result in a similar level of forces transmitted to the substructure in service and seismic conditions. In the extreme scenario of very long continuous decks and moderate seismicity, the forces transferred by the isolators during the service conditions could significantly exceed the seismic actions.

This paper presents a solution developed for the above mentioned scenario, i.e. a combined device able to diversify its performance in case of service or seismic input.

2. CURVED SURFACE SLIDERS COMBINED WITH SHOCK TRANSMISSION UNITS

The proposed device is based on the combination of a curved surface slider, a flat sliding surface and two shock transmission units.

Curved Surface Sliders (CSS), also known as friction pendulum isolators, are manufactured and used in USA since 1990 [Christopoulos & Filiatrault, 2006]; their manufacture and use in Europe is more recent [Castellano & Infanti, 2010]. 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 respectively in Figures 1 and 2 both in centred position and at their maximum displaced configuration.

CSS has a main sliding surface (at the bottom in Figure 1) providing energy dissipation through friction and restoring force, and a secondary sliding surface 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 as well as of the rotations. 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 movement the structure is designed for; consequently the space in plan required to accommodate the isolator is considerably reduced. In both variants the sliding surfaces consist on one side of an appropriate high-strength thermo-plastic material (UHMW-PE) and on the other side of mirror-polished stainless steel. In the combined anti-seismic device described in this paper, the curved surface slider can be with single or double curvature, but in the following the example with double curvature is discussed (Figure 4).

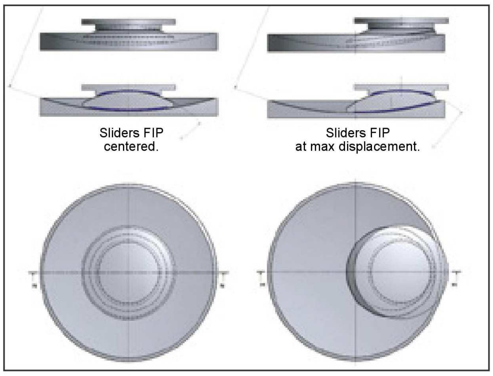

Figure 1. CSS configuration.

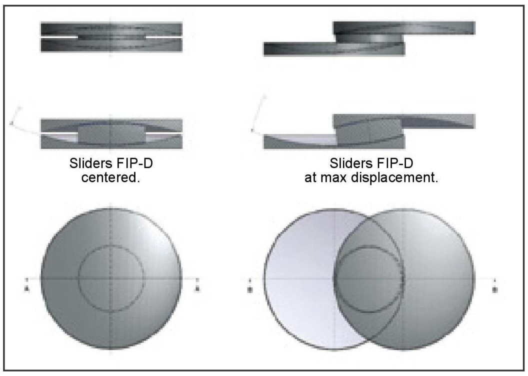

Figure 2. DCCSS configuration.

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 depends on the radius R of the curved sliding surface (or the equivalent radius for DCCSS), according to the formula:

$$T = 2\pi \sqrt{\frac{1}{g \cdot \left(\frac{1}{R} + \frac{\mu}{X}\right)}} \quad (2.1)$$

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 near rigid until the friction force $F_0 = \mu W$ is overcome, where W is the weight. Then the force increase is proportional to displacement, with stiffness K = W/R.

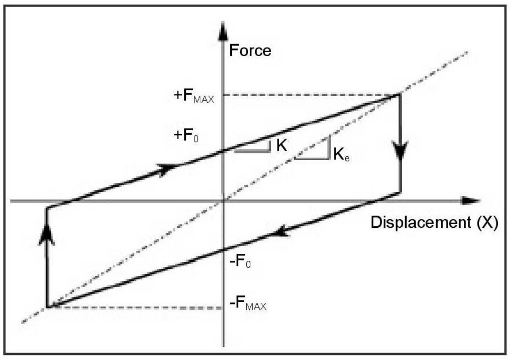

Figure 3. Theoretical force vs. displacement graph of a CSS or DCCSS.

The response of a CSS or DCCSS is almost independent from the velocity of the applied displacement. Thus, as discussed above, in continuous bridges of significant length the horizontal forces due to non-seismic displacements can be of the same order of magnitude, or even higher, than the seismic forces.

The use of Shock Transmission Units combined in series with CSS or DCCSS allows to obtain different behaviours of the device in service and seismic conditions. STUs (sometimes referred to as lock-up devices) are hydraulic devices that, thanks to the special hydraulic circuit that connects the two chambers in which the piston divides the cylinder, offer negligible reaction to low velocity applied displacements, e.g. due to thermal changes, while provide a very stiff dynamic connection in the event of an earthquake or other dynamic action. In the combined device (Figure 4), the STUs provide the dynamic connection between flat and curved components of the isolator: under an earthquake the shock transmission units become stiff and the DCCSS is activated, thus dissipating energy and ensuring the re-centring effect according to its force vs. displacement curve (Figure 3). Conversely, the slow movements (e.g. thermal deformations of the bridge) occur on the flat sliding component (at the bottom in Figure 4), realised with dimpled and lubricated UHMW-PE on one side and with mirror-polished stainless steel on the other side, and characterised by a very low friction coefficient. The horizontal force under service conditions is thus given by the reaction in the shock transmission units (usually lower than 10 % of their maximum capacity) and the friction force in the flat sliding surfaces. The theoretical model of this combined device is given in Figure 5. In particular, Figure 5a shows the global model, while Figures 5b and 5c show the corresponding models under service and seismic conditions, respectively.

This combination of devices allows to significantly reduce the horizontal forces transmitted to the piers under service conditions, while at the same time to benefit by all the advantages of seismic isolation.

It is worth noting that the European Standard on Anti-seismic devices [EN 15129:2009] provides for the combination of different components in an anti-seismic device, in Clause 9.

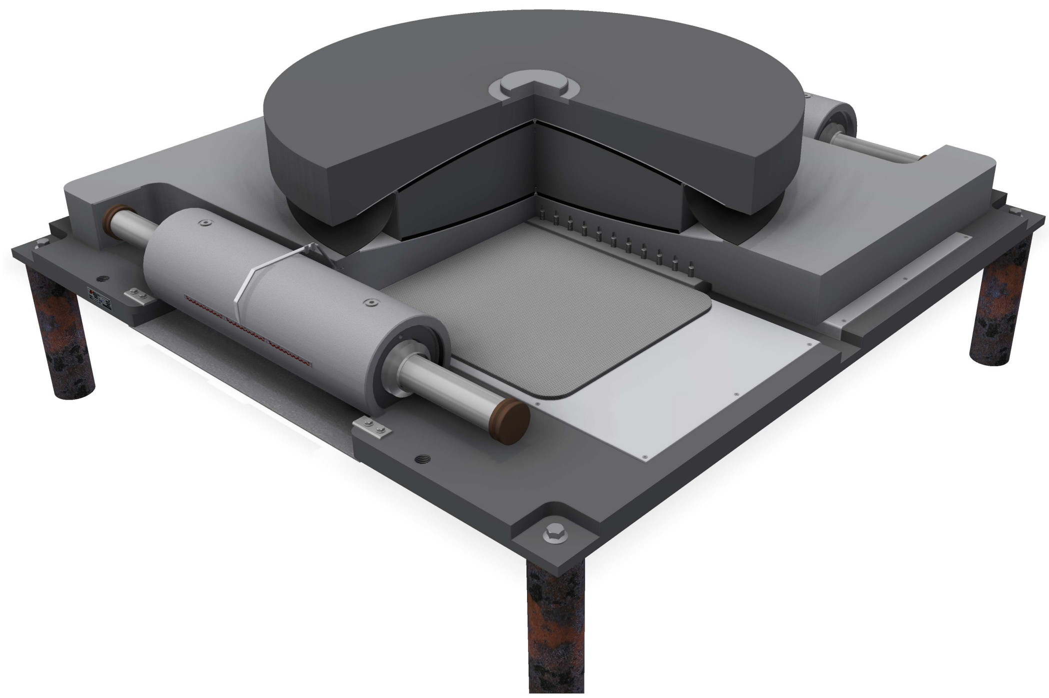

Figure 4. Rendering of a double concave curved surface slider combined with shock transmission units.

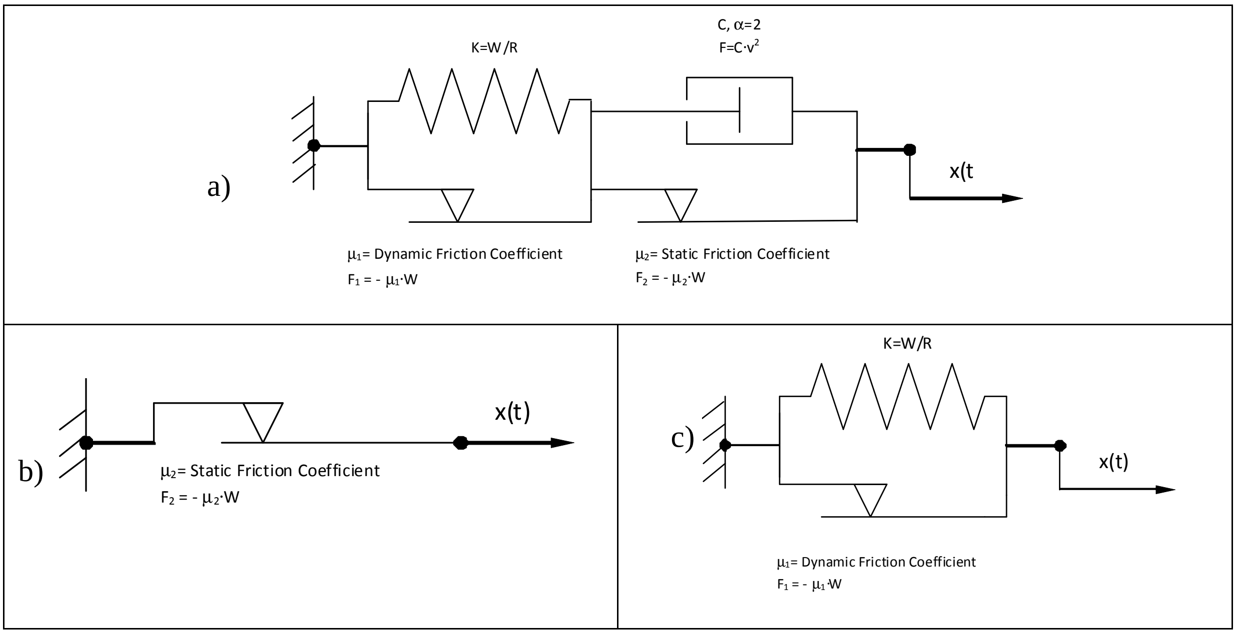

Figure 5. Theoretical model of the combined device: a) combined device; b) behaviour of the device under service conditions; c) behaviour of the device under seismic conditions .

3. THE ADDA, OGLIO AND SERIO BRIDGES OF THE BRESCIA-BERGAMO-MILANO HIGHWAY, ITALY

The combined antiseismic devices described above were recently installed in three bridge structures in the Brescia-Bergamo-Milano Highway in Italy, the Adda, Oglio and Serio bridges. Here below a short description of said bridges is given.

The length of the Adda, Oglio and Serio bridges is respectively 1260 m, 690 m and 930 m. All the bridges are double carriageways. The Adda bridge has 20 spans (Figure 6). Two combined devices as described above are installed on each pier as well as on the abutments. On the central pier (P9) there is a fixed point where all the horizontal forces due to service loads are sustained. This fixed point is realized by a mechanical fuse restraint, designed to fail at a certain value of horizontal force, higher than the horizontal force value due to service loads, in order to activate the seismic isolation system under strong earthquake (Figures 7 and 8). Under service conditions, the combined devices mainly behave as unidirectional bearings (Figure 8), because the shock transmission units allow low-velocity displacements along the longitudinal axis of the bridge. In transverse direction, displacements are not allowed until the friction force is not overcome; if the horizontal transverse force on the device is higher than the friction force, the device reaction is according to the constitutive law of the DCCSS (Figure 3). Under earthquake, after the failure of the mechanical fuse restraint, the combined devices behave as curved surface sliders (Figure 9), and the bridge is seismically isolated in all the horizontal directions.

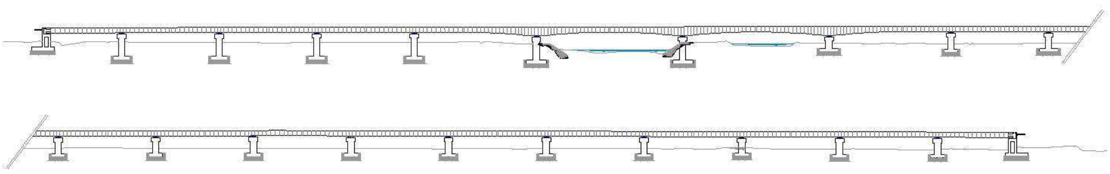

Figure 6. Elevation of the Adda bridge.

The Oglio and Serio bridges have respectively 11 and 16 spans. The bearing scheme is identical to that of the Adda bridge, with a central fixed point. In total, in the Adda, Oglio and Serio bridges of the Brescia-Bergamo-Milano Highway in Lombardy, North-Italy, 200 combined devices (curved surface sliders with shock transmission units) of 8 types were installed. The different types are characterised by different vertical loads and/or different horizontal loads and displacements in the shock transmission units. The maximum vertical loads at ULS are in the range 9000 ÷ 40000 kN. The maximum horizontal displacement in seismic conditions is ± 95 mm, while the stroke of the shock transmission units (and of the flat sliding components) varies in the range ± 125 ÷ 325 mm. The latter takes into account the maximum horizontal displacement in service conditions, as well as additional displacement needed during installation. Figures 10 and 11 show a phase of the installation and the devices as installed on the fixed pier, respectively.

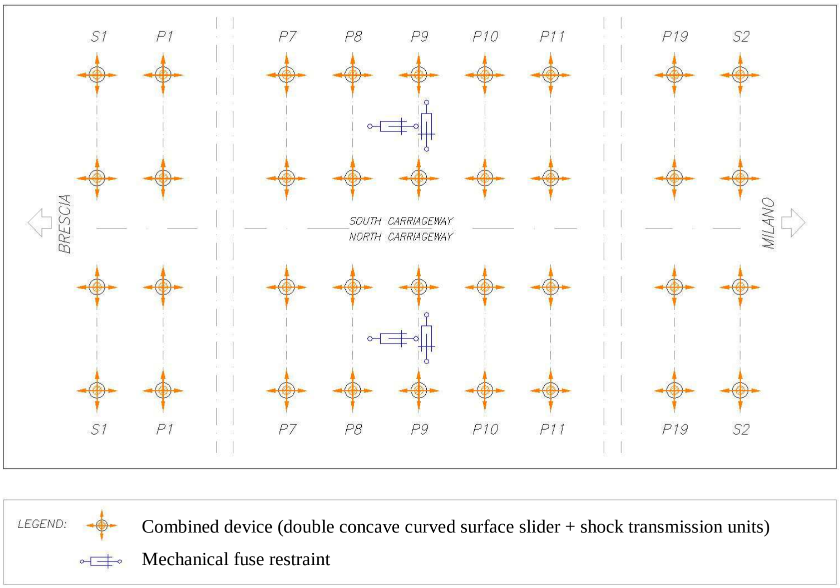

Figure 7. Seismic isolation scheme of the Adda bridge.

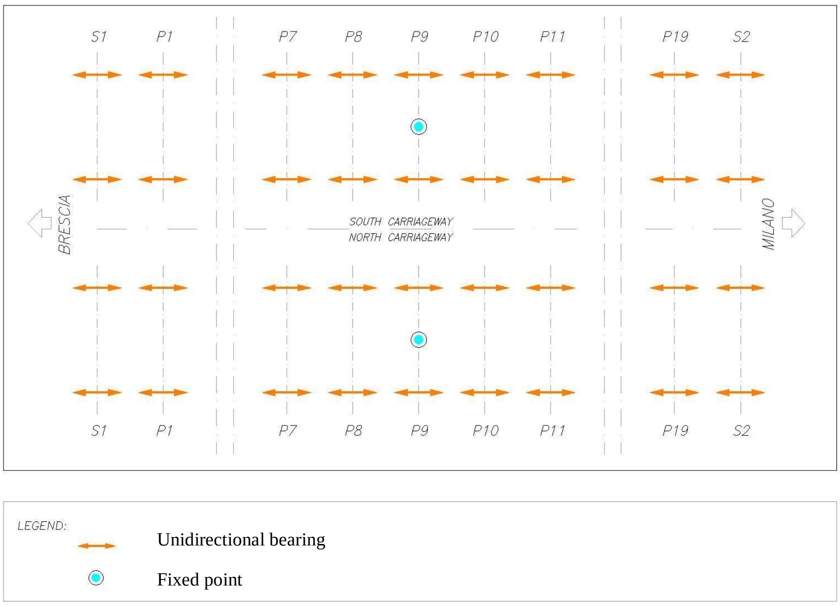

Figure 8. Bearing scheme of the Adda bridge under service conditions.

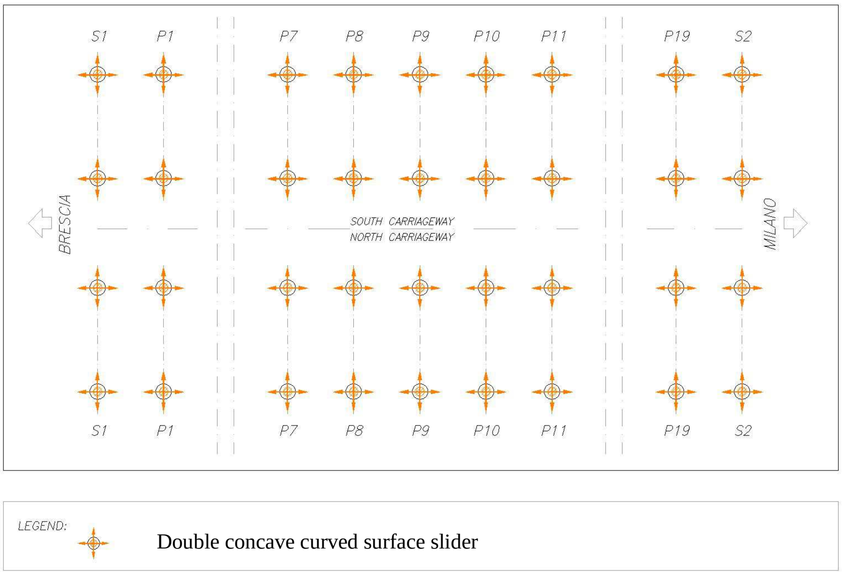

Figure 9. Bearing scheme of the Adda bridge under seismic conditions.

Figure 10. Installation of combined devices in the Oglio bridge.

Figure 11. Combined devices and mechanical fuse restraint as installed in the fixed pier of the Oglio bridge.

4. FACTORY PRODUCTION CONTROL TESTS

Factory production control tests have been carried out with the test methods given by the Italian Seismic Standard [D.M. 14/01/2008], at the Eucentre TREES Laboratory in Pavia, Italy (Figure 12). Both quasi-static and dynamic tests were carried out on full-scale devices.

The quasi-static test was carried out at constant velocity of 0.1 mm/s and amplitude of ± 25 mm, at three levels of vertical loads, applying 3 cycles for each value of vertical load. This test is aimed at checking that the DCCSS is not activated at low velocity, and the movement is on the flat sliding surface. At the maximum vertical load, the measured value of the coefficient of static friction is 0.85%.

Two different types of dynamic tests were carried out. The first type was aimed at measuring the dynamic coefficient of friction in different conditions of vertical load and velocity. Three different values of the vertical loads were used, and three different frequencies (design frequency and variation of ± 30 % on the design frequency) for each vertical load, applying 3 cycles for each test. The amplitude was constant and equal to ± 95 mm. Figure 13 shows typical force vs. displacement graphs obtained in two of these tests, at different loads but at the same frequency. The test results confirmed a significant variation of the dynamic coefficient of friction with the vertical load (the higher is the vertical load, the lower is the coefficient of friction) and a negligible variation with the frequency. The second type of dynamic test was aimed at checking the stability of the hysteretic loops and of the friction coefficient, at the maximum seismic load and at the design frequency, in 10 cycles, applied in two series of 5 cycles each. The test results confirmed a very high stability of the friction coefficient (Figure 14) within the limits required by the Italian standard, i.e. a ±25% variation in comparison with the 3rd cycle, excluding the 1st cycle. If the 6th cycle is excluded as well (because of the interruption of the 10 cycles) the maximum variation in the friction coefficient is about 8 %.

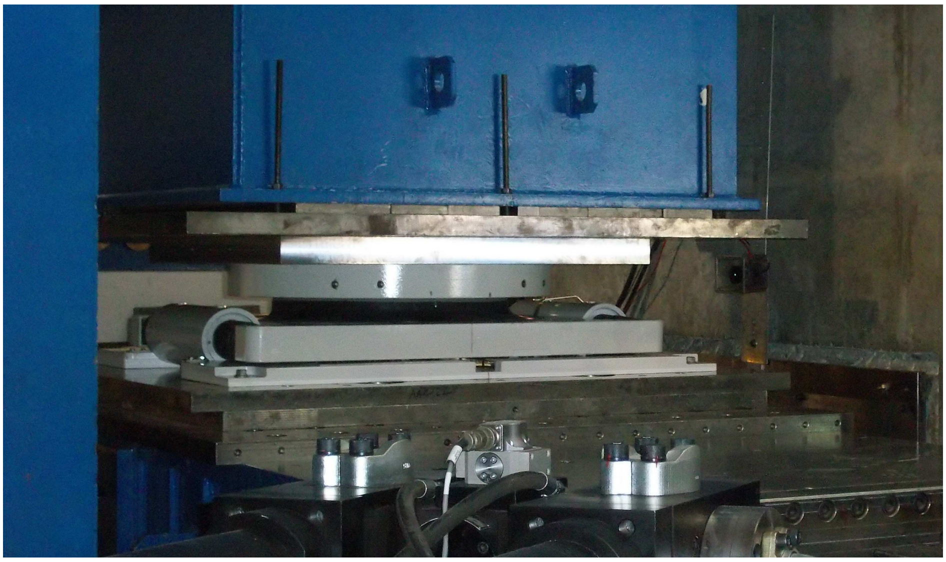

Figure 12. A combined device under test at EUCENTRE Laboratory.

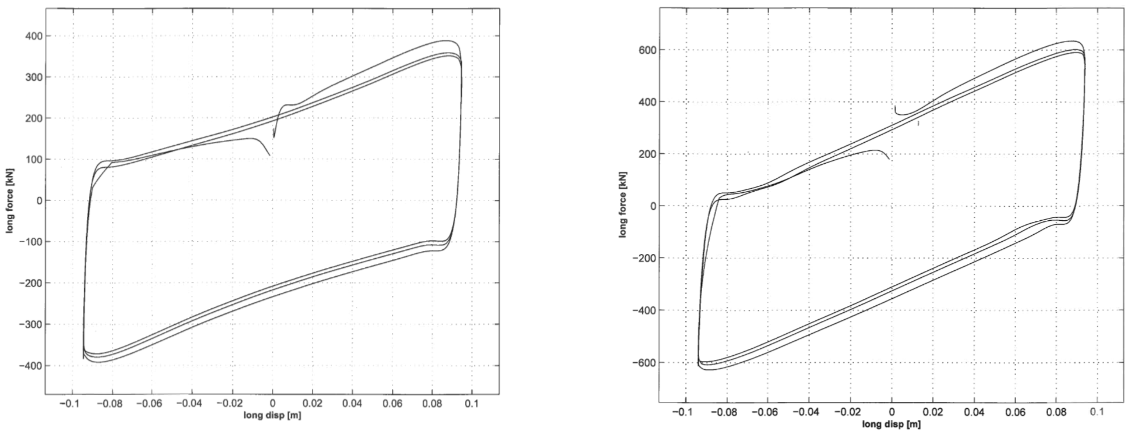

Figure 13. Force vs. displacement graphs obtained in tests at frequency of 0.239 Hz, at minimum (left) and maximum (right) seismic loads.

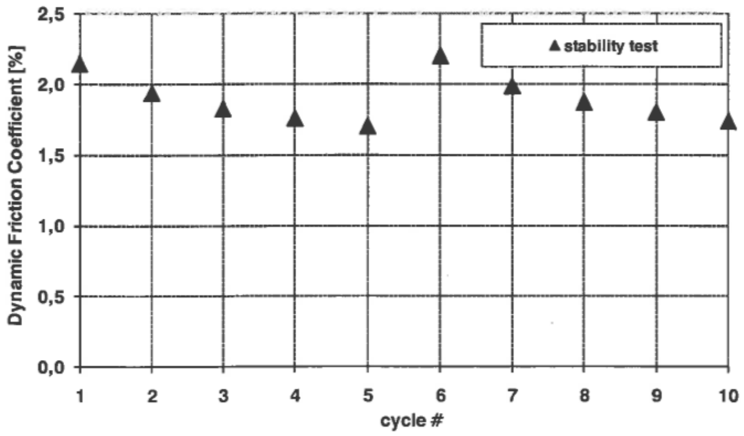

Figure 14. Results of the dynamic test aimed at checking the stability of the hysteretic behaviour.

5. CONCLUSIONS

The new anti-seismic device that combine a double concave curved surface slider with shock transmission units is a solution that allows to benefit of the advantages of seismic isolation even in very long continuous bridges, where the deformations induced by creep and shrinkage as well as transient thermal deformations are very large, and thus the horizontal forces transmitted to the substructure in service conditions could be of the same order of magnitude of the seismic forces, or even larger in areas with moderate seismicity. Thanks to said combined devices, the bearing scheme under service conditions is that of a non-isolated bridge, with very low horizontal forces associated to the deck movements, while the bearing scheme under earthquake conditions becomes that of a bridge isolated with curved surface sliders. The quasi-static and dynamic tests carried out on full-scale combined devices confirmed the validity of the adopted design solution.

These combined devices have been succesfully installed in three bridges of the new Brescia-Bergamo-Milano highway in North Italy, for a total of 200 devices. More recently, 20 combined devices have been installed in another bridge structure in Italy, the Ponte del Primo Sole Bridge over the Simeto River in Sicily.

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