EXPERIMENTAL VALIDATION OF RE-CENTRING CAPABILITY EVALUATION BASED ON ENERGY CONCEPTS

Renzo MEDEOT

Chairman of CEN TC 340: Anti-seismic Devices
Seismic Engineering Consultant
E-mail: medeot@iol.it

ABSTRACT :

Present Norms do not furnish an acceptable approach of general validity to evaluate the re-centring capability of seismic isolation systems and none of them is based upon solid theoretical fundamentals, but rather, make reference to empirical approaches. This author developed a theoretical approach to this problem, suggesting an energy-based criterion for its quantification, that also incorporates praiseworthy simplicity. It just involves the comparison of two calculable and measurable physical magnitudes, namely the elastically (or, better said, reversibly) stored and the irreversibly dissipated earthquake energy input. The newly proposed criterion was accepted for an oral presentation at the 13th World Conference (Vancouver, 2004) and since then gained an increasing consensus among the technical and scientific community. 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 only recently within the framework of the LESSLOSS Research Project funded by the European Commission, which lasted three years (2004-2007). Over 200 trials were conducted in two distinct testing campaigns at the shake-table facility of ENEA Casaccia near Rome. The results have fully substantiated the method for evaluating the re-centring capability of seismic isolated systems based on the energy approach. The scope of this paper is that of illustrating the testing program and reporting in detail the results thereof, as well as commenting on the blatant discrepancies with the criteria adopted in some international Norms.

KEYWORDS: Seismic Isolation, Re-centring Capability, Restoring Capability

1. INTRODUCTION

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 (Vancouver, 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, in particular for flat surface sliders coupled with steel hysteretic elements, which were used in the experimental testing campaign.
It is known that the four fundamental functions of a seismic isolation system are the following:
i) Transmission of vertical loads; ii) Lateral flexibility on the horizontal plane; iii) Dissipation of substantial quantities of energy and iv) Re-centring capability
It should be noted that Energy dissipation and Re-centring capability are two antithetic functions and their relative importance depends primarily on the case under examination.
Let's consider the energy balance equation in the following form valid for structures

$$E_i = E_S + E_H + E_V \tag{1}$$

where: Ei 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, potential energy and kinetic energy)
E_H is the energy dissipated by hysteretic deformation
E_V is the energy dissipated by viscous damping

According to the Energy approach, the criterion to establish the re-centring capability of a seismic isolation system is based upon a comparison between the energy stored by the system in a reversible form E_S (elastic, potential etc.) and that hysteretically dissipated E_H.
The energy dissipated by viscous damping does not participate in the re-centring process.
Re-centring capability is quantified through a comparison between the first two terms of the second member of equation (1)
For deformations from 0 up to the design displacement d_d, one has to check that the reversibly stored energy E_S is greater than a given portion of the energy dissipated by hysteretic deformation E_H, that is to say:

$$E_S \geq \lambda \cdot E_H \tag{2}$$

The results of numberless step-by-step non-linear analyses, as well as the experimental results of the testing campaigns conducted at the shake table rig at ENEA-Casaccia, demonstrated that a seismic isolation system possesses sufficient re-centring capability when:

$$E_S \geq 0{,}25\ E_H \tag{3}$$

The above criterion has proven to be valid and applicable to all types of existing isolation devices, as well as construction typologies.
The requirement (3) can be translated into formulae or design criteria for each type of isolator.
For example, for Lead Rubber Bearings expression (3) is satisfied for:

$$\frac{A_{Pb}}{A_r} \leq 0{,}2 \cdot G \cdot \gamma_d \tag{4}$$

where: A_{Pb} the cross-sectional area of the lead core; G is the rubber shear modulus; γ_d is the design shear strain and A_r the cross-sectional area of the rubber bearing.
For Friction Pendulum expression (3) is satisfied for:

$$d_d \geq \frac{R \cdot \mu}{2} \tag{5}$$

where: d_d is the design displacement; R is the radius of curvature of the spherical surface and μ is the dynamic coefficient of friction.
Finally, let's consider the case of flat surface slider equipped with steel hysteretic elements as energy dissipaters, which was the type of isolator used in the testing campaign at ENEA Casaccia.
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.

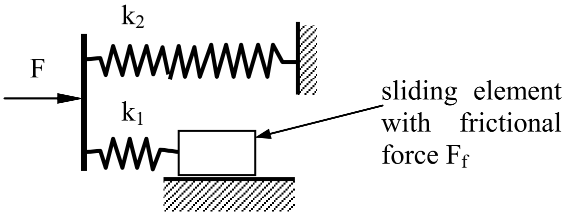

Figure 1: Model having the same characteristic bi-linear curve of a hysteretic system

The criteria for equivalence are given by the following expressions:

$$\begin{cases} k_e = k_1 + k_2 \\ k_p = k_2 \\ F_f = k_1 \cdot d_e \end{cases} \tag{6}$$

With reference to the Figure 2 on next page, expression (3) is satisfied for:

$$\eta \geq \frac{m-3}{2m^2 + m - 3} \tag{7}$$

where: – η is the ratio between the post-elastic and the elastic stiffness of the hysteretic element (i.e. $k_p = \eta \cdot k_e$)
– m is the ductility factor (i.e. $d_d = m \cdot d_e$).

Unlike the preceding two types of isolators, in the case of flat surface sliders equipped with steel hysteretic elements, the re-centring capability is governed by two dimensionless parameters only.

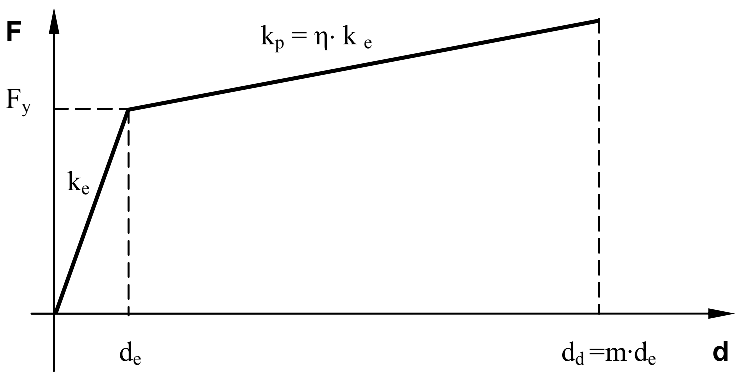

Figure2: Characteristic bi-linear curve of a hysteretic system

Equation (6) is graphically represented in Figure 3 below.

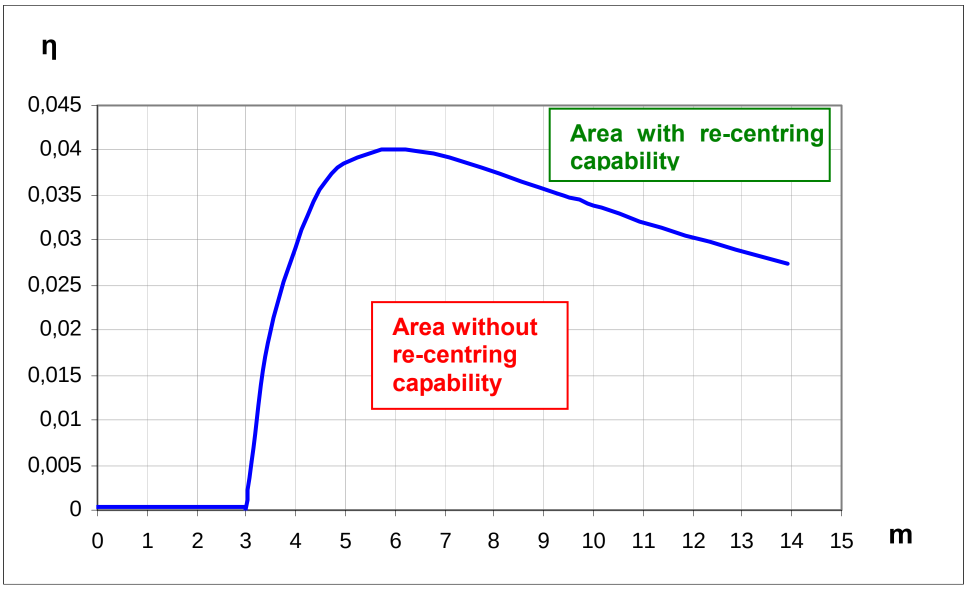

Figure 3: Graphical representation of the Re-centring capability evaluation according to the Energy Approach

2. THE TESTING PROGRAMME

The steel hysteretic elements were of the "Triangular Plate Damper" type , which was selected for its ease in both dimensioning and construction – but especially so because it is not subjected to any limitations patent-wise.
Several types of steel hysteretic elements were designed and manufactured, so as to cover the range of interest of both dimensionless parameters η (from 0,024 to 0,071) and m (from 1 to 13) that govern the behaviour of this type of devices.
All the steel hysteretic elements were subjected to the characterization tests at the Bundeswehr University in Munich during the month of December 2006.
For each type of device the testing procedure at the shaking table of ENEA-Casaccia was the following:

1) Subject the specimen to a harmonic sweep input in the range of frequency of expected resonance
2) Subject the specimen to progressively increasing seismic inputs, so as to obtain displacement time-histories with different values of ductility factor m.

Tests Nr. 1) were conducted at relatively low acceleration input, so as to keep the isolated system within the elastic limits.
After having determined the natural frequency f_0 of the isolated system, the elastic stiffness was evaluated through the expression:

$$K_e = (2\pi \cdot f_0)2 \cdot M \tag{8}$$

where M is the isolated mass.
These test were also conducted to remedy for possible "hidden springs" in the testing rig.
It must be observed that the precise determination of f_0 gave some problems, in that apparently there were two distinct peaks in the diagram oscillation amplitude vs frequency.
The only possible explanation for the above is the existence of two distinct values K_1 and K_2 of stiffness in the two direction. In this case, the correct value of the elastic stiffness K_e is given by the following expression:

$$K_e = \sqrt{K_1 \cdot K_2} \tag{9}$$

Once determined the actual value of the elastic stiffness, the characteristic curves of each type of hysteretic devices obtained from the tests at Bundeswehr University in Munich were corrected .
In this manner the actual values η and d_e (see e.g. Figure 4) were established.

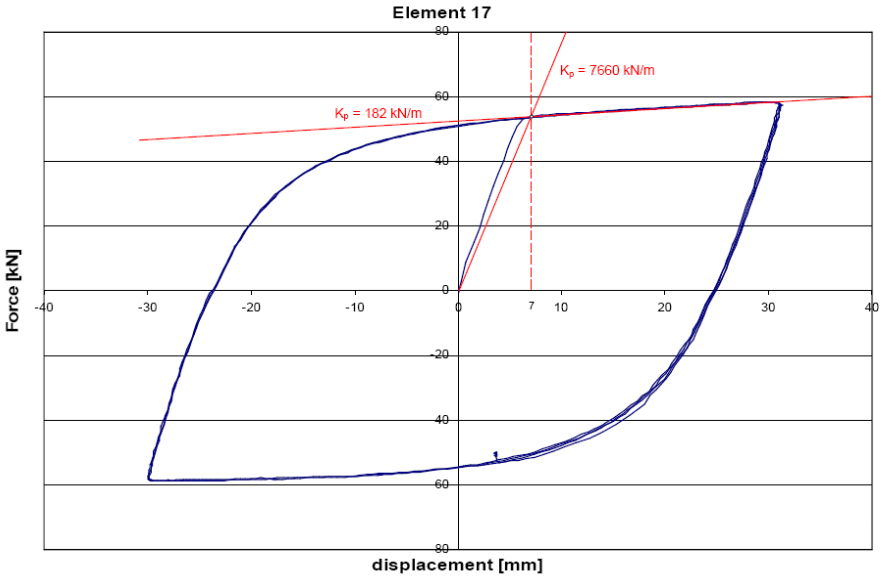

Figure 4: Five Hysteretic loops of Element # 17 and graphical evaluation of post-elastic stiffness K_p and elastic displacement d_e

It should be noted that the precise evaluation of the elastic displacement d_e is necessary to calculate the ductility factor m through the expression:

$$m = \frac{d_d}{d_e} \tag{10}$$

The seismic inputs were:

- various natural records, such as the Alkion, Bolu Mountain, Colfiorito, to name a few.
- a synthetic accelerogramme expressly prepared by Dr. Dario Rinaldis from ENEA, named "BCE";

Each device, which is characterized by a specific stiffness ratio η, was subjected to progressively raising seismic inputs (in terms of peak ground acceleration), which produced increasing maximum displacements.
If we interpret the latter as the maximum design displacement d_d for that specific test and calculate the relevant ductility factor m by means of expression (10), in the diagram η vs m of Figure 3 we will identify one precise point which univocally represents that test.
The mock up was a SDOF isolation system comprising:

- a steel frame ;
- Nr.4 MSM sliding spherical bearings (MSM is a special sliding material developed by Maurer Söhne);
- one (1) to three (3) steel hysteretic element(s), and
- a rigid reaction mass

Two distinct masses were used, equal to 12,2 and 16,4 t respectively.
The testing rig (see Figure 5 below) is completed with four guides that restrain the movement in one direction only, as well as other safety accessories that prevent the frame and the supported mass from running off the MSM sliding bearings in case the steel hysteretic element should break away (something that actually never occurred during the testing campaign).

Figure 4: Testing rig for flat PTFE sliding bearings equipped with steel hysteretic elements.
Reaction mass equal to 12,2 t

3. ANALYSIS OF EXPERIMENTAL DATA

During the testing campaign a formidable mass of data was gathered, with a total of over 200 runs executed, with 14 measure channels active.
The management and elaboration required considerable work from all who, through different tasks, participated in the execution of the tests.
The results were then used in quite different ways, depending on the intended objective.
For example ENEA in the Deliverable 39: *Numerical analysis of the Steel Hysteretic Devices* used the data for studies on mathematical modelling of the devices, while Maurer Söhne verified the repeatability of the results from distinct specimens of the same type of device, their reliability, fatigue resistance etc.
A word on this last characteristic of Steel Hysteretic Devices: it should be observed that no specimen has shown signs of failure, such as the appearance of draws, even though they were subjected to levels of strain superior to those foreseen by design, and for an elevated number of cycles.
Here below the results of the elaborations oriented toward experimental testing of the re-centring capability evaluation according to the energy approach are reported.
Due to space restraint, only the data relevant to a significative case are presented, precisely those of the steel hysteretic element #7.
This element has a stiffness ratio centred in an interesting area of the diagram η vs m in Figure 3.
In fact, in this area ($0{,}03 < \eta < 0{,}04$) the re-centring evaluation criterion based on energy concepts predicts the existence of a zone with low values for m, having adequate restoring capability, followed by a zone lacking this property for intermediate values of m, to then return to a zone with adequate restoring capability for high values of m.
This is precisely what has been observed during the tests, as proven by the results listed in Table 1 below.

Table 1: Experimental results of the shake table tests on Element # 07

Run #	PGA [g]	d_d [mm]	d_{res} [mm]	m	$\frac{d_{res}}{d_d}$
100	0,30	6,5	0,4	0,9	0,07
101	0,40	10,5	1,6	1,4	0,15
102	0,50	25,7	9,8	3,4	0,38
103	0,55	36,5	18,9	4,8	0,52
104	0,60	45,1	25,6	5,9	0,57
105	0,70	60,1	33,9	7,9	0,56
106	0,80	75,2	40,7	9,9	0,54
107	0,90	90,5	46,1	11,9	0,51
108	0,95	96,6	44,4	12,7	0,46
109	1,00	102,2	44,0	13,5	0,43

The red coloured numbers represent the cases in which the condition of adequate restoring capability suggested by Professor Mauro Dolce is not verified, that is to say:

$$d_{res} \leq 0{,}5 \cdot d_d \tag{11}$$

where d_{res} is the residual displacement.

4. GRAPHICAL REPRESENTATION OF THE RESULTS

As it has been already stated, each test is characterized by a pair of dimensionless parameters *η, m* and thus can be represented by a dot in the diagram of Figure 3, which univocally represents that test.
The individual displacement time-histories were divided up into two classes, i.e. those endowed with restoring capability and those which are not, according to a criterion (11) suggested by Prof. Mauro Dolce (residual displacement lesser than 0,5 times the design displacement.
Figure 5 here below a shows typical displacement time-history recorded during the testing campaign at ENEA.

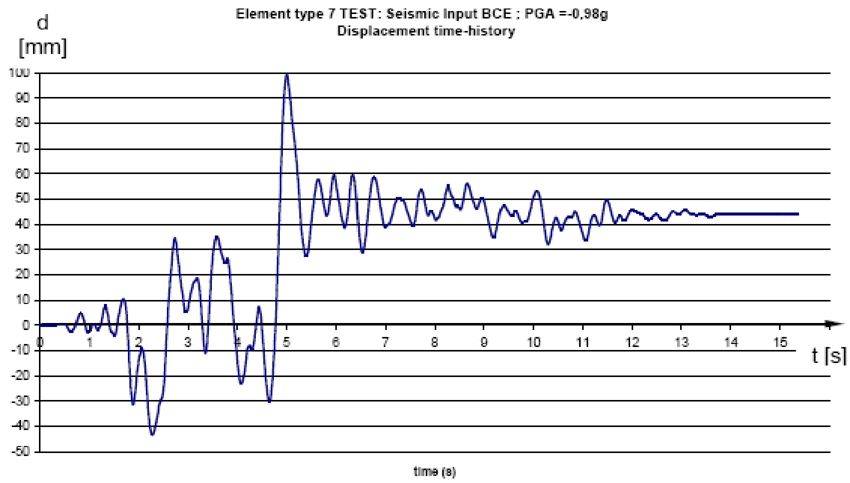

Figure 5: Displacement time-history for the test with Element #07 subjected to a BCE synthetic seismic input

Figure 6 the is a graphical representation of the results achieved during the test campaign carried out at ENEA Casaccia shake table.
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.

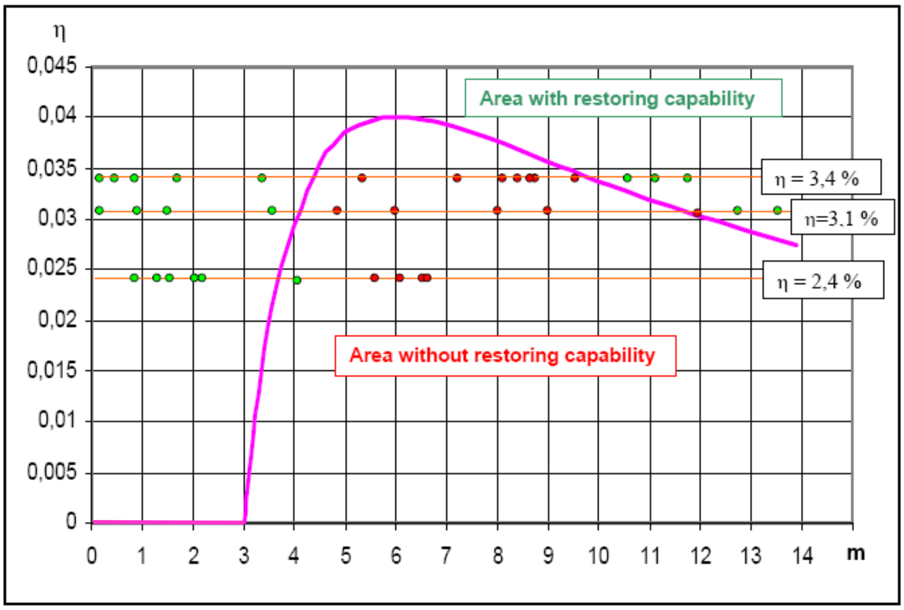

Figure 6: Graphical representation e of the results achieved during the test campaign carried out at ENEA Casaccia shake table and comparison with the Energy approach restoring requirement.

Figure 6 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 of seismic isolation systems based on energy concepts and the experimental results of the testing campaign carried out at the shake table of ENEA Casaccia.

CONCLUSIONS

- The re-centring evaluation method based on energy concepts incorporates praiseworthy simplicity, in that it just involves the comparison of two calculable and 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 only recently within the framework of the LESSLOSS Research Project funded by the European Commission, which lasted three years (2004-2007).
- The experimental results have fully substantiated this new method and at the same time disproved the criteria adopted for evaluating the re-centring capability included in some international Norms
- The re-centring evaluation method based on energy concepts has been adopted in the European Norm EN15129: *Anti-seismic Devices* which will be published in the early months of 2009.

REFERENCES

- Uang, C. M., (1988) “Use of Energy as a Design Criterion in Earthquake-resistant Design”, UCB/ERC-88/18, University of California at Berkeley – USA
- AASHTO (2001) - Guide Specification for Seismic Isolation Design, American Association of State Highways and Transportation Officials , Washington D.C , USA
- Medeot R., (2004) “Re-Centring Capability Evaluation of Seismic Isolation Systems Based on Energy Concepts”, 13th World Conference on Earthquake Engineering, - Vancouver, B.C., Canada
- EN1998-2 (2005): Design of structures for earthquake resistance - Part 2: Bridges, European Committee for Standardization, Brussels – Belgium,
- prEN 15129 (2007): Anti-seismic Devices - draft European Standard submitted to CEN members for second enquiry, European Committee for Standardization, Brussels – Belgium.

Acknowledgments

The author expresses his thanks to all the experts participating in the LESSLOSS Project and the technical staff at the ENEA Casaccia Laboratory.
Special recognition goes to the following persons:

- Prof. Ing. Gian Michele Calvi from University of Pavia, Scientific Co-ordinator of the overall Project
- Dr. Massimo Forni from ENEA Bologna, Co-ordinator of Sub-project 6
- Mr. Sebastian Fischer from MAURER SÖHNE – Munich.