EXPERIMENTAL ANALYSIS AND ANALYTICAL MODELLING OF AN INNOVATIVE ELASTIC-PLASTIC DISSIPATION DEVICE FOR SEISMIC PROTECTION OF THE STRUCTURES

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SUMMARY

The paper reports the study carried out on the evolution of a new hysteretical device previously proposed from the author and co. for seismic protection of the structure. Namely the problem is carried out in terms of analytical and experimental modelling. An introduction to the original idea of the device design is reported and the reasons which have led us to change the original configuration are discussed. Thus a first performed prototype is born from the analysis of a very simple static scheme capable of giving an uniform distribution of the bending moment along the structure. For this aim we have studied a beam constrained by a hinge and a double pendulum. This scheme has been experimentally realised by using a commercial steel profile belonging to “I” series. Subsequently, this prototype has been modified in order to better transfer the loads transmitted by the structure, so as to avoid some unsuitable effects on the braced frame. The prototype reported above has been realised and tested.

INTRODUCTION

The seismic protection of the structure can be obtained by the use of a particular device capable of reducing the energy transmitted by the earthquake. Since the plastic dissipation due to the seismic event occurs only in these devices, the structure works all the time, within the elastic range. The dissipation device can be of many different types such as plastic or friction devices, and they are commonly called hysteretical device because of their ability of dissipating the energy by means of loops of plastic hysteretical dissipation. Their design is based on the idea of distributing the device resistance uniformly along the device so that all the plastic deformations develop at the same time in each point of the hysteretical device. To this aim the dissipating device must present a yielding threshold lower than the main structure one. All these requirements are fulfilled when the device behaves as a elastic- perfectly plasticization structure without any hardening but with a ductility factor very close to the constitutive material one. These conditions are reached when devices with uniform plasticization are adopted. In the case of hysteretical device whose bending behaviour is prevalent this aim might be obtained by imposing the equality between the bending moment distribution and the plasticization bending moment. This fact explains the reason why sometimes these devices present very complicated tapered shapes due to a non-uniform bending moment distribution, as in the case of the cantilever dissipation device for which the uniform plasticization condition is obtained by means of a parabolic profile. This situation might get worse if the normal action is also present.

Thus, the paper treats the study of a particular dissipation device capable of ensuring a constant distribution of the bending moment and whose shape is so simple that it can be perform by the use of an appropriately constrained commercial steel profile.

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THE ORIGINAL PROTOTYPE: MODEL N.1

The hysteretical device we obtain is constituted by an element belonging to “I” series steel profile. It is constrained by means of a hinge and a double pendulum as shown in figure 1. The load is transmitted alternatively by the “Inverted K” braces of the frame, where the device must be inserted, so as to transfer solicitation which causes the uniform plasticization of the web profile.

The web of the device represents the dissipating element; in fact, the profile’s flanges have a bigger stiffness than the web and so they remain in the elastic domain during the life span of the device. So the use of the commercial profile seems to be very convenient from both the economical and mechanical point of view and it can be employed for the r.c. as well as for steel structures.

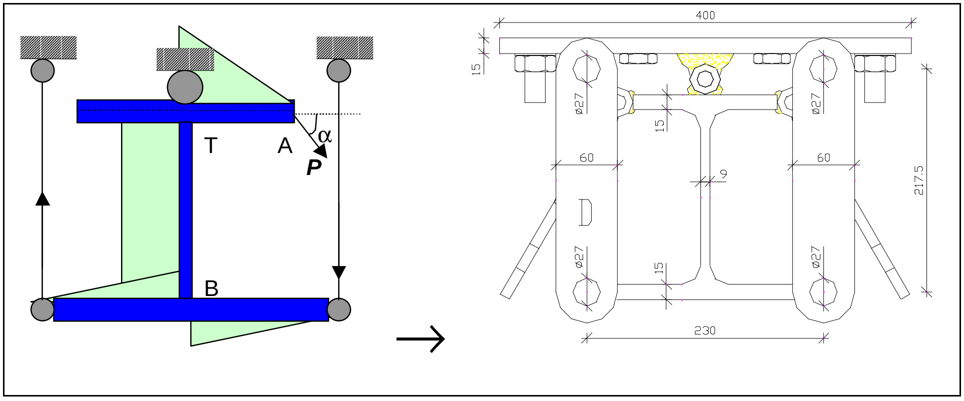


Fig.1- Statical scheme of the model n.1 and the original prototype

The fixed hinge welded at the top of the “I” profile permits it to absorb all the horizontal and vertical components of the P load so that the web withstands only the bending moment $P \cdot a \cdot sin\alpha = M_u = const$, where M_u represents the maximum bending moment at the limit of the ductility, α is the angle of the load inclination and “a” is the arm of the force which produce bending moment.

The analytical study of the device has been previously carried out in the small displacement hypothesis and the ideal hysteresis loop defined in terms of the hinge rotation (ω_T) versus load applied (P) has been obtained. Then, the hystereis loop was re-defined by removing the small displacement hypothesis due to the upper flange whose rigid rotation produces the variation of geometry where the actions are computed. Under this condition a hardening in the hystereis loop is obtained as highlighted in figure 2. In fact the bending moment evaluation in the case of small displacements is given only by the vertical component of the load, while in the case of a large displacement the horizontal component of the load must also be considered because the equilibrium is written by referring to the deformed configuration.

So the contribution of the vertical component of the load to the bending moment is :

$$M' = P \cdot a \cdot sin(\alpha)\cos(\omega_T)$$

the contribution of the horizontal component of the load to the bending moment is

$$M'' = -P \cdot a \cdot \cos(\alpha) sin(\omega_T)$$

The total bending moment is given by:

$$M = P \cdot a\left[sin\alpha \cos\omega_T - \cos\alpha sin\omega_T\right]$$

For a further increasing of the load, the upper flange aim at aligning with the load direction, this produces a decreasing of the vertical component so that to have a very little bending moment increase the load must be greatly increase and the hardening occurs. The model reported in figure 1 was performed and tested by using a IEB 200, 140 mm dept, steel profile inserted into a testing frame as reported in figure 3.

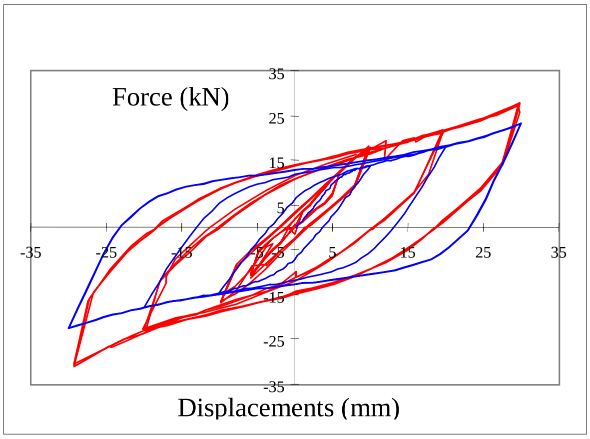


Fig.2- Hysteresis loops: theoretical (blue) and experimental (red)

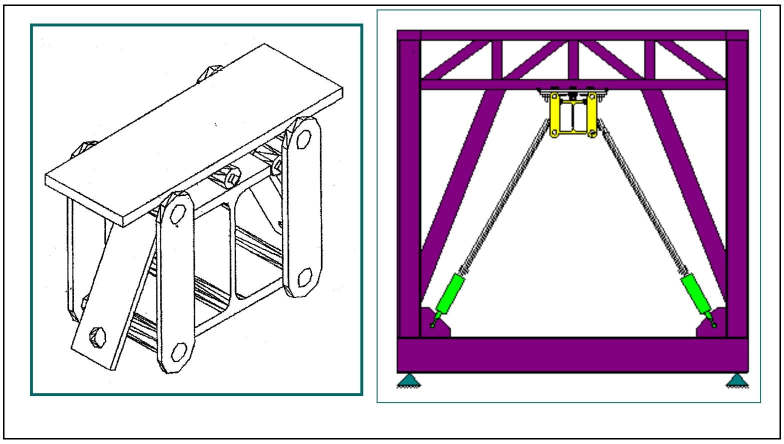


Fig.3- Hysteretical device and testing frame

The experimental analysis is carried out in order to evaluate the exact behaviour of the device employed and the hysteresis loops described in red in figure 2 are obtained. The load was applied by following four different steps of load each of them was constituted by three loops at an imposed displacement equal to ±6 mm (elastic range), ± 10mm, ±20mm and ±30 mm (plastic range) displacement. The data obtained showed a very good comparison between numerical prediction and experimental data. In fact, the plasticization occurs only along the web where the bending moment distribution is almost constant even beyond the yielding imposed displacement. Furthermore, no damaging occurs after a very high number of cycles because of the constant distribution of the bending moment, in fact the loops are placed one on top of the other (fig.2).

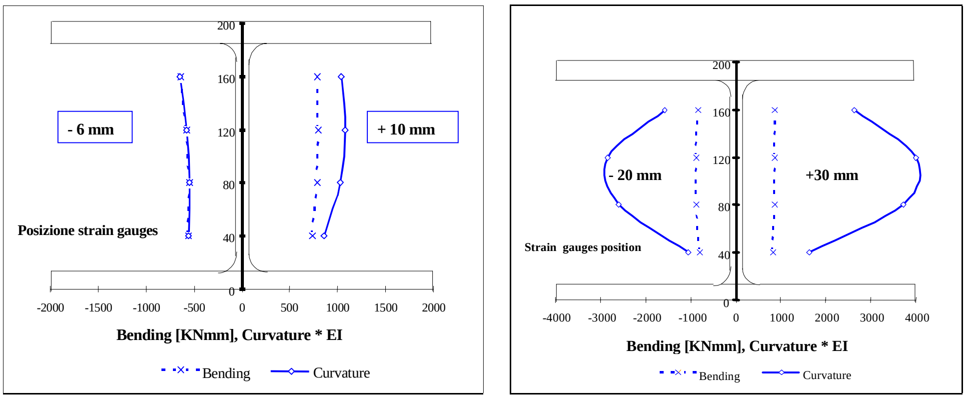


Fig.4- Bending moment and curvature distribution along the profile web

Thus, after this preliminary investigation, the attention was focused on the coupling of the device with the frame. At the first moment the transmission of the load from the frame to the device was studied in order to obtain its precise dimensioning.

THE TRANSMISSION LOAD METHODS

In order to schematize the whole system and so, determine the parameters that play a very important role for an efficient function of the dissipation device, the braced frame has been considered as a shear type model (Figure 5) while the device is represented by a rotation spring

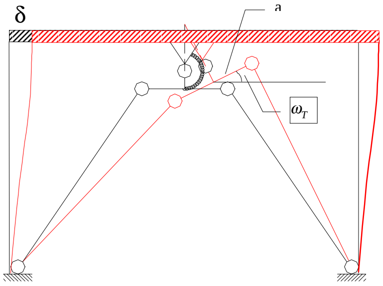


Fig.5- Coupled system schematisation

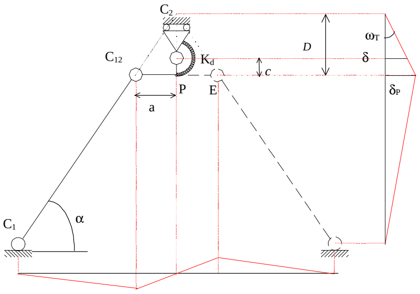


Fig.6- Kinematics chains configuration

The angular stiffness K_d is the term given to the device and it represents the bending moment to apply on the structure to obtain a unit rotation ω_T of the hinge. This bending moment is evaluated by either :

$$\omega_T = \frac{Ml}{EI_s} + \frac{2Mb}{12EI_a};$$

during the elastic phase or

$$\omega_T = l \cdot \chi_e \cdot \sqrt{\frac{M_e}{3M_e - 2M}} + \frac{2Mb}{12EI_a};$$

during the elastic-plastic phase.

This rotation depends on the δ displacement of the frame. So if we consider the figure 6, in the small displacement theory by applying the kinematics chains' theorems we can see that the good functionality of the system depends on the "a" and "c" parameters which are characteristic of the dissipating device as well as on the α angle joints to the frame geometry.

In fact, by looking at the E point displacements, it can be seen that the horizontal displacement δ_E determines on the right bar a contraction joined to the component $\delta_E\cos(\alpha)$, while the vertical displacement v_E determines, on the same bar, an alignment due to the component $v_E \cdot\sin(\alpha)$. Since the rod must work as a rafter, in order to fulfill the congruence, the following relationship must be respected:

$$\delta_E \cos(\alpha) \geq v_E \sin(\alpha)$$

Where:

$$\delta_E = \delta_P - \mathrm{a} \cdot (1 - \cos(\omega_T))$$

$$v_E = \mathrm{a} \cdot \sin(\omega_T) + \mathrm{c} \cdot (1 - \cos(\omega_T))$$

Besides, since the ω_T rotation is very small the first term of the previous disequation is zero, while the other terms are always negative. So the validity of this system for the loads transmission depends on the fulfilment of that relationship, so the application range of this dissipating device for this system of application of the load is very limited.

It is possible to maximise the rotation ω_T, at the same imposed displacement at the top of the braced frame, by lowering the position of the absolute centre of the instantaneous rotation C_2. This aim can be reached by modifying the transmission system of the load from the brace rod to the dissipating device. Thus the scheme of figure 7 is obtained. In this scheme the "*a*" arm of the force that produced bending moment along the web profile, is completely nullified, while the lever which produces bending moment, becomes the rigid trunk "c" whose position is rotated at 90° in respect to the previous scheme. Now the bending moment is due to the horizontal component of the load instead of the vertical one as in the prototype n.1.

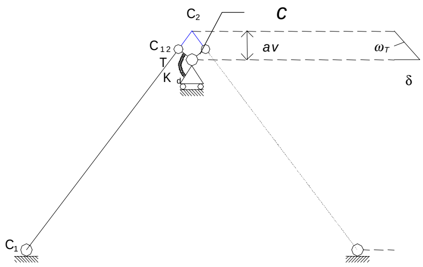


Fig.7- New system for the load transmission

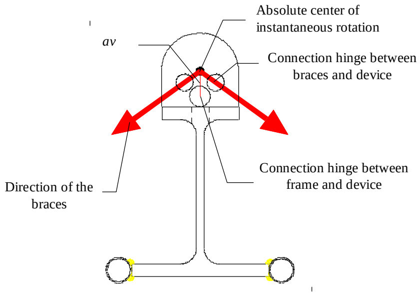


Fig.8- The modified hysteretical device

In small displacement theory the frame displacement is completely resisted by the rotation ω_T according to the expression reported above:

$$\omega_T = \arctan\left(\frac{\delta}{a_v}\right)$$

where a_v represents the distance between the load application hinge and the connection hinge to the frame. Under this condition the diagonal of the brace placed on the right cannot undergo buckling phenomena and so it can work immediately when the displacement δ is inverted. Now, by removing the small displacement hypothesis and considering both the bracing diagonal and the "c" portion as infinitely rigid, the new position of the "T" hinge, due to an imposed displacement δ of the roller bearing, will be given by the intersection between the circle arcs with L_p and a_v radius (L_p brace diagonal length) whose centre lies at the column base of the frame and on the roller bearing respectively. The dimensioning of the hysteretical device to be inserted within a braced frame structure depends on an energetic parameter as well as on the choice of both the device and the distance a_v which represents the arm of the couple.

THE MODIFIED PROTOTYPE

The connection among braces, hysteretical device and frame described in figure 7 can be realized by modifying the original prototype as shown in figure 8. This model still adopts the same static scheme of the model n.1 but differs from it because the position of the point of the load application is not on the upper flange of the profile but in a hinge with variable eccentricity in respect to the external hinge constrain. The possibility of changing the position of the connection hinge between device and braces, i.e. aligning either to the connection hinge between frame and device or in eccentric position compared to the latter, permits us to obtain a different shape of the hysteretical cycles. On the other hand, a very small a_v arm determines the transferring of a very high load from braces to device, although it permits it to come into play under very small δ displacements (i.e. comparable with the r.c. frame displacements). In this case sometimes, it can happen that a new force occurs in the mid-span of the frame determining an increasing of the shear and bending moment solicitation at this point. This fact might become relevant in the case of seismic retrofitting of the existing structure, so it should be much more convenient to have recourse to the use of the "X braced frame" (Fig. 9) instead of "inverted k braced frame". In this case the direction of the load application changes so as that all the entire force generates bending moment along the web profile.

In the following, model n.2 refers to the modified model to be inserted inside a "Inverted k braced frame" while model n. 3 refers to the modified model to be inserted inside a "X braced frame".

Theoretical investigation on the modified model

Whatever the direction of the load application may be, the statical scheme of the hysteretical device remains that of figure 9. The horizontal displacement of the "B" point is given by the sum of the component due to the rigid rotation of the "c" portion and the component due to the deflection of the portion "*L*" that may be deformed. In this case the stressed and strained conditions have been investigated by means of the study of the second invariant of the deviatoric tensor J_2 according to Von Mises yielding criteria. The trend of this, reported in figures 10-11, confirms the original requirement of having a uniform plasticization along the web while the flanges remain within the elastic domain It is evident that this permits us to avoid the damaging of the profile. In fact, when the imposed displacement increases, the elastic core decreases and the plasticisation propagates along the web.

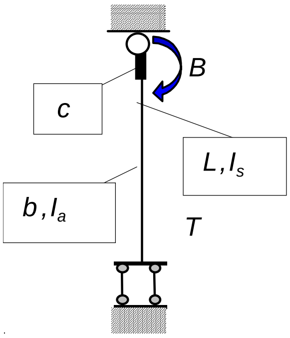
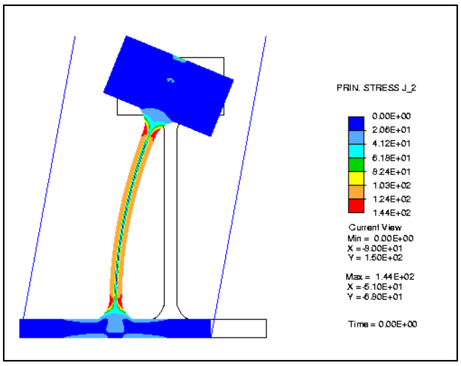


Fig.9- Statical scheme of the modified prototype



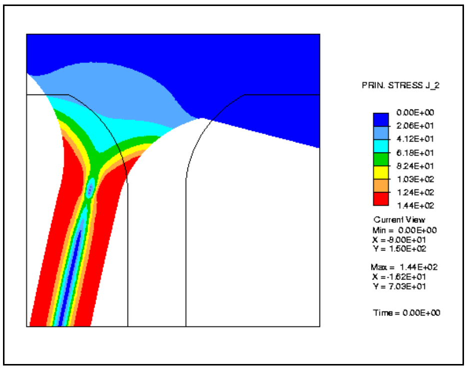
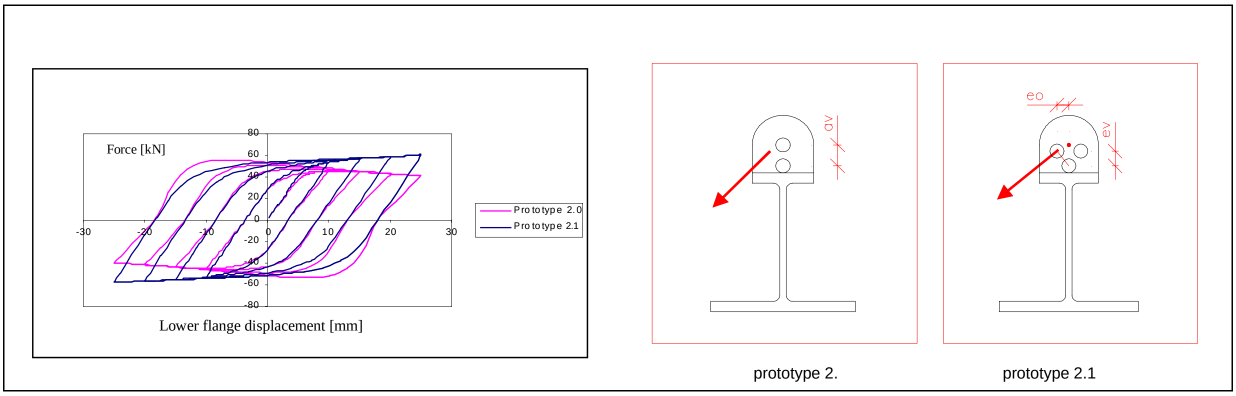


Fig.10- The flow of the deviator tensor J_2

Fig.11- Pasticization along the web

Furthermore, the possibility of changing the position of the connection hinge between device and braces, i.e. aligning either to the connection hinge between frame and device or in eccentric position respect to the latter, permits us to obtain a different shape of the hysteretical cycles as shown below.



prototype 2.

prototype 2.1

Fig.12- Hysteretical cycle for the device to be inserted in the Inverted k braced frame

Figure 12 highlights that the prototype 2 had shown a light softening which disappeared in the prototype 2.1. In fact in the latter the position of the hinge for the transmission of the load is such as to have the maximum bending moment from the beginning by means of the arm of the couple which is perpendicular to the direction of the applied load.

From figure 13 it can be seen that prototype 3.1b (*ecc*=6.87 mm) behaves as an elastic-perfectly plasticized device; while prototype 3 (ecc.=0) shows a light “hardening”, very close to the prototype 3.1a (*ecc*=1.32 mm), which presents a very small eccentricity. Both the prototypes 3.1c (*ecc*=14.74mm) and 3.1d (*ecc*=20mm) show, instead, a more or less evident softening. The data obtained from the investigation carried out on the prototype 3 confirm what we said before because in this case the arm that produces bending moment along the web decreases according to the rotation and the increasing of the load.

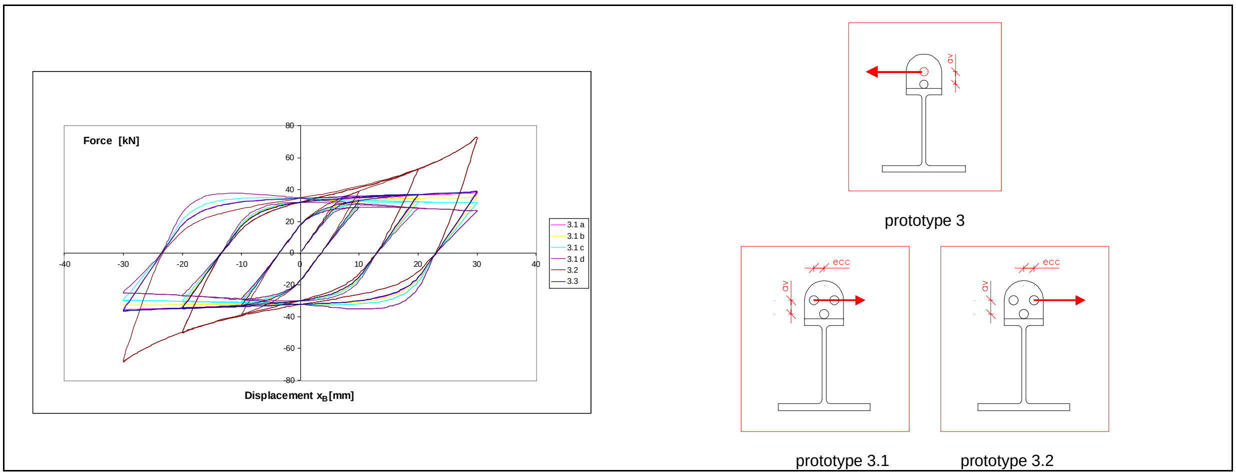


Fig.13- Hysteretical cycle for the device to be inserted in the Inverted k braced frame

Experimental investigation on the modified model

Prototype n.2 and n.3 have been subjected to an experimental investigation. The loading history had foreseen six different steps each of which constituted by three cycle at the same imposed displacement (±3 mm, ±6 mm, ±10mm, ±15 mm, ±20 mm and ±25 mm).

Prototype n.2: experimental results

The tests carried out on this model have confirmed the theoretical prediction. The rotation diagram is almost uniform for all the web and the normal action is practically zero. The hysteresis loops (fig.14) are very stable and no damaging appears along the web. The theoretical softening disappears during the experimental investigation because of some friction effects. The high value of the ratio between the plasticization and the bending moment and its constant distribution along the web, highlights the good performance of this hysteretical device as well as that of the material.

Furthermore, the vertical alignment of the hinges reduces the effects due both to great displacements found in the case of prototype 1 and the axial deformation which, in this case, is zero.

Prototype n.3: experimental results

In this case the data obtained from the tests have also confirmed the numerical prediction. Namely, the plastic deformations occur along the web profile and they are constant along it. The all value of the strain is lower than 10000 µm/m, so as the material is not hardened and the risk of cracks for the oligicyclic fatigue, decreases.

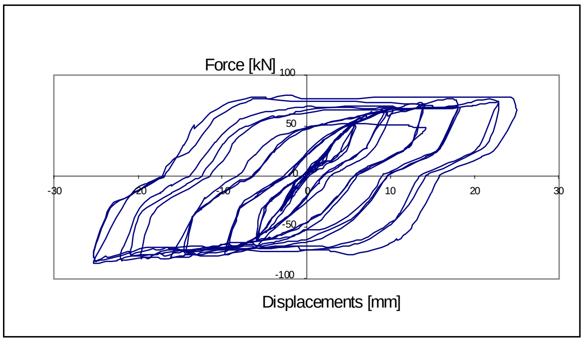


Fig.14- Hysteresis loops for the experimental investigation on prototype 2

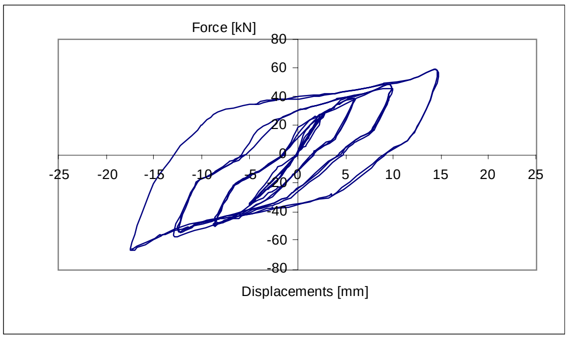


Fig.15- Hysteresis loops for the experimental investigation on prototype 3

However the study of this prototype confirms the efficacy of inserting it within X braced frames. In fact, the hysteresis loops (fig.15) are characterised by a level of the applied load, for the same imposed displacement used in the tests carried out on the other models, lower than the case of the device inserted in the inverted k braced frame. This has given an advantage in terms of solicitations on the mid-span of the beam which in this case does not have to absorb the vertical component of the applied load.

CONCLUSIONS

The evolution of a new hysteretical device for seismic protection of the framed structures is discussed in the paper. This device is obtained from the cutting of an opportunely constrained commercial steel profile. The statical scheme adopted permits it to have a uniform distribution of the bending moment along the dissipating portion without any damage as shown from the tests carried out on the prototype 1. In fact, the hysteresis loops are very stable even after a very high number of loading cycles.

The original scheme adopted has been modified in order to have a good performance of the same when it is inserted in a braced frame mesh. To this aim the position of the hinge for the application of the load has been moved (prototype 2 and 3), while the statical scheme remained the same. It has been possible to obtain a different shape of the hysteretical cycle, and thus of the dissipated area, by changing the angle between this hinge and the external constrained one. The ideal solution seems to be obtained by placing the hinge in a way that the arm of the force forms an angle of 90° with the direction of the load applied. In this way both the hardening, or softening effects are avoided.

Besides, the modified prototype permits us to decrease the effects of the large displacement and to make irrelevant the presence of the axial strains along the web. Under this condition the plasticization is connected only to the presence of the bending moment.

The tests carried out on the prototypes 2 and 3 have also given the hysteresis loops as very stable without any damage. The effects of the friction permit to delete the softening effects found during the numerical investigation carried out on the prototype 2 and so to obtain cycles that are wide enough with great dissipation of the energy. In fact, in the case of prototype 2 the model behaves as an elastic-perfectly plastic device very close to the ideal one with a performance factor equal to the unit.

Prototype 3 permits us to avoid any inconvenient effects in the mid span of the beam, the hardening found in its hysteresis loops can be avoided by moving the position of the hinge for the transmission of the load, as shown in figure 13 or by changing the eccentricity between the hinges.

In conclusion, this new hysteretical device has been inserted in a braced r.c. frame mesh, and the coupling is studied out as reported in [3]. The data obtained were very good and confirm, once again, the excellence of the proposed device.

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