



## RE-CENTERING CAPABILITY EVALUATION OF SEISMIC ISOLATION SYSTEMS BASED ON ENERGY CONCEPTS

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### SUMMARY

It was not until the most recent years that self-centering 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 self-centering capability.

With the introduction in the market of other types of isolators, that are generally not fitted with an intrinsic self-centering capability, the problem of providing this function has re-asserted its vital role.

The purpose of the self-centering capability requirement is not so much that of limiting residual displacement at the end of a seismic attack, as instead that of preventing cumulative displacements during the seismic event. This type of defect assumes particular importance in cases involving isolators comprising PTFE sliding elements (sometimes referred to as sliders).

Moreover, during the last quarter of the past century energy dissipation has increasingly gained the favor of the design engineers to mitigate the disastrous effects of a seismic attack.

However, energy dissipation and self-centering capability are two antithetic functions. Self-centering assumes particular importance in structures located in close proximity to a fault, where earthquakes characterized by highly asymmetric accelerograms are expected (Near Field or Fling effect).

Notwithstanding, self-centering capability was never paid sufficient attention by seismic engineering experts, to the point that the formulation of a criterion to quantify it was only acknowledged for the first time in 1991 by the AASHTO *Guide Specification for Seismic Isolation Design*.

Then other criteria were developed, but none of them is based upon solid theoretical fundamentals, but rather make reference to an empirical approach, valid for only one class of devices.

In conclusion, present Norms do not furnish an acceptable approach of general validity to evaluate the self-centering capability of seismic isolation systems.

This author developed a theoretical approach to this problem, suggesting an energy-based criterion for its quantification.

The scope of this paper is precisely that of introducing the newly proposed criterion. To correctly formulate the problem, some elementary cases are examined that serve to illustrate as well as interpret the requirements adopted to date by the Norms on this subject.

### INTRODUCTION

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The idea of protecting structures through decoupling them from the disastrous ground motion generated during seismic attacks is certainly an old one. A first example in recorded history is that of the temple of Diana in Ephesus, Asia Minor, where a layer of sand extended between the foundations and the elevated structure was utilized.

However, in order to witness the first practical applications of seismic isolation it was necessary to wait until the last quarter of the 20th century.

Although the causes of such delay are multiple, they can be essentially subsumed under lack of:

- i) adequate software (both Norms and calculation methods), and
- ii) reliable hardware (anti-seismic devices).

On the one hand, the academic world and the most renowned seismic engineers have endeavored to fill this gap through the development of theoretical frameworks and calculation methodologies whilst, on the other hand, research laboratories and specialized sectors of industry have invented and perfected numerous mechanical devices apt to satisfy both the theoretical and practical requirements set forth by design specifications.

It goes without saying that, besides transmitting vertical loads, a seismic isolation system must permit free relative movements on the horizontal plane between foundation and superstructure, precisely to ensure decoupling between the soil and the predominant structural mass (e.g.: the bridge deck in cases concerning bridge structures).

Even though the principles of Physics that govern the effects of energy dissipation on the control of dynamic phenomena were studied more than two and a half centuries ago (D'Alembert, *Traité de dynamique*, 1743), it took some time before energy dissipation came to be identified as the most important instrument in the hands of the design engineer to adequately control seismic response in terms of forces and displacements between super- and substructure, as well as have it listed amongst the fundamental functions of a seismic isolation system.

Furthermore, it was not until the most recent years that a fourth fundamental function, *self-centering capability*, was identified.

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 self-centering 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 self-centering 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, [1], Braun[2]).

Notwithstanding, to the latter was never paid sufficient attention by 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”.*

The first version of Eurocode 8, *Part2: Bridges* has also acknowledged the same criterion, even though it does not expressly cite self-centering capability.

However, it appears as though the above criterion :

- i) has no scientific foundation, and, most importantly,
- ii) cannot offer any indication of the actual re-centering capability of the isolation system in question.

Let's consider the Figure 1 below, which is a graphical representation of the above cited criterion.

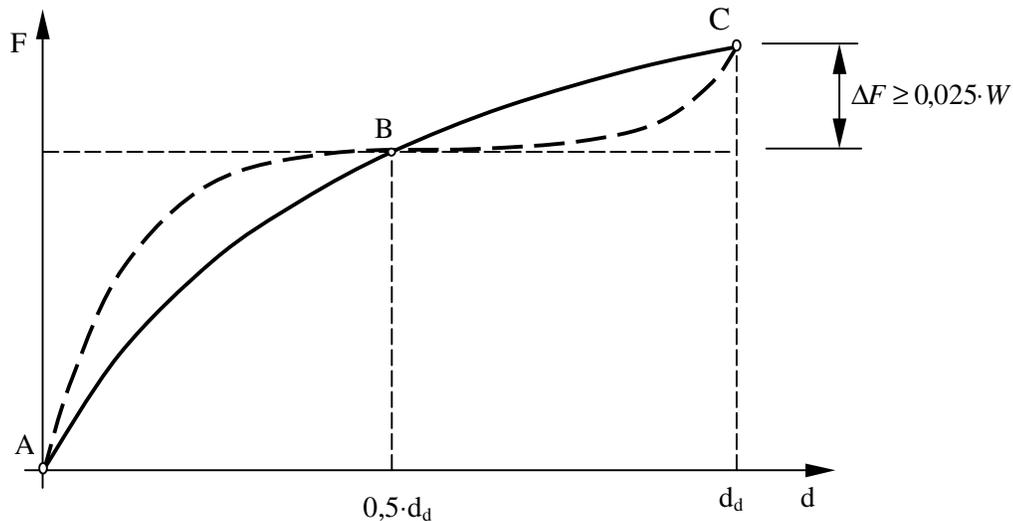


Figure 1: Graphical representation of the re-centering capability of an isolation system in accordance with AASHTO *Guide Specification for Seismic Isolation Design* (version 1991)

Both characteristic curves – which, by the way, are representative of the very type of devices in today's market – fully comply with the requirement  $\Delta F \geq 0,025 \cdot W$ . However, it should be noted that they possess distinctly different re-centering capabilities between them.

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 new requirement states the following:

“The isolation system shall be configured to produce a lateral restoring force such that the period corresponding to its tangent stiffness ... at any displacement ... up to its design displacement, shall be less than 6 seconds”

Neither of the two above criteria is based upon solid theoretical fundamentals, but rather make reference to an empirical approach, valid for only one class of devices, that is to say, those in which the restoring force increases with displacement – in other words, that which uses a spring-like restoring force – as it is asserted in the Commentary.

So much so, that it was deemed necessary to add a third self-centering capability verification criterion for those systems with constant restoring force. In this category the AASHTO *Guide Specifications* cite the compressible fluid springs with preload and sliding bearings with conical surface.

Regarding the cases with constant restoring force, the *Guide Specifications* prescribe the following:

*“Isolation systems with constant restoring force need not satisfy the requirements above. In these cases, the combined constant restoring force of the isolation system shall be at least equal to 1.05 times the characteristic strength of the isolation system under service conditions”.*

It can be readily seen that specifying a 5% tolerance on the friction forces is not all that conservative from static point of view. In fact, friction forces largely depend on several uncontrollable parameters and physical conditions of the contact surfaces. It should also be noted that just the uncertainty of the loads transmitted by the isolator – to which the friction force is proportional – is usually much greater than 5% (Medeot,[3]). Conversely from dynamic (or energy) point of view this requirement is extremely severe, as it will be demonstrated further in this paper.

The scope of this document is that of attempting a first theoretical approach to the self-centering problem, suggesting a criterion for its quantification, without pretending to exhaust the subject nonetheless.

## FORMULATION OF THE PROBLEM

As mentioned before, the four fundamental functions of a seismic isolation system are the following:

- Transmission of vertical loads
- Lateral flexibility on the horizontal plane
- Dissipation of substantial quantities of energy
- Self-centering capability

Each function can be performed by a single element or one element can perform more functions.

For example, in the case of suspended bridges, the hanging links can perform the first three functions and, in order to create a valid seismic isolation system, it is necessary to resort to energy dissipation devices such as hydraulic dampers inserted at strategic points in the structure.

In the rubber bearings mentioned earlier, especially those in the *High Damping Rubber Bearings (HDRBs)* version, the four functions are performed by a single element, i.e. the rubber.

Those devices that can ensure all four functions internally are called *isolators*. Amongst them, the *Lead Rubber Bearing, Friction Pendulum, Friction Sliders*, etc. are mentioned besides the HDRBs.

It should be noted that energy dissipation and self-centering capability (sometimes referred to as *restoring force*) are two antithetic functions and their relative importance depends primarily on the case under examination (Medeot, [4]).

The term “*restoring force*” is misleading inasmuch as it would seem to suggest that the evaluation of the self-centering capability of a Seismic Isolation System must be conducted through a comparison of forces, something that is conceptually erroneous.

Actually, comparisons must be made between the Isolation System’s capability to elastically (or, better said, reversibly) store and irreversibly dissipate the earthquake energy input.

Self-centering assumes particular importance in structures located in close proximity to a fault, where earthquakes characterized by highly asymmetric accelerograms are expected (*Near Field effect*).

The purpose of the self-centering capability requirement is not so much that of limiting residual displacement at the end of a seismic attack, as instead that of preventing cumulative displacements during the seismic event, as indicated in Figures 2 and 3, as well as to remedy isolator installation imperfections such as their being out of level. This type of defect assumes particular importance in cases involving isolators comprising PTFE sliding elements (sometimes referred to as *sliders*).

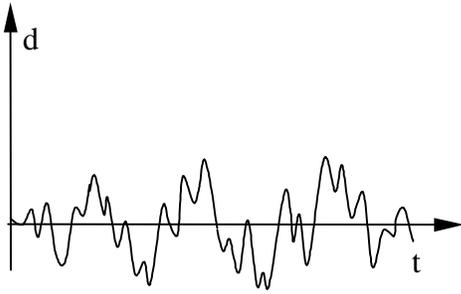


Figure 2. Seismic Isolation System with adequate self-centering capability

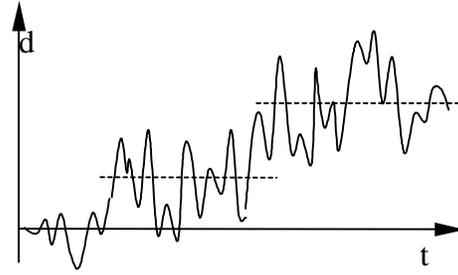


Figure 3. Seismic Isolation System with poor self-centering capability

To correctly formulate the problem, some elementary cases are examined here below that will serve to introduce and further understand the proposed criterion as well as interpret the requirements adopted to date by the Norms to guarantee good self-centering capability.

### The Friction Pendulum

Let us first consider the case of the Friction Pendulum outlined in Figure 4 below.

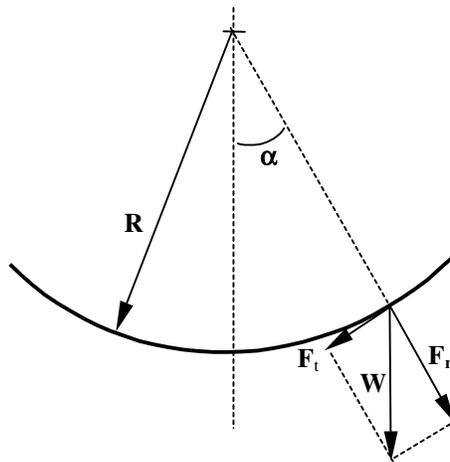


Figure 4. Model of Friction Pendulum

With the symbols of Figure 4, the restoring force is equal to the tangential component of the supported weight W:

$$F_t = W \cdot \sin \alpha \quad (1)$$

while the resisting force is that produced by friction, which is equal to:

$$F_f = \mu_s \cdot F_n = \mu_s \cdot W \cdot \cos \alpha \quad (2)$$

where  $\mu_s$  is the static coefficient of friction between the articulated sliding element and the concave plate. Any position that results in  $F_t \leq F_f$  that is:

$$W \cdot \sin \alpha \leq \mu_s \cdot W \cdot \cos \alpha \quad (3)$$

$$\tan |\alpha| \leq \mu_s \quad (4)$$

is in fact an equilibrium position.

At this point, one could spontaneously conclude that the restoring force is active up to a limit displacement equal to:

$$d_0 = R \cdot \sin \alpha_0 \quad (5)$$

( $\alpha_0 = \arctan \mu_s$ ), inasmuch as from this point on, the restoring force becomes lesser than the resisting friction force.

Actually, things are not that simple but quite different. In fact, suppose the sliding element is displaced to a position  $|\alpha_1| > \alpha_0$  and then released.

With the progression of the motion, the initial potential energy  $E_{P1} = W \cdot R (1 - \cos \alpha_0)$  (referred to the inferior point of the spherical surface) becomes partly kinetic energy and is partly dissipated by friction into heat.

On the basis of the Energy Conservation Principle, the motion will cease when the variation in potential energy equals the energy dissipated through friction, namely:

$$- W \cdot R \int_{\alpha_1}^{\alpha_2} \sin \alpha \, d\alpha = \mu \cdot W \cdot R \int_{\alpha_1}^{\alpha_2} \cos \alpha \, d\alpha \quad (6)$$

$$\text{that is: } \cos \alpha_2 + \mu \cdot \sin \alpha_2 = \cos \alpha_1 + \mu \cdot \sin \alpha_1 \quad (7)$$

For example, for a dynamic friction coefficient  $\mu = 0,07$ , the angle at which the restoring force equals the friction force is  $\alpha_0 = 4^\circ$ . Nonetheless, for an initial angular displacement  $|\alpha_1| = 7^\circ$ , there results a final angular displacement  $\alpha_2 = 1^\circ < \alpha_0$ .

### Sliders

In second place, let us examine the case of Sliders, i.e. a combination of conventional sliding bearing and a polyurethane or rubber spring unit that can be represented by the model illustrated in Figure 5 below:

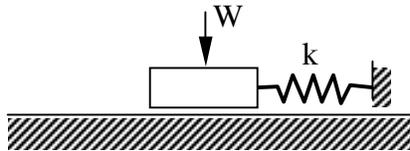


Figure 5. Model of a Slider

The restoring force is furnished by the spring and is equal to  $F_t = -k \cdot x$ , where  $x$  is the displacement, while the resisting force is due to friction and is equal to  $F_f = \mu \cdot W$ .

Even in this case, any position that results in:

$$F_t \leq F_f \quad \text{that is: } |x| \leq \frac{\mu \cdot W}{k} \quad (8)$$

is in fact a position of equilibrium.

If  $x_0 = \mu \cdot W/k$  represents the limit value of the possible positions of equilibrium and the device undergoes a displacement  $|x_1| > x_0$ , there will develop motion up to point  $x_2$  upon release, where the variation in elastic strain energy will equal the energy dissipated through friction, namely:

$$\frac{1}{2}k(x_1^2 - x_2^2) = \mu \cdot W |x_1 - x_2| \quad (9)$$

Simplifying and substituting  $\mu \cdot W/k = x_0$ , yields:

$$x_2 = 2x_0 \cdot \text{sgn } x_1 - x_1 \quad (10)$$

from which it can be deduced that it always results in  $|x_2| < x_0$ .

Analogous considerations can be made with other types of hysteretic isolators such as lead rubber bearings, steel hysteretic bearings, etc.

The conclusions arrived at are always the same, that is:

- The comparison between restoring force and characteristic strength of the isolator (i.e. friction force for sliding devices, yield force for lead or steel hysteretic devices, etc.) serves the purpose of determining the possible static equilibrium positions.

This is sometimes referred to as “Static Self-centering Capability”.

- The criterion to establish the entity of the self-centering is based upon a comparison between the energy stored by the system in a reversible form (elastic, potential etc.) and that hysteretically dissipated.

This criterion allows to determine the so called “Dynamic Self-centering Capability”.

## **THE ENERGY APPROACH**

To better illustrate this last assertion, let us consider the energy balance equation in the following form valid for structures (Bertero, [5], [6] and Uang, [7]):

$$E_i = E_S + E_H + E_V \quad (11)$$

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, potential energy and kinetic energy)
- $E_H$  is the energy dissipated by hysteretic deformation
- $E_V$  is the energy dissipated by viscous damping

Self-centering 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

$$F = C \times v^n \quad (12)$$

For  $v \rightarrow 0$  also  $F \rightarrow 0$ , 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-centering 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.

In other words, 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:

$$E_S \geq \lambda \cdot E_H \quad (13)$$

It goes without saying that the larger is the value of  $\lambda$ , the higher is the re-centering capability of the system.

The results of numerous step-by-step, non-linear analyses demonstrated that a seismic isolation system possesses sufficient self-centering capability when  $\lambda = 0,25$ .

More precisely, for deformations from 0 to  $d_d$ , it shall be:

$$E_S \geq 0,25 E_H \quad (14)$$

The above criterion has proven to be valid and applicable to all types of existing isolation devices, as well as construction typologies.

### Sliding isolator with steel hysteretic elements

The requirement (14) can be translated in formulae or design criteria for each type of isolator.

For example, consider the bi-linear characteristic curve of a PTFE sliding isolator (Figure 6 below) equipped with steel hysteretic elements as energy dissipaters.

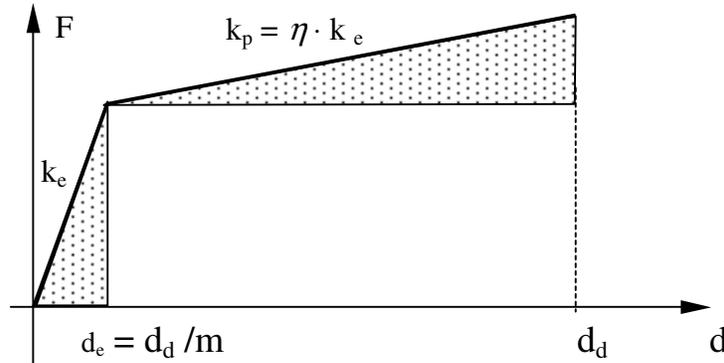


Figure 6. Characteristic bi-linear curve of a hysteretic system

If, for the sake of simplicity, the dissipation produced by the PTFE sheet is ignored (\*) and the case under consideration has a ductility factor  $m$  (i.e.  $d_d = m \cdot d_e$ ), the energy stored elastically is equal to:

$$E_S = \frac{1}{2} k_e \times \left( \frac{d_d}{m} \right)^2 + \frac{1}{2} \eta \cdot k_e \times \left( \frac{m-1}{m} \times d_d \right)^2 = \frac{1}{2 \cdot m^2} k_e \cdot d_d^2 (1 + \eta \cdot (m-1)^2) \quad (15)$$

where  $k_p = \eta \cdot k_e$  represents the slope of the post-elastic branch expressed as a fraction of that of the elastic branch of the characteristic curve .

The energy dissipated hysteretically is equal to:

$$E_h = \frac{k_e \cdot d_{dx}}{m} \times \frac{m-1}{m} \cdot d_d = k_e \cdot d_d^2 \cdot \frac{m-1}{m^2} \quad (16)$$

It can be concluded that requirement (14) is satisfied for:

$$\eta \geq \frac{m - 3}{2 \cdot (m - 1)^2} \quad (17)$$

It is interesting to notice that in this case Self-centering Capability is governed by the post-elastic slope of the characteristic curve and its limit value depends only on one magnitude, i.e. the ductility factor  $m$ .

### Lead Rubber Bearings

Let us now consider the Lead Rubber Bearings (LRBs) of the type shown in Figure 7 below (Skinner et alii,(9)).

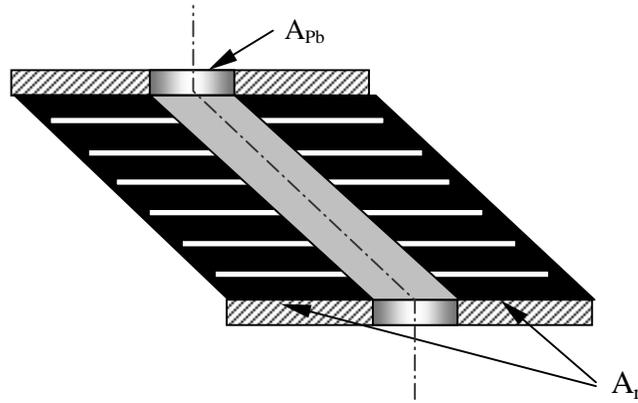


Figure 7: Deformed Lead Rubber Bearing

Indicating with  $A_r$  the cross-sectional area of the rubber bearing, with  $h$  as its total rubber thickness and  $G$  as the rubber shear modulus, the elastically stored energy equals:

$$E_s = \frac{1}{2} \cdot \frac{G \cdot A_r}{h} \times d_d^2 \quad (18)$$

In (18) the modest contribution of the energy elastically stored in the lead core was conservatively ignored.

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(\*) Note: *This is not a conservative hypothesis and in practice it is opportune to take into account the contribution of friction forces.*

Indicating with  $A_{pb}$  the cross-sectional area of the lead core and  $\tau_{pb}$  as the shear stress at which the lead yields, the hysteretically dissipated energy then equals:

$$E_h = \tau_{pb} \cdot A_{pb} \cdot d_d \quad (19)$$

Placing the typical values  $G = 0,9$  MPa,  $\tau_{pb} = 10,5$  MPa in (19) and (20), condition (14) is satisfied if:

$$A_{pb} \leq 0,171 \cdot \gamma_d \cdot A_r \quad (20)$$

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

From the above it can be inferred that for the LRBs Self-centering Capability is governed by the ratio between lead core and rubber cross sections and its limit value depends only on the design shear deformation.

### Friction Pendulum

Consider now the case of the Friction Pendulum. Using the symbols already used previously in Figure 4, and indicating with  $\alpha_d$  the design angular displacement, the energy accumulated under the form of potential energy is:

$$E_s = W \cdot R \cdot (1 - \cos \alpha_d) \quad (21)$$

while the energy dissipated through friction is:

$$E_h = \mu \cdot W \cdot R \cdot \int_0^{\alpha_d} \cos \alpha \, d\alpha = \mu \cdot W \cdot R \cdot \sin \alpha_d \quad (22)$$

Therefore, for the Friction Pendulum, requirement (14) is satisfied by:

$$\mu \leq 4 \cdot \frac{1 - \cos \alpha_d}{\sin \alpha_d} \quad (23)$$

The design angular displacement  $\alpha_d$  is linked to the linear displacement  $d_d$  and the radius of curvature  $R$  of the spherical surface by:

$$d_d = R \cdot \sin \alpha_d \quad (24)$$

On its turn the radius of curvature is linked to the natural period of the structure through the formula (Zayas,(8)):

$$R = g \cdot \left( \frac{T}{2\pi} \right)^2 \quad (25)$$

From the above one can conclude that in the case of the Friction Pendulum the Self-centering mechanism is governed by three parameters, of which two can be chosen at will, while the limit value of the third is determined by the expressions (23) – (25).

For example, if we choose the period  $T$  and the maximum (design) displacement  $d_d$ , by using (25) the radius of curvature  $R$  will be firstly calculated.

Thereafter with (24) the angle  $\alpha_d$  is determined and finally with (23) the maximum value of the coefficient of friction  $\mu$  is assessed. Conversely, if we choose  $\mu$  and  $T$ , the limiting parameter becomes the minimum value of the design displacement  $d_d$ .

For instance, the radius of curvature of a Friction Pendulum that can ensure the structure a natural period equal to  $T = 3,5$  s is equal to  $R = 3,04$  m and thus, assuming a coefficient of friction  $\mu = 0,07$ , expression

(24) yields to  $\alpha_d \geq 2^\circ$ .

Finally, to attain good self-centering capability, in the case under examination the design displacement  $d_d$  shall exceed  $\pm 106$  mm.

The above explains why the shake table tests have experimentally shown substantial residual displacements with earthquakes of lesser magnitude than the design earthquake.

### COMPARISON WITH AASHTO GUIDE SPECIFICATIONS

At this point, it is noteworthy to attempt a comparison with the requirements set forth by the AASHTO *Guide Specifications*.

Let's start with the case of the Friction Pendulum just examined.

### Comparison for Friction Pendulum

As mentioned in the Introduction, the *Guide Specifications* require that the restoring force at design displacement  $d_d$  shall be greater than the restoring force at  $0,5 d_d$  by not less than  $W/80$ .

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

$$\Delta F = \frac{k \cdot d_d}{2} = \frac{W \cdot d_d}{2R} \geq \frac{W}{80} \quad (26)$$

that is: 
$$d_d \geq \frac{R}{40} \quad (27)$$

It is observed that the self-centering capability verification conducted in accordance with the AASHTO *Guide Specifications* is independent from the value of the dynamic coefficient of friction  $\mu$ .

This is paradoxical and confirms the doubts expressed by this author in the Introduction.

For  $R = 3,04$  m it results  $d_d \geq 76$  mm (vs. 106 mm). From this comparison, it can be concluded that, for the Friction Pendulum, the present AASHTO *Guide Specifications* are less restrictive than the criterion proposed in this paper.

On the contrary, the 1991 version would have been stricter ( $d_d = 152$  mm). This therefore determines that for the Friction Pendulum the newly proposed criterion places itself right between the two versions of the *Guide Specifications*.

### Comparison for Sliding isolators with steel hysteretic elements

Referring to Figure 8 on next page, the comparison is conducted with the following design assumptions

- Lateral design force of the Isolation System:  $F_d = 0,10 W$  ( $W$  is the weight of the isolated structure)
- ductility factor  $m = 10$

From the design assumption it results:

$$F_d = 0,10 \cdot W = k_e \frac{d_d}{m} + \eta \cdot k_e \cdot d_d \left(1 - \frac{1}{m}\right) \quad (28)$$

The verification requirement calls for:

$$\Delta F = 0,5 \cdot d_d \cdot \eta \cdot k_e \geq \frac{W}{80} \quad (29)$$

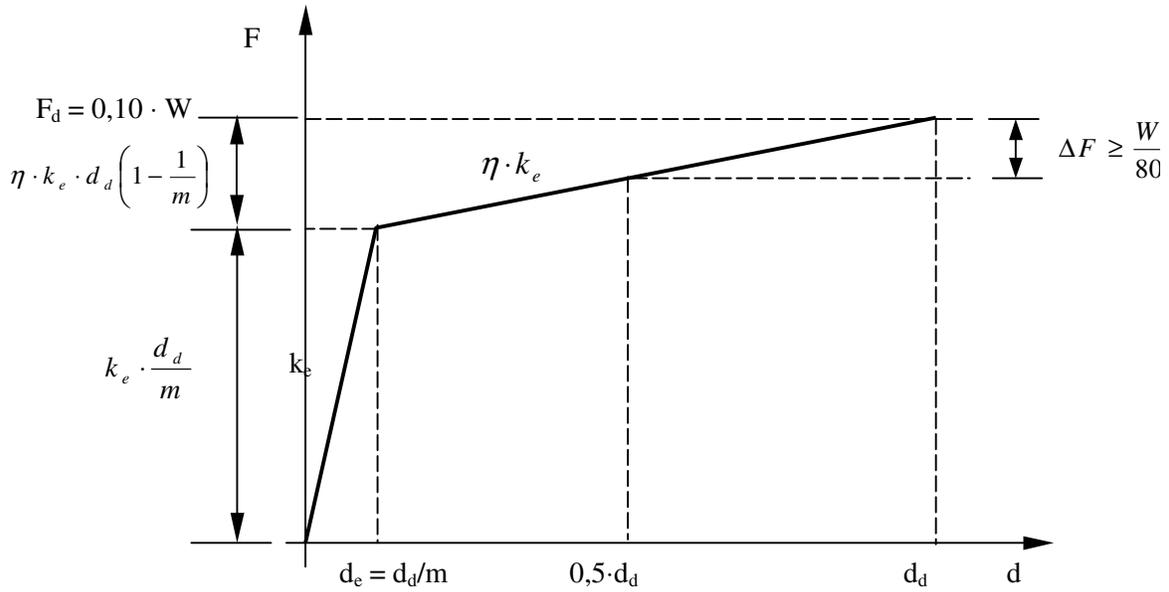


Figure 8: Characteristic bi-linear curve of Sliding isolators with steel hysteretic elements

Obtaining  $W$  from (27) and substituting it in (28) the fulfillment of the requirement in the *Guide Specifications* is obtained if:

$$\eta \geq \frac{1}{3+m} \quad (30)$$

For the case under examination it is  $\eta \geq 3,2\%$ , versus the value  $\eta \geq 4,2\%$  calculated - for  $m=10$  - with the expression (18)  $\eta \geq (m-3) / [2(m-1)^2]$  valid for the energy approach.

Similar to the case of Friction Pendulum, it can be concluded that the present AASHTO *Guide Specifications* are less restrictive than the criterion based on energy considerations.

However, the 1991 version was far more restrictive (over a factor of 2).

### Comparison for Lead Rubber Bearing

Referring to Figure 9 on next page and similarly to the former case, the comparison is conducted under the design assumption that the design force of the Isolation System is  $F_d = 0,10 W$ .

For the sake of simplicity the elastic deformations of the lead core have been ignored.

From the design assumption it results:

$$F_d = 0,10 \cdot W = A_{pb} \cdot \tau_{pb} + A_r \cdot G \cdot \gamma_d \quad (31)$$

The verification requirement calls for:

$$\Delta F = 0,5 \cdot d_d \cdot \frac{A_r \cdot G}{h} = 0,5 \cdot \gamma_d \cdot A_r \cdot G \geq \frac{W}{80} \quad (32)$$

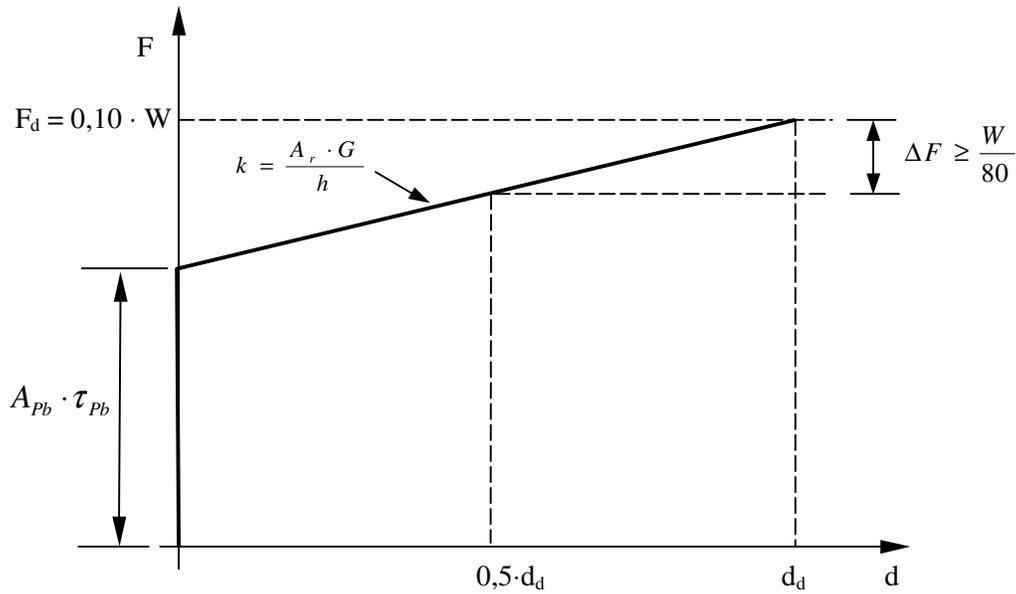


Figure 9: Characteristic curve of Lead Rubber Bearings

Obtaining  $W$  from (31) and substituting it in (32) the fulfillment of the requirement in the *Guide Specifications* is obtained if:

$$A_{pb} \leq 3 \cdot \frac{\gamma_d \cdot A_r \cdot G}{\tau_{pb}} \quad (33)$$

Placing the typical values  $G = 0,9$  MPa,  $\tau_{pb} = 10,5$  MPa in (32), condition (31) is satisfied if:

$$A_{pb} \leq 0,257 \cdot \gamma_d \cdot A_r \quad (34)$$

Also in this case the AASHTO *Guide Specifications* are less demanding than the criterion based on energy considerations, by which it follows that (see (20)):

$$A_{pb} \leq 0,171 \cdot \gamma_d \cdot A_r$$

#### Comparison for Sliders with constant restoring force

The *Guide Specifications* for this case request the following:

“...the combined constant restoring force of the isolation system shall be at least equal to 1.05 times the characteristic strength of the isolation system under service conditions”.

The elastically stored energy equals:  $E_S = 1,05 \mu \cdot W$

The hysteretically dissipated energy is:  $E_H = \mu \cdot W$

Therefore it results:

$$E_S = 1,05 E_H$$

Compared with the energy approach criterion ( $E_S \geq 0,25 E_H$ ), the constant restoring force requirement of the *Guide Specifications* appears to be extremely strict.

## CONCLUSIONS

For the sake of description simplicity and, above all, so as to avoid uselessly complicated mathematical working out, the examples given in this paper refer to cases where only single types of devices have been considered instead of combined entire isolated systems.

It goes without saying that similar considerations are also valid regarding the latter.

Self-centering capability is a characteristic of the entire isolation system, not necessarily of each of its components.

Present Norms do not furnish acceptable criteria of general validity to evaluate the self-centering capability of seismic isolation systems.

The comparison conducted between the proposed method based on energy concepts and those with the existing Norms show remarkable discrepancies that depend notably from the type of isolator.

Except for the constant restoring force requirement, in all of the cases taken in consideration for the comparison it was observed that the *AASHTO Guide Specifications* are less restrictive, especially for Lead Rubber Bearings.

Even though this paper does not pretend to give a definitive answer to the problem of quantifying the re-centering capability, it nonetheless serves to suggest a general validity criterion (i.e.: one applicable to any type of device) that also incorporates praiseworthy simplicity (it just involves the comparison of two calculable and measurable physical magnitudes).

The suggested verification requirement can be easily translated in formulae or design criteria for each type of isolator or isolation system.

The criterion suggested is based on energy concepts and thus couples very well with the intrinsic nature of the phenomenon in question (the earthquake).

In this author's professional experience, the proposed criterion has shown itself very valid to preliminarily define the isolation system's characteristics before undertaking a burdensome step-by-step non-linear analysis.

The latter still represents today the most valid method to verify an isolation system's self-centering capability inasmuch as it permits to quantify the residual displacement as well as – most importantly – reveal any eventual drift of the system mean oscillation point that causes cumulative displacements during a seismic event.

Nonetheless, a requirement for self-centering capability in a Norm is necessary. This serves to accommodate unpredictable adverse factors - such as bearings' out of level - which in the dynamic analyses are normally not taken into account.

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