# A NEW ELASTIC-PLASTIC DISSIPATION DEVICE FOR SEISMIC PROTECTION OF THE BRIDGE PILE STRUCTURES: EXPERIMENTAL INVESTIGATION

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## SUMMARY

The paper describes of a new hysteretic device for seismic protection of the bridge. capable of limiting the forces transmitted by the earthquake to the pile leaving it in the elastic domain. This hysteretic device is obtained by assembling some pieces of I series steel profile. This prototype is derived from another one designed by the same authors and used for seismic protection of braced framed structures. That prototype represents here the main dissipating part of the studied device.

The advantage of this device compared to the ones in common used ones is in the peculiar structural scheme which allows it to have a very simple shape as well as being an inexpensive one. Namely the paper treats the experimental investigation carried out on it while the theoretical study is reported in another work

## INTRODUCTION

The bridge's piers mainly withstand compression strength and so they are built in r.c. also when the span is in steel. The operating condition checks are carried out by searching the most unfavourable load condition for each cross section. Each of this normally, produces both normal actions and bending moments along the longitudinal and the transversal plane. This is due to the horizontal forces such as wind, braking actions etc. But shear solicitation can also appear.

For the seismic action, the design philosophy foresees that two different earthquakes can occur: namely:

a frequent earthquake with a very low back period and with a medium intensity during which the bridge can resist without great damage to the structure by moving itself in elastic range;

a violent earthquake with a very high back period and with a great intensity during which the bridge might be damaged in some parts due to the overcoming of the yielding threshold without collapse of the structure although the bridge will have to be repaired or rebuilt.

During the seismic events the most stressed elements of the multi-spans bridges are the piers because the scaffolds are considered very rigid in their plane. To avoid the collapse of the structure two solutions can be used:

by inserting a peculiar anti-seismic device, capable in the case of violent earthquake, of either changing the structural response or isolating the structure at its base;

by permitting displacement of the structure much beyond the elastic threshold thanks to the plasticization of some of its parts and especially of the piers. This property is commonly known as "ductility".

The former might be distinguished by the normal bearing constrains whose aim is to guarantee the normal function during the operating condition or that can be unified to these so as to realise a unique device capable of

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solving different functions. An anti-seismic device is designed so as to withstand the maximum foreseeable earthquake without collapsing. They can undergo plasticization or local cracks that can be substituted after these events. The ideal behaviour of these devices is characterised by a two-linear elastic-plasticization diagram which is independent from both the velocity of the imposed deformations and the temperature.

Furthermore, their capacity of dissipating the energy input from the earthquake should have to remain constant for all the cycles drawn during the seismic event. Only after this event can the device be replaced. In other words these devices represent a "fusible" of the structure which limits the maximum force transmitted from the scaffold to the pier within a fixed value. In order to permit large displacement during the plasticization phase, the elastic plasticization dissipation device must always be coupled to mobile bearing constrains.

The authors have studied and developed a new hysteretical device [1] whose main characteristic is that of presenting a uniform plasticization by using a constant profile in contrast with the commonly used tapered shape (i.e. spindle). The fulfilment of the uniform plasticization condition has been obtained through the adopted static scheme, which consists in a statically determined system performed by means of a beam constrained at one extremity with a roller bearing and at the other, with a double-pendulum, so as to have a constant distribution of bending moment along the structure. To this aim, a prototype device has been made by using a commercial I series profile; the web profile is the dissipating element because it is more flexible than the flanges. The load is applied on the superior flange of the profile by means of a cylindrical hinge. The single profiles can be coupled to each other in parallel connection in order to have a higher stiffness. Both the design procedure and the numerical investigation are reported in [2] where the experimental analysis, carried out on the single dissipating element is also reported. The actions transferred by the over-structure produce a constant distribution of the bending moment along the web of each profile, in the case of direction of the seismic action parallel to the span axis, where both profiles react in the same way. If, instead, F1 and F2 are inclined at a generic $\alpha$ angle in respect to the direction of the span axis, the reaction of the two tracts is different and, consequently the distribution of bending moment becomes as reported in figure 1. In this condition the distribution of the bending moment is still constant but a combined bending moment and compressive strength could occur on the dissipating element and this is not negligible.

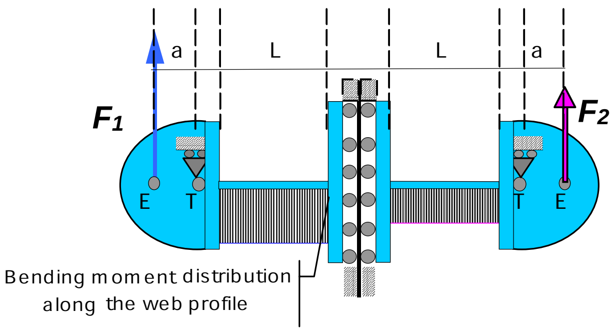


**Fig 1: Static scheme of the prototype**

However, it must note that for the scheme adopted the displacement of the point of the load application is given by:

$$u = a \cdot \text{sen}(\omega)$$

where "a" is the force's arm and $\omega$ is the rotation of the beam proximity to the roller bearing. The force's arm must permit the last displacement $u_u$ with a rotation $\omega_u$ which must not to create damage to the mechanism. From the experience, the rotation which does not compromise the cyclic life of the device, can be assumed equal to $\omega_u = \frac{\pi}{8}$. Thus the arm length is equal to $a = u_u\sqrt{2}$; and the choice of the profile must regard the element which fulfils the relation at the elastic limit:

$$u_e = a \cdot \text{sen}(\omega_e)$$

where $u_e$ and $\omega_e$ represent, respectively, the limit elastic displacement and rotation. Because the beam element withstands a constant bending moment, the rotation at the elastic threshold can be written as

$\omega_e = \frac{2\varepsilon_e h}{s} \cong 0{,}004\frac{h}{s}$ , where $\varepsilon_e$ is the deformation at the elastic limit, adopted equal to 2 ‰, and h and s are respectively the length and the thickness of the web profile used.

**Table 1-Rotation at the elastic threshold of some of the commercial profiles**

| Profile type | | | H [mm] | e [mm] | h=(H-2e) | s [mm] | □e [rad] | Me [kN m/ml] | Mp [kN m/ml] |
|---|---|---|---|---|---|---|---|---|---|
| IE | 200 | A | 190 | 10 | 170 | 6.5 | 0.1046 | 2.90 | 4.35 |
| | | B | 200 | 15 | 170 | 9.0 | 0.0756 | 5.56 | 8.34 |
| | | M | 220 | 25 | 170 | 15.0 | 0.0453 | 15.45 | 23.18 |
| IE | 220 | A | 210 | 11 | 188 | 7.0 | 0.1074 | 3.36 | 5.05 |
| | | B | 220 | 16 | 188 | 9.5 | 0.0792 | 6.20 | 9.30 |
| | | M | 240 | 26 | 188 | 15.5 | 0.0485 | 16.50 | 24.75 |
| IE | 240 | A | 230 | 12 | 206 | 7.5 | 0.1099 | 3.86 | 5.79 |
| | | B | 240 | 17 | 206 | 10.0 | 0.0824 | 6.87 | 10.30 |
| | | M | 270 | 32 | 206 | 18.0 | 0.0458 | 22.25 | 33.37 |
| IE | 260 | A | 250 | 12.5 | 225 | 7.5 | 0.1200 | 3.86 | 5.79 |
| | | B | 260 | 17.5 | 225 | 10.0 | 0.0900 | 6.87 | 10.30 |
| | | M | 290 | 32.5 | 225 | 18.0 | 0.0500 | 22.25 | 33.37 |
| IE | 280 | A | 270 | 13 | 244 | 8.0 | 0.1220 | 4.39 | 6.59 |
| | | B | 280 | 18 | 244 | 10.5 | 0.0930 | 7.57 | 11.36 |
| | | M | 310 | 33 | 244 | 18.5 | 0.0528 | 23.50 | 35.25 |
| IE | 300 | A | 290 | 14 | 262 | 8.5 | 0.1233 | 4.96 | 7.44 |
| | | B | 300 | 19 | 262 | 11.0 | 0.0953 | 8.31 | 12.46 |
| | | M | 340 | 39 | 262 | 21.0 | 0.0499 | 30.28 | 45.42 |
| IE | 320 | A | 310 | 15.5 | 279 | 9.0 | 0.1240 | 5.56 | 8.34 |
| | | B | 320 | 20.5 | 279 | 11.5 | 0.0970 | 9.08 | 13.62 |
| | | M | 359 | 40 | 279 | 21.0 | 0.0531 | 30.28 | 45.42 |
| IE | 340 | A | 330 | 16.5 | 297 | 9.5 | 0.1251 | 6.20 | 9.30 |
| | | B | 340 | 21.5 | 297 | 12.0 | 0.0990 | 9.89 | 14.83 |
| | | M | 377 | 40 | 297 | 21.0 | 0.0566 | 30.28 | 45.42 |
| IE | 360 | A | 350 | 17.5 | 315 | 10.0 | 0.1260 | 6.87 | 10.30 |
| | | B | 360 | 22.5 | 315 | 12.5 | 0.1008 | 10.73 | 16.09 |
| | | M | 395 | 40 | 315 | 21.0 | 0.0600 | 30.28 | 45.42 |
| IE | 400 | A | 390 | 19 | 352 | 11.0 | 0.1280 | 8.31 | 12.46 |
| | | B | 400 | 24 | 352 | 13.5 | 0.1043 | 12.51 | 18.77 |
| | | M | 432 | 40 | 352 | 21.0 | 0.0670 | 30.28 | 45.42 |
| IE | 450 | A | 440 | 21 | 398 | 11.5 | 0.1384 | 9.08 | 13.62 |
| | | B | 450 | 26 | 398 | 14.0 | 0.1137 | 13.46 | 20.19 |
| | | M | 478 | 40 | 398 | 21.0 | 0.0758 | 30.28 | 45.42 |
| IE | 500 | A | 490 | 23 | 444 | 12.0 | 0.1480 | 9.89 | 14.83 |
| | | B | 500 | 28 | 444 | 14.5 | 0.1225 | 14.44 | 21.66 |
| | | M | 524 | 40 | 444 | 21.0 | 0.0846 | 30.28 | 45.42 |
| IE | 550 | A | 540 | 24 | 492 | 12.5 | 0.1574 | 10.73 | 16.09 |
| | | B | 550 | 29 | 492 | 15.0 | 0.1312 | 15.45 | 23.18 |
| | | M | 572 | 40 | 492 | 21.0 | 0.0937 | 30.28 | 45.42 |
| IE | 600 | A | 590 | 25 | 540 | 13.0 | 0.1662 | 11.60 | 17.41 |
| | | B | 600 | 30 | 540 | 15.5 | 0.1394 | 16.50 | 24.75 |
| | | M | 620 | 40 | 540 | 21.0 | 0.1029 | 30.28 | 45.42 |

Table 1 reports the elastic rotation for the commercial profile belonging to "I series". From this table we can observe that the available choice is quite continuous for a range of elastic rotation from 0.045 rad up to 0.166 rad. In other terms, by considering an eccentricity of the force, in respect to the roller bearing of 100 mm, we must choose a profile whose elastic allowed displacement is in the range defined from 5 up to 15 mm. So by changing the arm length we can greatly modify the elastic displacement. By taking into account that the relative displacement between pier and scaffold is variable in the range 1÷3 cm, it can be said that the profiles existing in commerce are able to cover the design requirements.

**The realization of the model**

The choice of the profile is directly connected to both the bridge's span dimensions and the seismic design required by the local code for the studied zone. Following the procedure reported in [2], for the pier structure examined, we have employed two profiles belonging to the IEB 340 [2]. At every portion of length equal to 310 mm, two pins were welded to the lower flange. These pins realise the double pendulum constrain by sliding along the box guide in parallel direction to the bridge span. On the other flange, in axis to the web profile, another pin capable of moving itself along the horizontal guide of the box so as to simulate the roller bearing action was welded. On these same flanges four cantilever are also welded in order to apply the load transferred by the bridge scaffold. The system for the load application was made by using two pendulum in series connected so as to work only in traction. The two profiles, are placed inside a box which represents the external constrain between scaffold and pier. The box was created in a prismatic shape by means of steel profile 80x8 of "L" series.

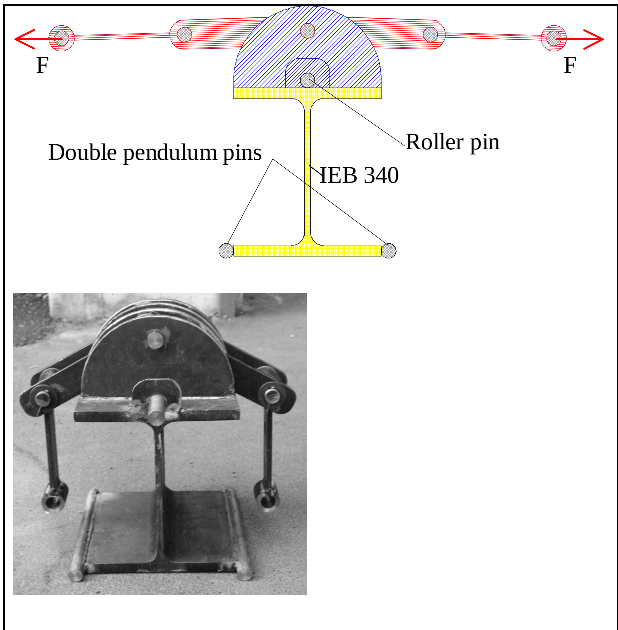


**Fig 2:Single dissipating element-front view**

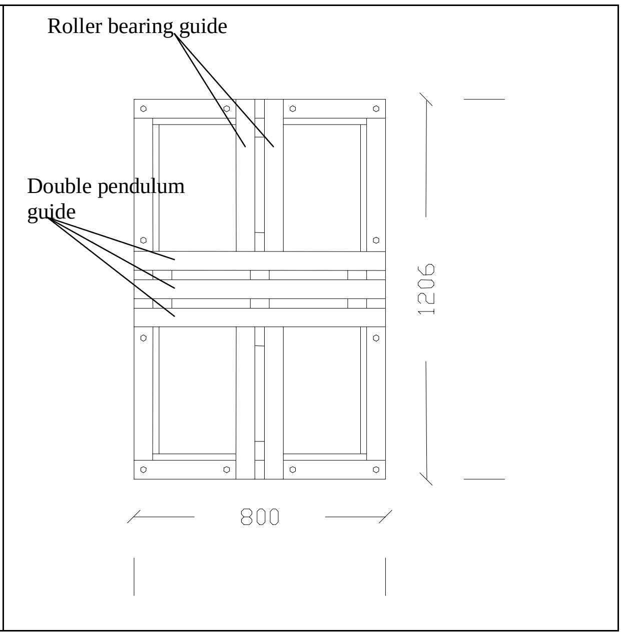


**Fig 3:Box container- plan view**

In order to limit the friction effects between the dissipating elements and the box covers, some Teflon layers were placed around the roller bearing pins as well as around the double pendulum ones.

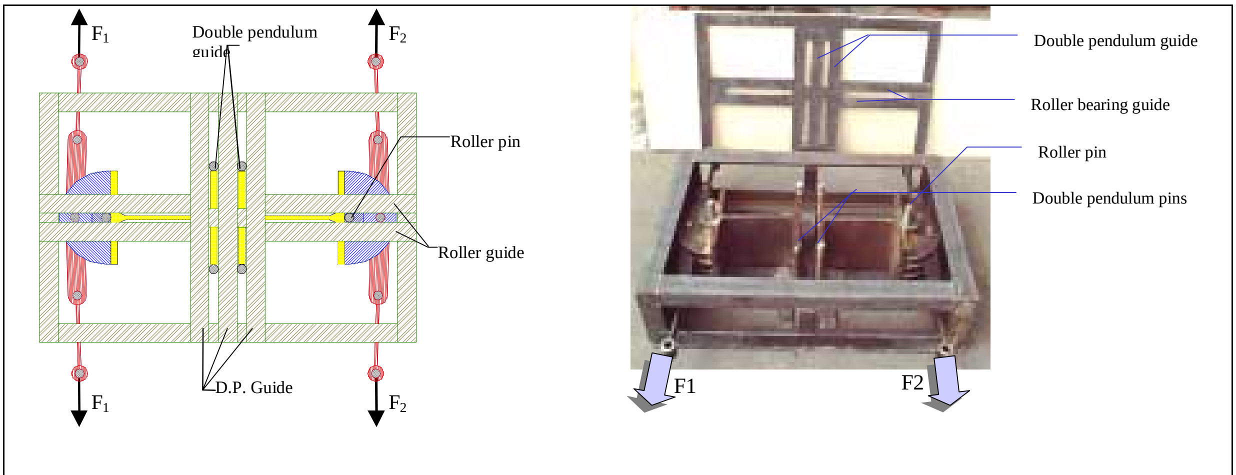


**Fig 4: Assembled device**

The lower and upper covering surfaces form a couple of guides perpendicular to each others. Those placed along the direction of the span axis need to permit the movements of the roller bearing while those placed along the direction perpendicular to the span axis need to permit the movements of the double pendulum. The dimensioning of the box is carried out so as that it always works within the elastic domain even when the profile transfers the maximum actions to the piers.

As shown in previous pictures, both actions F1 and F2 are transferred to the cantilever welded to the upper flanges of the employed profiles. The connection to the span is at the extremities of these traction rods; in these way, in fact, the two elements work symmetrically also under actions whose direction is not parallel to the span axis.

**Testing equipment**

In order to apply a cyclic load, a particular testing equipment was used as described in the following figures. The load was applied by means of a digital controlled actuator; this load was transferred to both sides of the device by a very rigid beam. This beam has been realised in a IPE 500 profile, whose aim is to simulate the action of the bridge scaffold, and it is connected to the IEB 180 portion for each side of the profile (Figure 5-6). In the lower part the IEB 180 profiles are constrained by some sliding bilateral bearings, which are the fixed guides representing the rails for the "L" profile cantilevers. A preliminary tests was carried out in order to evaluate the frictions which occur during the working of the system; a total friction equal to 1,1% of the vertical load applied during the operating condition was measured. This permits us to consider these as perfect constrains. The floor connection was realised by a L100x10 profiles that act as a rafter. The whole system was erected on a r.c. plate from where a steel beam permit the anchorage.

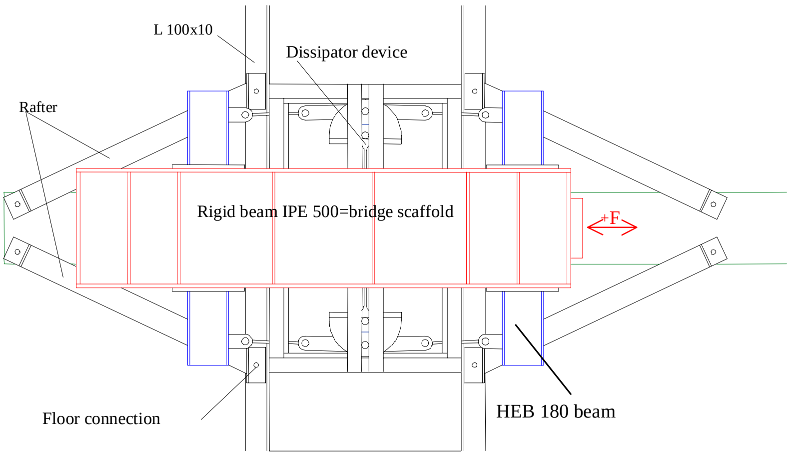


**Fig 5: Plan view of the testing equipment**

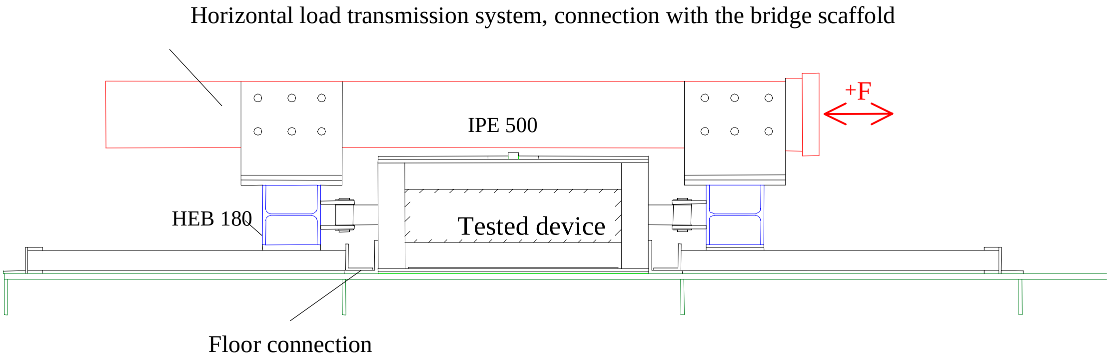


**Fig 6: Front view of the testing equipment**

The experimental investigation carried out on the device differs in two steps. The first part, regards the application of a cyclic load carried out by controlling the displacement whose amplitude increases progressively; in order to make the device working firstly in elastic domain then in the elastic-plasticization one.

The second part regards, instead, a dynamic test with a variable displacement amplitude.

The two profiles were distinguished by the letters “A” and “B”, where the “A” element lies on the right side in respect to an observer who looks at the device from the actuator side.

The entire system was instrumented by means of strain gauges and displacement transducers. Namely the displacements are:

the movements of the double pendulum along the box guides measured by displacement transducers W100;

the movement of the roller bearings measured by electric transducers;

the rotation of the roller bearings.

The strains have been evaluated by means of some strain gauges PFL-10-11 placed along the faces of the web profiles. These data permit us also to evaluate the curvature as well as the axial deformations along the plasticized portion of the device. Other strain gauges were placed along the double pendulums’ faces.

The device for the application of the load is constituted by a displacement transducer and a loading jack. The digital controller of the actuator INSTRON permits us to impose either the displacement or the desired load with great precision, namely 0.1% for the load and 0.02 % for the displacement. The acquisition of the data has been obtained by a dynamic device with a capacity 100-200 times, thanks to the possibility of operating with a frequency equal to 0.2-1 Hz, much greater than the static one.

**Fig 7: View of the instrumented system**

**Pseudo – static test**

The controlled parameter has been the point of the load application. The loading history foresees three elastic cycles at ±5 mm and other three cycles at the elastic threshold evaluated at about to ±10 mm. Further increasing of the load, within the elastic-plastic phase, is carried out by imposing a displacement $x_B$ equal to ±20 mm, ±35 mm e ±50 mm.

**Dynamic test**

The dynamic test is carried out by imposing some cycles of load at an imposed displacement and by changing the amplitude of the frequency. Namely, a sinusoidal cycle with amplitude equal to 7 mm at 0.5Hz, was used for the test in the elastic domain, while the same shape for the load but with an amplitude of 40 mm at 0.2 Hz was used during the plastic investigation. The dynamic test in the elastic phase was made before than the pseudo-static one to be able to work without a damaged prototype.

## ANALYSIS OF THE HYSTERETIS LOOPS

### Pseudo – static test data

The analysis of the hysteresis loops in terms of the load measured and of the displacement applied shows some friction effect in correspondence to the inversion of the load. This fact, already recorded in the cycles at ±35 mm and which becomes more evident for the cycles at ±50 mm, is due to an imperfection during the prototype construction which gave some friction effects.

However the loops obtained from the experimental investigation (Figure 8) seem to be very stable also for a high number of cycles, since no variation of the stiffness is recorded and no process of damaging appears.

### Dynamic test data

The dynamic test carried out on the device has confirmed the data obtained from the pseudo-static one. In this case too the hysteresis loops obtained are very stables even after a very high number of loading cycles (200 loops circa) as shown in Figure 9. The area described from these loops is the same that obtained from the previous test so that they are placed one on top of the others..

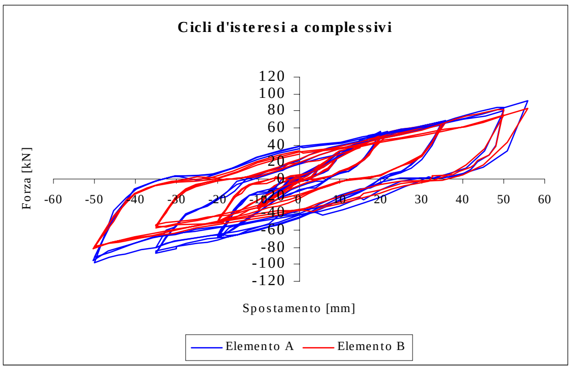


**Fig 8: Hysteresis loops obtained from the pseudo-static test**

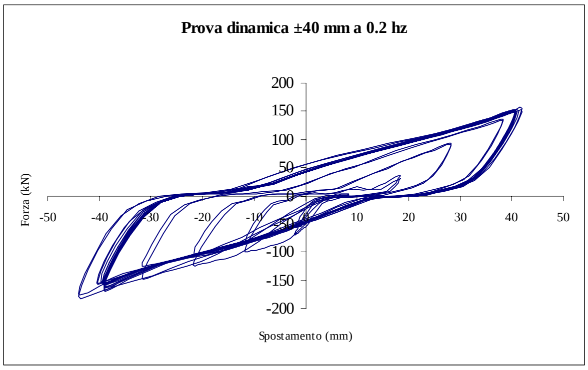


**Fig 9: Hysteresis loops obtained from the dynamic test**

## ANALYSIS OF THE BEHAVIOUR OF THE DEVICE

The data obtained from the experimental investigation show that the first plastic strains occur only for values of the imposed displacement up to ±20 mm. At this stage the residual displacement evaluated at the lower flanges is equal to 5 mm and the distribution of the bending moment is almost constant along the web. During these loops a different behaviour of the two dissipating element is recorded during the unloading process. This fact is due to the high value of the friction in play directly connected to some construction effects. In the further loops at ±35 mm , in fact, the residual displacement of the lower flanges differs in “A “ and “B” elements. This behaviour is also shown for an imposed displacement equal to ±50 mm

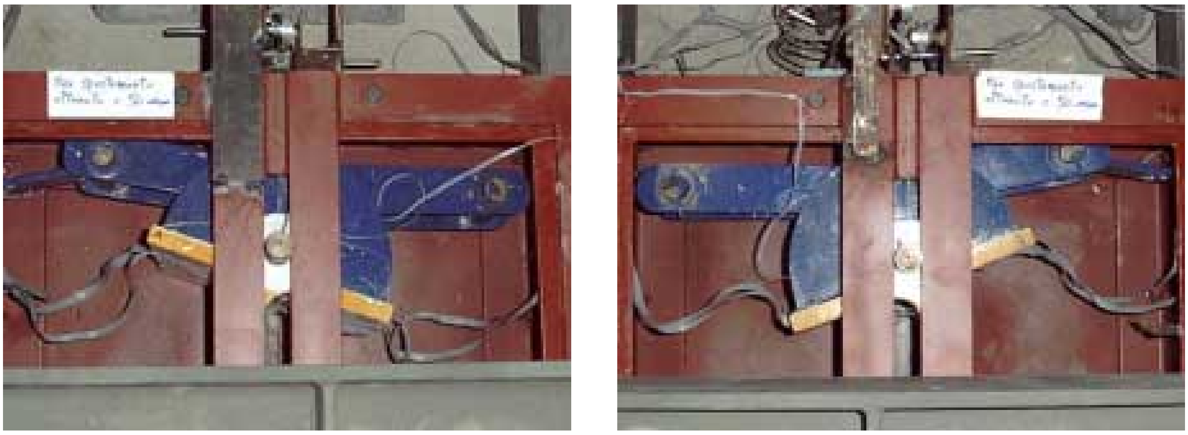

**Fig 10: A step of the experimental test: deformed elements (imposed displacement ±50 mm)**

The analysis of the diagram defined in terms of distribution of the bending moment along the web during both the elastic and plastic range is almost constant, although during the elastic phase it is similar to a trapezoidal distribution.

This effect, found only during the investigation in the elastic phase, is caused by to the presence of the friction forces whose effect was not taken into account during the theoretical investigation and they are occurred because of faults during the construction process.

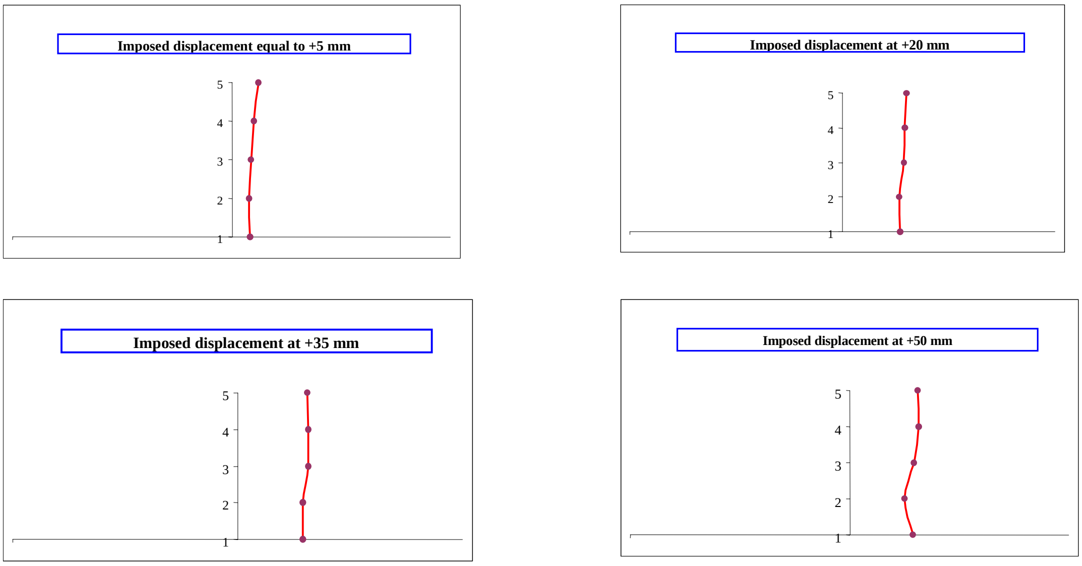


**Fig 11: Average distribution of the bending moment along the web profile**

## CONCLUSIONS

The great difference between the measured bending moment and the elastic one as well as its constant distribution along the web profiles show the worth of the device and of the material which we intended to dedicate for the dissipation of the energy. The loops obtained from the experimental investigation seem to be very stable also for a high number of cycles, since no variation of the stiffness is recorded and no process of damaging appears. Also, if we compare hysteresis cycle given by the INSTRON (dynamic acquisition) equipment according to the imposed displacement and the force transmitted to the system, as well as the loop obtained by adding up the sum of response of the two elements that constitute the device, given by the data acquisition instrument UPM 60 (statical acquisition), we can see how similar the two cycles are. All the force applied had been use to plasticise the profiles and to avoid any internal friction on the damper. The quantity of energy used to make the load transmission system was very low. In fact, in the case of a friction coefficient between steel and Teflon equal to 0.05, we have a total of 1% of the whole energy applied. This explains the reason why in the diagram where the load directly measured along the rods and that applied by the actuator no significant differences appear. In the numerical test we note that compared to the tests results the load level is lower. This is partly because of internal friction between the dissipating elements and the box guides which produce a linear distribution of the moment measured particularly during the elastic phase which is slightly different from the constant one theoretically calculated where there is no friction. The advantage of this device compared to the ones in common used ones is in the peculiar structural scheme which allows it to have a very simple shape as well as being an inexpensive one.

## REFERENCES

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