Re-centring Capability of Seismic Isolation Systems: A controversial matter moving scarcely towards its settlement

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SUMMARY

The re-centring capability is, among the four main functions of seismic isolation systems, the one least kept in due consideration by designers. This has led, in certain cases of earthquake attack, to serious damage and even structural collapse in the wake of excessive cumulative displacements. This author developed a theoretical approach to this main function, suggesting an energy-based criterion for its quantification and the newly proposed criterion was accepted for an oral presentation at the 13th WCEE (Vancouver, 2004).Its experimental validation occurred within the framework of the LESSLOSS Research Project funded by the European Commission and has been adopted in the European Norm EN 15129 : *Anti-seismic Devices*. The scope of the paper is that of illustrating the state-of-the-art in the framework of re-centring capability evaluation and confront the problems involved, comparing the requirements specified in the different standards, as well as commenting on the blatant discrepancies thereof.

Keywords: re-centring capability, self-centring capability, lateral restoring capability

1. INTRODUCTION

It was not until the most recent years that re-centring capability (sometimes referred to as restoring force) was identified as a fundamental function of an isolation system. This tardy occurrence can perhaps be explained by the fact that, historically, the first seismic isolators were conventional laminated rubber bearings – which are endowed with an optimal re-centring capability owing to the elastic restoring force developed when the same undergo shear deformation.

With the introduction in the market of other types of anti-seismic devices that are not fitted with an intrinsic re-centring capability (i.e.: lead rubber bearings, sliding isolators with steel hysteretic elements, friction devices, etc.), the problem of providing this function has assumed a key role (Medeot, 2004).

Notwithstanding, the latter never received sufficient attention from seismic engineering experts, to the point that the formulation of a criterion to quantify it in a Standard was only acknowledged for the first time in 1991 by the AASHTO Guide Specification for Seismic Isolation Design, expressly requiring the following:

"*The Isolation System shall be configured to produce a lateral restoring force such that the lateral force at the Design Displacement is at least 0.025 W greater than the lateral force at 50 percent of the Design Displacement*" (where W is the weight of the supported mass).

The revision of the aforesaid AASHTO Guide Specifications, published in 1999, adds a new requirement, but still maintains the old one. However, curiously enough, it became much less restrictive:

"*… the restoring force at d_i shall be greater than the restoring force at 0.5 d_i by not less than W/80.*" [Note: W/80 = 0,0125 W, that is the half of the value stated in 1991].The application of this criterion leads in some cases to paradoxical conclusions, as we will see in the follow-up to the paper.

The first version of Eurocode 8, Part 2: Bridges has also acknowledged the same criterion, even though it does not expressly cite re-centring capability. In its first revision, a new criterion has been introduced in section 7.7.1 *Lateral restoring capability* that was so strict that no one of the isolators' types existing on the European market was capable of fulfilling it.

The legitimate complaints of the European manufacturers led to a new revision in which a new criterion appears, the strictness of which is reduced by a factor of 10 compared to its predecessor.
Even this new version did not stand up to experimental verification, in that it excludes some devices that are perfectly re-centring, while it absolves others that are not.

The above leads to the conclusion that in the field of evaluating re-centring capability of seismic isolation systems, in accordance with the two above mentioned norms, there is great uncertainty and a high degree of confusion. None of them is based on solid scientific fundamentals and, above all, they are not supported by exhaustive experimental results.

2. THE RECENTRING CAPABILITY EVALUATION BASED ON ENERGY CONCEPTS

In 2003 this author developed a theoretical approach to the evaluation of the re-centring capability of seismic isolation systems, suggesting an energy-based criterion for its quantification, that also incorporates praiseworthy simplicity.

The newly proposed criterion was accepted for an oral presentation at the 13th World Conference in Vancouver (Medeot, 2004) and since then gained an increasing consensus among the technical and scientific community. To better understand this paper it is opportune to summarize the fundamentals of the new criterion, with the conclusions achieved for the main types of existing isolators.

It is known that the two most powerful tools to reduce structural response during an EQ attack are the period shift and the damping, which may be achieved through the adoption of a seismic isolation system. The four fundamental functions of the latter are the following:

- i) Transmission of vertical loads
- ii) Lateral flexibility
- iii) Energy dissipation and
- iv) Re-centring capability

It should be noted that Energy dissipation and Re-centring capability are two antithetic functions, in that, other conditions being equal, the larger the Energy dissipation, the lesser the Re-centring capability.

Let's consider the energy balance equation in the following form valid for structures (Uang, 1988):

$$E_i = E_S + E_H + E_V \qquad (1)$$

where: - E_i represents the mechanical energy transmitted to the structure by the seismic ground motion through its foundations.
- E_S is the reversibly stored energy (elastic strain energy, gravity potential energy and kinetic energy)
- E_H is the energy dissipated by hysteretic deformation
- E_V is the energy dissipated by viscous damping

The term E_S may be interpreted as “total potential energy” of the Dirichlet-Lagrange theorem that deals with the dynamic stability concept. Said theorem states that all the mechanical systems tend to reach the condition where the total potential energy is minimum and this condition is stable.

According to the Energy Approach the re-centring capability is quantified through a comparison between the first two terms of the second member. In fact, the energy E_V dissipated by viscous damping is associated with the forces F that depend only on the velocity v through a constitutive law of the type:

$$F = C \times v^{\alpha} \qquad (2)$$

where are constants that depend on the type and size of the damper.

For v→0 also F→0, that is, there does not exist a characteristic strength associated with this type of force. In this regard the AASHTO *Guide Specifications* state the following:

“*Forces that are not dependent on displacements, such as viscous forces, may not be used to meet the minimum restoring force requirements”.*

In conclusion, in the proposed approach, the verification of the re-centring capability of an isolator (or an isolation system) consists in the simple comparison between the two types of energy in act during a seismic attack, which are calculable or experimentally measurable.

In other words, one has to check that, for a displacement from 0 to design displacement d_d, the reversibly stored energy E_S is greater than a given portion λ of the energy dissipated by hysteretic deformation E_H , that is to say:

$$E_S \geq \lambda \cdot E_H \qquad (3)$$

Adopting the condition of adequate restoring capability suggested by Professor Mauro Dolce (residual displacement lesser than 0,5 times the design displacement d_d) that takes into account a reliability factor $\gamma_x = 1{,}5$ for the isolation devices specified in the Eurocode 8, Part 2, it results $\lambda = 0{,}25$, that is:

$$E_S \geq \frac{1}{4} \cdot E_H \qquad (4)$$

This value has been validated by some hundreds step-by-step time-history analyses conducted on real cases and, above all, by an exhaustive experimental study conducted within the framework of the LESSLOSS Research Project funded by the European Commission, which lasted three years (2004-2007). Over 200 trials were carried out in two distinct testing campaigns at the shake-table facility of ENEA Casaccia near Rome.

The requirement (4) can be easily translated in verification formulae for each type of isolator. The three most popular types of isolator are examined hereinafter.

2.1 Lead Rubber Bearing

In the case of Lead Rubber Bearings (LRBs), if we indicate with A_r the cross-sectional area of the rubber bearing, with h as its total rubber thickness, G as the rubber shear modulus and d_d as the design displacement, the elastically stored energy E_S equals:

$$E_S = \frac{1}{2} \cdot \frac{G \cdot A_r}{h} \times d_d^2 \qquad (5)$$

In (5) the modest contribution of the energy elastically stored in the lead core was conservatively ignored.

Indicating with A_{Pb} the cross-sectional area of the lead core and τ_{Pb} as the shear stress at which the lead yields, the hysteretically dissipated energy E_H then equals:

$$E_H = \tau_{Pb} \cdot A_{Pb} \cdot d_d \tag{6}$$

Placing the typical value $\tau_{Pb} = 10\text{MPa}$ in (6), condition (4) is satisfied if:

$$\frac{A_{Pb}}{A_r} \leq \frac{1}{5} \cdot G \cdot \gamma_d \tag{7}$$

where $\gamma_d = \frac{d_d}{h}$ is the design shear strain.

From the above it can be inferred that, for the LRBs, re-centring capability is governed by the ratio between lead core and rubber cross sections and its limit value depends on the product of rubber shear modulus G and the design shear deformation γ_d.

2.2 Flat Surface Slider

These are seismic isolators obtained through a combination of a conventional flat sliding bearing and steel hysteretic elements (as developed in Italy) or polyurethane springs (as developed in the USA).

These devices can be represented by the model illustrated in Figure 1 below:

To evaluate both the reversibly stored energy E_S and the energy dissipated by hysteretic deformation E_H we resort to the model represented in Figure 1 below.

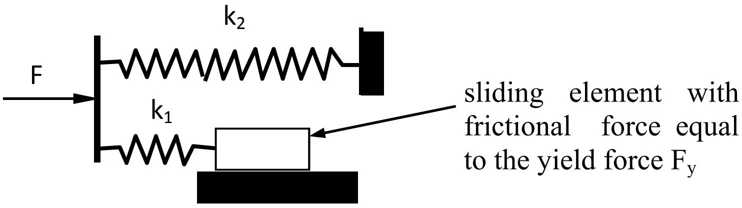

Figure 1: Model having the samecharacteristic bi-linear curve of a hysteretic system

The criteria for equivalence with a conventional bi-linear characteristic curve of a hysteretic device are given by the following expressions:

$$\begin{cases} \text{initial (elastic) stiffness } k_e = k_1 + k_2 \\ \text{post-elastic stiffness } k_p = k_2 \\ \text{yield force } F_y = k_1 \cdot d_e \end{cases} \tag{8}$$

The yield force F_y shall include also the frictional force of the sliding surface.

The energy stored elastically is equal to:

$$E_S = \frac{1}{2} k_1 \cdot d_e^2 + \frac{1}{2} k_p \cdot d^2 = \frac{1}{2} k_e \cdot d_e^2 \left(1 - \eta + \eta \cdot m^2\right) \tag{9}$$

The energy dissipated hysteretically is equal to:

$$E_H = k_1 \cdot d_e \cdot (d - d_e) = k_e \cdot d_e^2 (1 - \eta) \cdot (m - 1) \tag{10}$$

where:$\eta = k_p / k_e$ represents the ratio between the post-elastic branch stiffness and the elastic branch stiffness of the characteristic curve, and m is the ductility factor (i.e. $m = d_d / d_e$).

It can be concluded that requirement (4) is satisfied for:

$$\eta = \frac{k_p}{k_e} \geq \frac{m-3}{2m^2 + m - 3} \tag{11}$$

It is interesting to notice that, in the case of Flat Surface Sliders, re-centring capability is governed by the ratio η between the post-elastic branch stiffness and the elastic branch stiffness of the characteristic curve and its limit value depends only on one magnitude, i.e. the ductility factor m.

2.3Curved Surface Slider

This type of seismic isolator is usually referred to as Friction Pendulum®(Zayas ,1995). In this case the energy accumulated under the form of gravity potential energy is:

$$E_s = W \cdot R \cdot (1 - \cos \alpha_d) \tag{12}$$

where: W is the supported weight

R is the radius of curvature of the spherical surface

α_d is the design angular displacement

The energy E_H dissipated through friction is:

$$E_H = \mu_{dyn} \cdot W \cdot R \cdot \int_0^{\alpha_d} \cos \alpha \cdot d_\alpha = \mu_{dyn} \cdot W \cdot R \cdot \sin \alpha \tag{13}$$

where μ_{dyn} is the dynamic coefficient of friction.

The design angular displacement α_d is linked to the design linear displacement d_d and the radius of curvature R of the spherical surface by the equation:

$$d_d = R \cdot \sin \alpha_d \tag{14}$$

Introducing expression (14) into (12) and (13) we obtain that, for the Friction Pendulum®, requirement (4) is satisfied by:

$$\frac{d_d}{R} \geq \frac{8 \cdot \mu_{dyn}}{16 + \mu_{dyn}^2} \tag{15}$$

Considering that $\mu^2 << 16$, the requirement expressed by (4) simply becomes:

$$\frac{d_d}{R} \geq \frac{\mu_{dyn}}{2} \tag{16}$$

From the above one can conclude that, in the case of the Friction Pendulum®, Re-centring Capability is governed by the ratio between design displacement d_d and radius of curvature R of the spherical surface, and the limit value depends only on the dynamic coefficient of friction μ_{dyn}.

Similar mathematical considerations may be developed for any other type of seismic isolator (or isolation system) and the result will be always the same: the comparison between a parameter that is characteristic of the type of isolators under examination and a limit value.

3. THE EXPERIMENTAL VALIDATION

The experimental validation of the new energy-based criterion to evaluate the re-centring capability of isolation systems occurred within the framework of Sub-project 6 of the LESSLOSS Research "Mega Project" –which was funded by the European Commission (EC) with 6,4 M (Medeot, 2008)

Actually, the general scope of the above mentioned Sub-project 6 was that of evaluating the benefits, as well as ascertaining the limitations, of the two important types of isolators, namely:

a) flat surface slider coupled with steel hysteretic elements
b) curved surface slider (Friction Pendulum®)

Two distinct Sub-tasks were reserved to the examination of the two above mentioned classes of devices and the objective common to them was that of improving knowledge of device behaviour in the presence of different seismic inputs.

Sub-task a) covers all the devices with a bi-linear force *vs.* displacement characteristic curve.

The reason for undertaking this study on the above types of devices resides in the fact that, conversely to the case of rubber isolators, experimental studies regarding them are essentially private-party type and their results have seldom been published, at least with respect to the devices' limitations or shortcomings themselves.

Due to space constraints, this paper is focusing only on the matters of re-centring capability of the devices of Sub-task a).As we have seen in the preceding section, each test is characterized by a pair of the dimensionless parameters (η, m), which univocally identifies it.

Figure 2 below is a graphical representation of the results achieved during the test campaign carried out at ENEA Casaccia shake table and the same are compared with the Energy Approach prediction (the fuchsia curve is the plot of Eqn. 11).

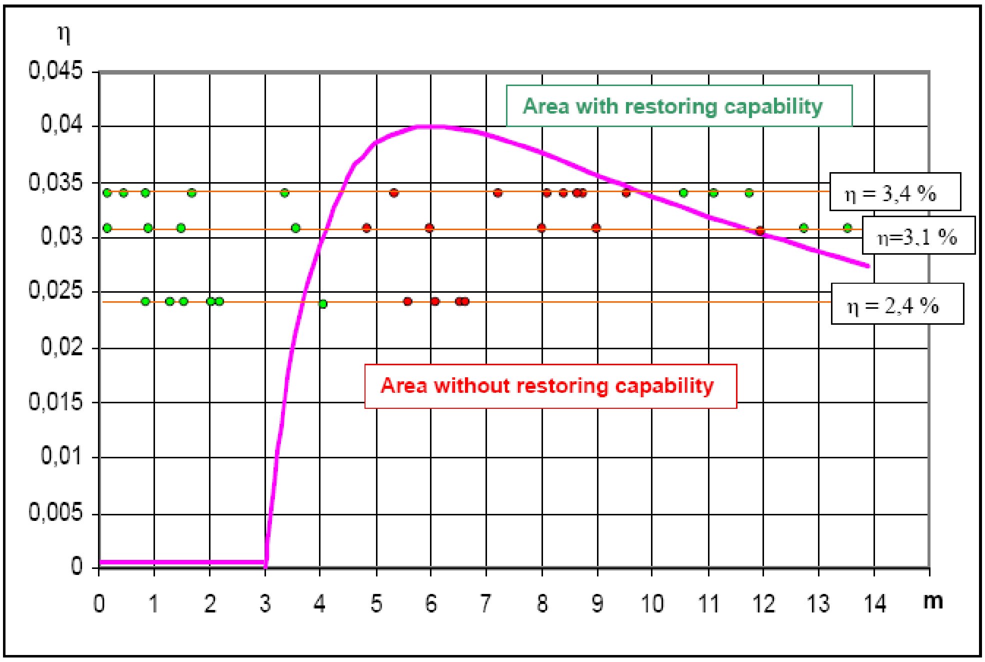

Figure 2: Graphical representation some of the results achieved during the test campaign carried out at ENEA Casaccia shake table and comparison with the Energy approach re-centring requirement.

The green coloured dots represent the cases (displacement time-histories) in which the condition of adequate restoring capability suggested by Professor Dolce is satisfied, while the red colour dots represent those cases where the same is not verified.

Figure 2 does not show the results relating to cases with $\eta > 0{,}04$, which turned out to be all represented by green coloured dots.

As we can observe, there is a very good agreement between the Re-centring evaluation method based on energy concepts and the experimental results of the testing campaign carried out at the shake table of ENEA Casaccia.

4. COMPARISON WITH US AND EUROPEAN NORMS

Due to space restraints, it is not possible to go on at length on this interesting subject. For those interested in following up, It is suggested reading the papers *Medeot, R. (2007)* and *(2011)* listed in the References.

The Norms taken into consideration are the following:

- AASHTO *Guide Specification for Seismic Isolation Design* (third edition, 2010)
- Eurocode 8: *Design of Structures for Earthquake Resistance-* Part 2

As already cited in the Introduction, the following requirement related to the re-centring capability that appears in the AASHTO *Guide Specifications* (under section 12.2-*Lateral restoring force*) :

"*... the restoring force at* d_d *shall be greater than the restoring force at 0.5* d_d *by not less than W/80.*"

The above criterion is not based upon solid theoretical fundamentals, but rather makes reference to an empirical approach.

To demonstrate this assertion, let's consider the case of the curved surface sliding isolator (i.e. the Friction Pendulum®).

The stiffness for this type of isolator is constant and equal to $k = W/R$. Thus, with the symbols used in Section 2.3 ,the above requirement is satisfied when:

$$\Delta F = \frac{k \cdot d_d}{2} = \frac{W \cdot d_d}{2R} \geq \frac{W}{80} \qquad (17)$$

that is:

$$\frac{d_d}{R} \geq \frac{1}{40} \qquad (18)$$

We conclude that according to the AASHTO *Guide Specifications* the re-centering capability of a Friction Pendulum® device is independent from the value of its dynamic coefficient of friction μ_{dyn}. This is obviously a paradox.

Actually, according to the energy-based approach, a seismic isolation system is endowed with an adequate re-centering capability when:

$$\frac{d_d}{R} \geq \frac{\mu_{dyn}}{2} \qquad \text{(see Eqn. 16)}$$

Thus, the dynamic coefficient of friction μ_{dyn} plays a fundamental role in the re-centring evaluation.

Let us now consider the case of Eurocode 8: *Design of Structures for Earthquake Resistance*- Part 2,

Figure 3 here below shows the graphic comparison between the re-centring requirements as in the last official version of Eurocode 8 (August 2005) and EN 15129 (energy based approach).

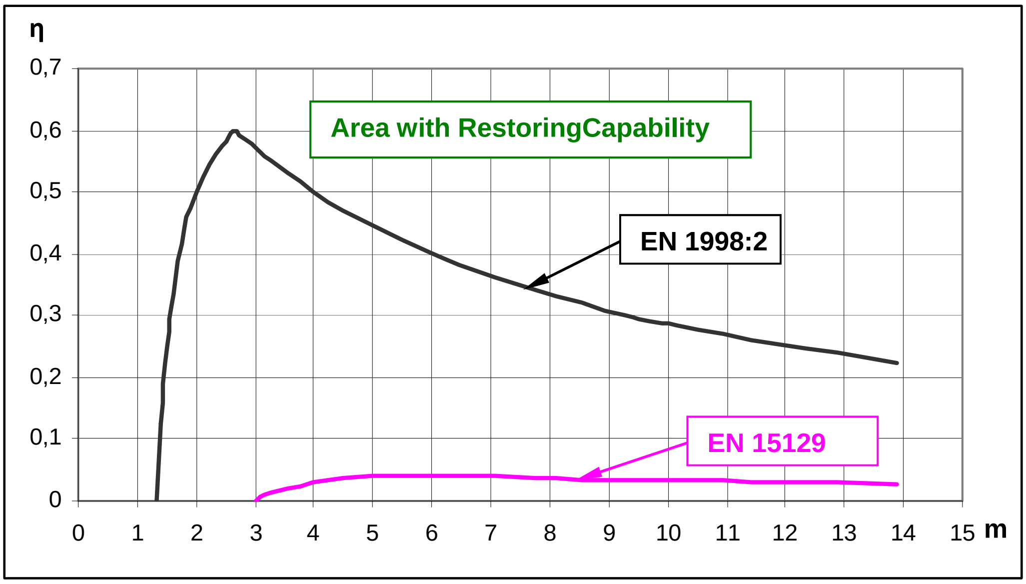

Figure 3 : Comparison between the restoring capability requirements of EN 1998-2 (version August 2005) and EN 15129

Please notice that the ordinate scale (parameter η) of Figure 3 is ten times larger than that of Figure 2.

As already mentioned in the Introduction, the requirement expressed in section 7.7.1 *Lateral restoring capability* was so strict that no one of the isolators' types existing at that time on the European market was capable of fulfilling it.

To the legitimate remonstrations of the European manufacturers of seismic hardware, the Working Group in charge for the second revision of Eurocode 8 – Part 2 responded with the following requirement proposal:

$$d_{\mathrm{m,i}} - d_{\mathrm{o,i}} \geq \gamma_{\mathrm{du}} d_{\mathrm{bi}} \left[1 + 1.35 \frac{1 - \left(d_{\mathrm{y}} / d_{cd} \right)^{0.6}}{1 + 80 \left(d_{\mathrm{cd}} / d_{\mathrm{r}} \right)^{1.5}} \right] \qquad (19)$$

where:

$d_{m,i}$ is the displacement capacity of the isolator i in the considered direction, i.e. the maximum displacement that the isolator can accommodate in this direction,
$d_{bi,d}$ is the design displacement of isolators in the examined direction,

$d_{o,i}$ is the non-seismic offset displacement of isolator i,

d_y is the yield displacement of the equivalent bilinear system

d_{cd} is the design displacement of the isolating system in the examined direction

d_r is the static residual displacement of the system in the same direction

γ_{du} is a numerical coefficient reflecting uncertainties in the estimation of design displacements.

Equation (19) is graphically represented in Figure 4 on next page and compared with the curve of Eq. (11) representing the Energy approach re-centring requirement.

Please notice that for Eq. (19) it has been assumed $d_{m,I} = 1{,}5 \cdot d_{bi,d}$ that represents the minimum requirement in EN 1998-2.

In both cases, the areas below the respective curves are those not endowed with adequate re-centring capability.

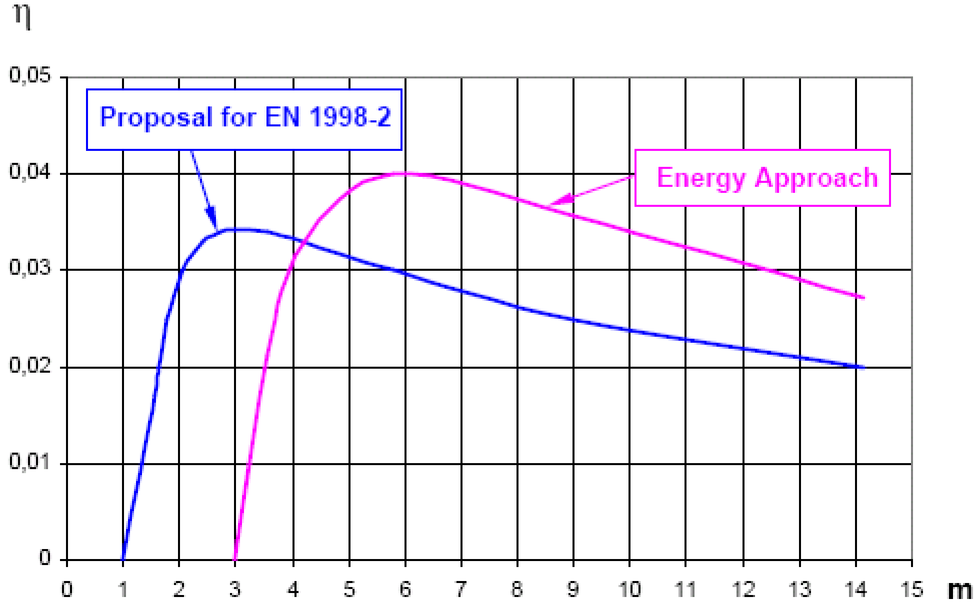

Figure 4: Graphical representation of the Re-centre capability evaluation according to the Energy Approach and the new proposal for EN 1998-2

Surprisingly, the new curve is reduced by about a factor 13 with respect to the previous one (see Figure 3) and this fully justifies the complaints of the European Seismic Hardware manufacturers.

However, the new curve is in sharp disagreement with experimental results reported in Figure 2, in the sense that it considers non-re-centring certain devices that are almost elastic (m = 1 to m = 3), and more importantly, attributes re-centring capability to devices that do not have it at all.

At the end of this paper, it should be noted that, even before entering into the merits of the validity of the methods for evaluating the re-centring capability of a seismic isolation system, it would be necessary to establish a common criterion (or criteria) for assessing whether or not a system has an adequate re-centring capability.

In other words, when examining a displacement time history obtained from the recording of a seismic attack on an instrumented isolated structure, or from a shake table test, or more simply from a dynamic analysis performed on the computer, what is the rule (or rules) necessary in order to determine whether it is a re-centring system or not?

In the testing campaign reported in this paper, we have taken the approach proposed by Prof. Mauro Dolce, mentioned in Section 2.

5. CONCLUSIONS

- The re-centring capability is, among the four main functions of seismic isolation systems, the one least kept in due consideration by designers and this has led, in certain cases of earthquake attack, to serious damage and even structural collapse in the wake of excessive cumulative displacements.

- The main Standards that deal with re-centring capability evaluation are the AASHTO *Guide Specification for Seismic Isolation Design* (third edition, 2010), the Eurocode 8: *Design of*

Structures for Earthquake Resistance- Part 2 and the EN 15129: *Anti-seismic Devices,* which adopt criteria very dissimilar to each other and with conflicting results, something that leads to great uncertainty and a high degree of confusion among the designers.

- The first two do not furnish acceptable criteria of general validity and are not based on solid scientific fundamentals, but rather make reference to empirical approaches; above all, there is no evidence of being supported by exhaustive experimental results.

- The European Norm EN 15129 adopted the re-centring evaluation method based on energy concepts, which incorporates praiseworthy simplicity, in that it just involves the comparison of two calculable or measurable physical magnitudes, namely the reversibly stored and the irreversibly dissipated earthquake energy input.

- The validity of the new criterion has been confirmed by the results of several hundreds of step-by-step non-linear analyses conducted on real cases, as well as by a degree thesis at the University of Padua (Italy).Its experimental validation occurred within the framework of the LESSLOSS Research Project funded by the European Commission; the experimental results have fully substantiated this new method.

- It would be necessary to establish a common criterion (or criteria) for assessing, on the basis of a displacement time history, whether or not a given seismic isolation system possessesan adequate re-centring capability.

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