NEW DESIGN APPROACHES BASED ON ENERGY CONCEPTS AND RELATED SEISMIC HARDWARE

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SUMMARY

During the last quarter century we have witnessed the appearance of numerous types of anti-seismic devices in the market. Progress has mainly been the result of a need to fulfil the requirements arising from the newly developed design strategies taking hold (e.g.: Seismic Isolation).
Thus, several pioneering industries and research laboratories have decided to invest important resources in this field, inventing and perfecting a series of devices exploiting well known Physics phenomena and adapting them to seismic protection of structures.
This paper aims to provide a classification of the main types of devices in existence. Authors decided to adopt the energy criterion for said classification. This choice stems from the awareness that presently the design approach based on energy concepts is swiftly spreading amongst the seismic engineering community.
The introduction to this paper lists the fundamental concepts of such a design approach. It also illustrates how the use of the energy balance equation offers a rational basis for defining a design strategy that takes into account the type of structure, yielding maximum advantage in terms of the existing categories of seismic devices.
Subsequently, the paper also lists the possible design choices the seismic engineer can adopt and indicates on a case per case basis, the categories of devices that can enable their implementation.
In this manner, devices are automatically classified according to a logical order as well as by their increasing energy dissipating capacity.
In the end, the most commonly used types of devices are briefly described and an interpretation of their functioning from an energy-based approach is given.

INTRODUCTION

Today, everyone knows what an earthquake consists of and which are the mechanisms that produce it owing to the programs of information disseminated throughout most countries, especially after the occurrence of an important seismic event.

Notwithstanding, not all seismic engineers today have a clear vision as to how such disastrous natural phenomena visit damages upon the works constructed by man's creative genius. The most spontaneous idea that comes to mind to seismic engineer practitioners is that of interpreting an earthquake in terms of forces and deformations induced upon the structure. As a consequence, there is a tendency to think only about increasing the strength of the latter.

Actually, forces and displacements are but a mere manifestation of seismic attacks and do not in fact represent their very essence. Earthquakes are essentially energy phenomena in which enormous amounts of mechanical energy are accumulated throughout the bedrock for decades or even centuries, to be suddenly released in very short periods of time. Therefore, in order to be efficacious, design defence strategies must be organised duly accounting for the intrinsic nature of destructive phenomena.

Although Housner already suggested an energy-based design method in 1956, it has been only recently that this approach has gained widespread attention. Akiyama (1985), Uang [1] and Bertero [2] (1988) made a

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valuable contribution to the development of the theoretical aspects of an energy-based approach, which presently meets with great consensus, especially within the academic community.

However, it cannot be said that practical application factors have commanded similar attention. Specifically, neither adequate relevance has been given to the development of proper seismic hardware suitable to this design strategy nor its being fit to the task.

This paper aims to provide a brief overview of the problems involved in such endeavour by summarising the theoretical principles governing the above mentioned anti-seismic design approach, illustrating the manner in which the correct utilisation of energy concepts can enable tailor-made design solutions that duly account for the type of structure being protected, yielding maximum advantage in terms of existing hardware.

The latter are presented in a logical manner with an interpretation of their functioning according to energy concepts.

THE ENERGY APPROACH

The principles of Physics that govern the effects of dissipation on the control of dynamic phenomena were studied more than two centuries ago (D'Alembert, *Traité de dynamique, 1743*). Nonetheless, their practical application has come about much later and within a much different time-frame in several sectors of Engineering.

The sector that was the first to adopt such damping technologies was the military (France, 1897) and let the country enjoy world supremacy in artillery for the better part of a decade.

In not too short order, the automobile industry followed in these steps by using dampers in their suspension systems to ensure the comfort and stability of motor vehicles.

It took some time before Civil Engineering applications were forthcoming. In effect, it is necessary to arrive at the last quarter of this century to find their first appearance.

One of the factors that may have delayed the application of dissipative systems to Civil Engineering could be the innate diffidence of civil engineers toward those mechanical devices nonchalantly termed "machines", which, for the purpose of damping, have to be suitably inserted into a structure and properly interact with it.

A second delaying factor could be ascribed to the absence of reliable calculation methods (*i.e.*: modelling and dynamic analysis). That is, appropriate "*software*".

Nonetheless, the delay in development with respect to other engineering fields has been rapidly overcome during the last two decades. Progress has mainly been the result of newly developed design strategies taking hold (*e.g.*: Base Isolation) and the awareness that energy dissipation can be a powerful tool in the hands of the design engineer to control the response of structures struck by windstorms or earthquakes.

In other words, as stated in the introduction, these natural events are being increasingly perceived as phenomena involving the transmission of mechanical energy instead of being interpreted only in terms of forces and displacements resulting from the simple application of mathematical equations.

However, said awareness has mainly concerned the academic world and has spread only to a limited extent amongst civil engineer practitioners.

And the last, but not least, delaying factor might be identified in the lack of mechanical devices capable dissipating energy, *i.e.*: appropriate and reliable "*hardware*". As we will see further on in this paper, this limiting factor does not longer exist thanks to the commitment of several pioneering and research laboratories that have decided to invest important resources in this field, inventing and perfecting a series of devices that exploit well known Physics phenomena and adapting them to the protection of structures.

In fact, newly conceived design strategies could not have found useful application without the parallel development of the hardware needed for their implementation.

In order to gain a better understanding of this paper subject, some general concepts should be called to mind.

As it is known, any resistance criterion adopted in the dimensioning of a structure (*e.g.*: permissible stresses, limit states, etc.) always necessitates the verification that:

$$\text{DEMAND} \leq \text{CAPACITY} \tag{1}$$

where the terms DEMAND and CAPACITY assume, from time to time, their appropriate meaning.

Expression (1), sometimes referred to as Design Equation, is valid in Earthquake Engineering even when the energy concepts are applied in the sizing of the structural members.

Let us consider a generic physical system (schematically represented by the box in fig.1), that interacts with the external environment through energy exchanges.

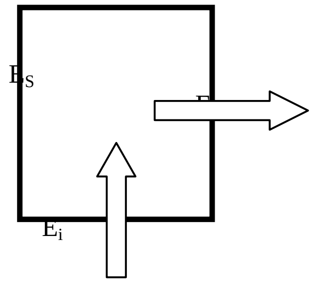

Fig. 1 : Physical system that interacts with the external environment through energy exchanges.

In accordance with the Principle of Energy Conservation:

$$E_i = E_s + E_d \qquad (2)$$

where,

E_i is the energy input
E_s represents the stored energy
E_d is the dissipated energy

If, instead of a generic physical system, one considers a structure (e.g.: a building, bridge, etc.) undergoing a seismic attack, then the term E_i represents the mechanical energy transmitted to the structure by the ground motion through its foundations.

Still within the premise of the above case, the energy E_s can be stored in two distinct ways, one of which depends only on deformations and the other on velocity, to wit:

$$E_s = E_e + E_k \qquad (3)$$

where,

E_e is the elastic strain energy
E_k represents kinetic energy

By the same token, the energy E_d can also be dissipated by two distinct mechanisms, one of which depends only on deformations and the other on velocity, and precisely,

$$E_d = E_h + E_v \qquad (4)$$

where,

E_h is the energy dissipated by hysteretic (or plastic) deformation.
E_v is the energy dissipated by viscous damping

It should be pointed out that the energy E_v is associated with the forces F that depend only on the velocity v through a constitutive law of the type

$$F = C \times v^n \qquad (5)$$

where exponent n ranging from 0 to 1,8, depending on the type of device.

By introducing expressions (3) and (4) in equation (2), we obtain the energy balance equation in the following form valid for structures (Bertero, [7]):

$$E_i = E_e + E_k + E_h + E_v \qquad (6)$$

When one compares the above equation to the Design Equation (1) it becomes clear that E_i can be interpreted as the Demand while the four terms of the other side of the equation can represent the possible capacities of the structure.

Equation (6) clearly points out the fact that the design engineer must, at the onset of his project, make a good estimate of E_i for the Design Earthquake.

To demonstrate how this is possible, it is necessary to develop the energy balance equation (6) through a rigorous mathematical process. For the sake of simplicity, let us consider an oscillating system with one-degree-of –freedom. In this case, the equation of motion reads as follows:

$$m\ddot{x} + c\dot{x} + kx + h(x) = -m\ddot{x}_G \qquad (7)$$

where *x* represents relative displacement between the mass *m* and the ground, while x_G stands for the absolute ground displacement with respect to an inertial system. In the same vein, the exponent *n* in $F = C \times v^n$ has been assumed as 1, but the subsequent result we will develop applies for any value of *n*.

The four terms on the left-hand side of equation (7) respectively represent the inertial, viscous, elastic and hysteretic forces.

We know that introducing in (7) the accelerogram $\ddot{x}_G(t)$ of an earthquake and by integrating the individual force terms over the entire duration of the seismic event, yields the response *x(t)* of the structure as a solution for that specific seismic event.

By integrating equation (7) with respect to *x*, results in:

$$\int m\ddot{x}dx = \int m\frac{d\dot{x}}{dt}dx = \int m\dot{x}d\dot{x} = \frac{1}{2}m\dot{x}^2 = E_k \quad (8)$$

$$\int c\dot{x}dx = \int c\dot{x}^2 dt = E_v \quad (9)$$

$$\int kxdx = \frac{1}{2}kx^2 = E_k \quad (10)$$

$$\int h(x)dx = E_h \quad (11)$$

As it can be surmised, the individual contributions included on the left side of equation (7) represent the relative kinetic energy, the dissipative energy caused by viscous damping, the elastic strain energy and the hysteretic energy.

The summation of these energies must balance the input energy imposed on the structure by the seismic event and thus:

$$\int -m\ddot{x}_G dx = E_i \quad (12)$$

It should be noted that the above formula is a rather simplified one for a more complex analysis goes beyond the scope of this paper. Nonetheless, it should be pointed out that:

- Each energy term in the equation is a function of time. In order to integrate (7) it is necessary to enter $dx = \dot{x}dt$).
- The energy imparted to the structure does not only depend on the accelerogram $\ddot{x}_G(t)$ and the structure mass *m*, as (12) would seemingly suggest, but on other parameters as well.

Going back to the energy balance equation (6), let us try to interpret old and new anti-seismic design approaches.

When structures are designed by suitably strengthening their members so as to avoid damage during a seismic attack (which obviously presupposes the same remain within elastic limits), it practically requires resorting to only the terms E_e and E_k. It should be noted that, even though it remains within elastic limits, the structure have intrinsic dissipating capacity of the viscous type, and thus the term E_v comes also into play.

To account for this fact, the linear analysis of reinforced concrete structures a damping coefficient $\xi = 0{,}05$ is normally assumed whereas for steel structures $\xi = 0{,}02$ should be used.

However, the above approach often represents an illusion, and seismic protection can only be ensured to slender structures subject to modest intensity earthquakes.

Conversely, when the energy transmitted to the structure by the earthquake exceeds the structure's capacity to store the same elastically, portions of the structure typically yield or crack. In other words, it can be stated that in such cases, the structure automatically resorts to the third term E_h of the energy balance equation.

For a good number of years and unfortunately until this days, structures are still being designed deliberately using the term E_h , and thus accepting the fact that structural members undergo deformation beyond elastic limits, resorting to their *ductility*. The latter concealing a decidedly undesired reality despite the elegant terminology.

In fact, accepting deformations beyond the elastic limit means resorting to a dissipating mechanism that induces permanent structural damage (typically, the creation of *plastic hinges* in bridge piers or building *pilotis*) and thus accepting the need for costly refurbishing interventions – which implicitly entail the structure being temporarily out of service.

This design approach, termed *traditional* or *conventional*, is still accepted by most existing anti-seismic standards. One of its universally acknowledged drawbacks is the risk of structural collapse at greater than design earthquake intensity.

Only in recent years has it been recognised that it is possible to significantly increase at will E_h as well as E_v, and thus fully control the response of the entire structure through the use of energy dissipating devices inserted at properly determined strategic locations. This is referred to as the *Passive Energy Dissipation* approach as opposed to *active energy dissipation*, an approach considered up to now futuristic.

If it is not technically feasible or it is economically disadvantageous to balance the energy input E_i using the terms E_e, E_k , E_h and E_v, there is still the option to attempt decreasing the energy input E_i itself. This design approach is called *Seismic Isolation* and essentially entails de-coupling the structural prevailing mass from its foundations. Therefore, this approach is sometimes improperly referred to as *Base Isolation.*

Seismic Isolation was proposed over a century ago (Kelly [1]), but it has found extensive application only during the last two decades. Such delay finds its explanation in the lack of adequate seismic hardware suitable to effectively and reliably implement the desired de-coupling of elevated structures and foundations.

From the above, one must obviously conclude that the most rational approach can only resort to all the terms in the energy balance equation (6). That is, a combination of *Seismic Isolation* and *Passive Energy Dissipation* whenever practically and economically feasible.

Seismic Isolation and Energy Dissipation represent today the most efficient tools in the hands of design engineers in seismic areas to limit both relative displacements as well as transmitted forces between adjacent structural elements to desired values. This means being able to control at will the structure's seismic response and ensure the same the required degree of protection.

THE SEISMIC HARDWARE

The previous paragraph interpreted the energy balance equation in terms of the strategies that can be adopted during the design phase so as to organise anti-seismic defences. The following paragraph will place into perspective the design choices and the different types of anti-seismic devices available in the market.

Before setting off to develop a project, the seismic engineer must make certain strategic choices and the same - beyond personal preferences - depend on the type of structure, the seismicity and geological nature of the site, the norms currently in force, and any client requirements to be met as well as other incidental parameters.

In the past, it was *also* necessary to take into account one more limitation; that is to say, the unavailability of suitable seismic hardware that could also prove to be reliable. Such a limiting factor does no longer exist.

Today, seismic engineers can rely upon numerous solutions and relevant types of seismic devices that have already been adopted with success within the last two decades. Said solutions, notwithstanding their large variety, can be roughly grouped into two main types, and precisely those:

a. that provide the *structural members* with sufficient flexibility, strength and ductility to absorb and dissipate the energy input; these solutions are part of that which we have already pointed out as *"conventional design approaches"*;

b. that aim at protecting the structure against earthquake damage by limiting the effects of a seismic attack (rather than resisting it) through the use of *seismic devices* properly inserted into the structure; this approach is usually referred to as *"seismic mitigation"*.

Without delving deeper into the matter of selection criteria insofar as the diverse possible technical solutions and strategies they govern, which goes beyond the scope of this paper, what follows illustrates some concepts that inter-relate design choices and anti-seismic devices enabling their practical application. To this purpose, the flow chart in fig. 2 below will be used.

The design engineers who has selected the adoption of traditional techniques - which as stated before essentially consist in strengthening the structure - has before him two possible alternatives, to wit:

a.- only endow the structure with *permanent restraints* and its members with adequate flexibility, strength and ductility

b.- also insert *temporary restraints* in strategic points of the structure

The superior seismic behavior of hyperstatic structures, and bridges in particular, is well known. The simple explanation for the fact is that in hyperstatic structures, all structural members are forced to work together at a critical moment.

However, especially in the case of bridges, construction techniques (e.g. prefabricated beams) and the risk of occurrence of differential settling on the foundations often suggest the choice of isostatic arrangements.

The advantages of the two concepts can be maintained through the adoption of hydraulic shock-transmitters that create temporary restraints in critical structural points. In fact, the latter allow slow displacements (*e.g.*: those due to thermal variations) without appreciable resistance, but prevent those of sudden onset due to an earthquake. As a consequence, the structure remains isostatic under service loads while it becomes hyperstatic during a seismic attack through the creation of temporary restraints.

Shock-transmitters obviously cannot dissipate energy. Notwithstanding this, it is still possible to give an interpretation of their function from the standpoint of the energy-based approach. In fact, by forcing all the structural members to co-operate by moving jointly, they increase both the overall capacity of the structure to store energy and dissipate it through the intrinsic viscous mechanism (see § 2)

Figure 2 shows that the alternative to *Strengthening* or *Conventional Design Approach* is *Seismic Mitigation*. It has already been anticipated that his can be achieved through *Seismic Isolation* or *Energy Dissipation* (better yet, through a combination of both).

In turn, the Seismic Isolation can be implemented in two ways, both of which rely on "seismic isolators", to wit:

- Through the reduction of the seismic response subsequent to the shift of the fundamental period of the structure in an area of the spectrum poor in energy content (the so called T-Approach).
- Through the limitation of the forces transmitted at the base of the structure (the Y-Approach). This approach is also characterised by a high level of energy dissipation so it represents a combination of the two strategies of *seismic mitigation* cited above.

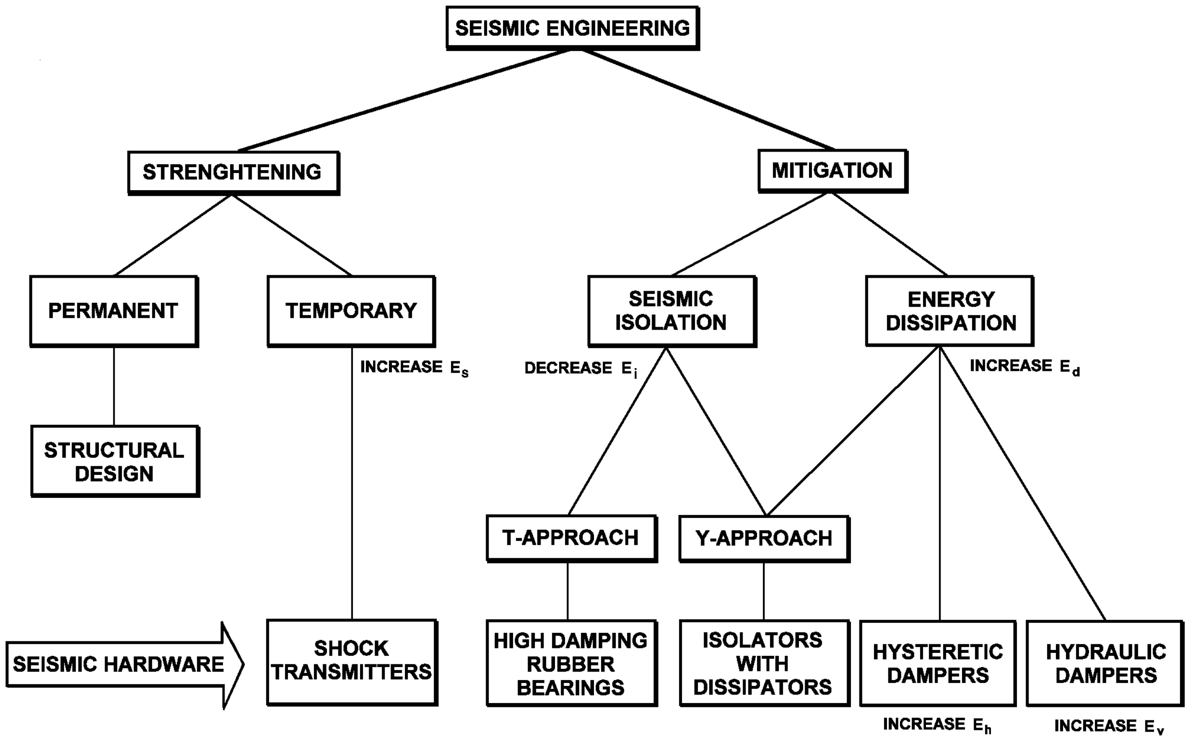

Figure2.- Seismic Design Approaches and the respective Seismic Hardware.

Both of these approaches are carried out using *isolators* or, more generally, *isolation systems*. The latter must be capable of ensuring the following four functions:

- transmit vertical loads
- provide lateral flexibility
- provide restoring force
- provide significant energy dissipation

The difference between *isolators* and *isolation systems* resides in the fact that in the former, the four fundamental functions are achieved by a single device (even though the same might include distinct elements within it which carry them out separately) while in the latter, the four functions are implemented by different devices.

An example of an *isolation system* is that usually adopted with suspension bridges, where deck loads (or prevailing mass) are transmitted by vertical cables that also provide transverse flexibility and re-centering (by gravity). Vertical cables are not yet capable to dissipate energy (fourth fundamental function), thus between deck and piers dissipating devices are installed, usually *Hydraulic Dampers*.

The seismic hardware presently used to implement the T-strategy mainly comprises high-damping rubber bearings. Essentially, these are laminated rubber bearings fabricated from dissipative elastomer. Despite the name (high-damping...) their dissipating capacity is limited, because their equivalent damping ratio does not go beyond 15%.

An interpretation of their function from the standpoint of the energy-based approach is that of considering them reflectors of energy throughout the spectrum, with the exception of the frequencies close to the natural frequency of the structure. However, their dissipating capacity, though modest, nonetheless impedes the accumulation of energy through resonance.

Conversely, the isolators that permit the implementation of the so-called Y-approach are characterized, aside of their representing very different construction solutions, by their essentially very high capacity to dissipate energy. Due to this characteristic, devices in this category afford excellent control of relative displacements and avoid any risk of resonance to the point that, in the structures where they are utilized, it is even difficult to define a natural frequency for them.

The devices developed for the *Y-approach* constitute by far the most numerous category to date present in the market and the most important types are the following:

- Friction pendulum
- Friction sliders
- Lead rubber bearings
- Sliders with steel hysteretic dissipators

In the first two, dissipation is achieved through friction whereas in the last two, use is made of the plastic deformation of a metal (lead and sweet steel respectively). In each device, the constructive elements assume one or more of the four fundamental functions cited.

In the case of *Lead Rubber Bearings*, the elastomer ensures the first three while energy dissipation is entrusted to the lead insert.

In the case of *Sliders with steel hysteretic dissipators*. vertical loads are transmitted through traditional sliding bearings of the "free" type, which thus also ensure lateral flexibility and the other two isolator functions are provided by steel hysteretic dissipators. The latter can be of the most diverse geometric shapes, and at least a dozen different types have found practical application.

Several combinations of bearings (*i.e.*: elastomeric, pot or spherical) and steel hysteretic dissipators are possible, and the choice of an optimal combination depends either on the basis of requirements to be fulfilled (*i.e.*: elastic stiffness, post-elastic stiffness, amount of displacement, dissipative efficiency, etc.) or considerations of a practical nature such as overall dimensions, ease of installation, maintenance, etc.

Energy dissipating efficiency (*) of Lead Rubber Bearings and Friction Pendulum can easily reach 50% of equivalent damping ratio, while Friction Sliders and Sliders with steel hysteretic dissipators can even exceed 70%.

(*) Note: Dissipative *efficiency* is defined as the ratio of the area of the hysteretic cycle and that of the circumscribed rectangle. In a multi-modal linear analysis, to characterize a device's dissipative capacity, the *equivalent damping coefficient* ξ is used, which is related to the dissipative efficiency η by the simple equation: $\xi = \frac{2}{\pi}\eta$

It should be noted that almost all the devices in this category suffer from poor re-centering capability. Energy dissipation and re-centering capability are in fact two antithetic functions and make necessary to find a satisfactory compromise between the two on a case-by-case basis.

In the Seismic Isolators used to implement the Y-approach, the interpretation of their function according to the energy-based approach is similar to that given for the high-damping rubber bearings. However, they are imperfect reflectors of energy in that they let high frequencies pass through. This is not significant in bridge design, but can constitute a disadvantage in some other applications (*e.g.*: civil edifices).

If the adoption of Seismic Isolation is not feasible, seismic mitigation can be implemented by solely resorting to energy dissipation as indicated in fig. 2, as long as the structure in question possesses sufficient flexibility. In other words, appreciable relative displacements occur during an earthquake due to elastic deformation of its structural elements. In this case, the seismic response reduction is achieved by inserting Hysteretic Dampers and/or Hydraulic Dampers into the structure.

The interpretation of their function in terms of the energy-based approach is elemental: they constitute a sort of *relief valve*s to let off, in the form of heat, the earthquake-imparted mechanical energy, thus eliminating (or at least minimizing) the energy dissipation demands (plastic hinge formation) in the primary structural members.

It should be noted that the amount of energy at play in a structure during a design level seismic attack ranges from 1 to 50 MJ ! The above raises the fundamental question: "Will the seismic device survive the damage produced in itself by the energy it dissipates during an earthquake?".

To date, very few full-scale devices have been tested with an actual seismic input. The reason is quite simple: there are very few testing rigs (°) in the world with adequate power to conduct such an experimental test, requiring between several hundred kW or even more than one MW depending on the size of the device. In effect, precisely this level of power at play should invite reflection on the part of design engineers when selecting the type of hardware, making them tend toward those types that offer greater guarantee in terms of survival reliability.

In closing, this exposition per force simplified of the design strategies interpreted in terms of underlying energy concepts and the respective devices capable of achieving the same, it is important to point out that in both new and retrofit seismic project, the selection of the type of seismic hardware must not necessarily fall upon a single type of device. In many cases, the adoption of combinations of devices can accrue significant advantage.

Seismic engineers are showing a trend toward increased interest in the adoption of different types of seismic hardware within the confines of a single project.
As examples of successful applications of the above in the United States, it is appropriate to mention the combination of High Damping Rubber Bearings with Hydraulic Dampers (Los Angeles City Hall -CA), as well as the combination of Isolators with steel hysteretic dissipators and Shock-transmitters (Marquam Bridge in Portland, OR)

(°) Note: At present (August 1999) at the University of California at San Diego, the construction and the preliminary testing of a new test rig named *Seismic Response Modification Device Test Facility* has been completed. This testing rig is capable of developing a vertical load of 54 000 kN, a horizontal force of 8 000 kN, peak velocity of 1,8 m/s and allowing ± 1,2 m displacements.

CONCLUSIONS

Earthquake Engineering has witnessed significant development during the course of the last two decades. The result has been reached owing to the parallel development of new design strategies (the "*seismic software*") and the perfection of suitable mechanical devices to implement said strategies (the "*seismic hardware*").
The seismic design of a bridge cannot be a simple application of mathematical equations, but requires the evaluation and understanding of the phenomena involved, so as to set up a "plan of defence", *i.e.*: the delineation of a specific design strategy.
The use of an energy approach, and particularly the use of an energy balance equation, offers a promising rational basis for defining the design strategy, as well as deriving maximum advantage from the type of structure under study and the existing seismic hardware.
In terms of the state-of-the art in technical-scientific knowledge, the most promising strategy is that of limiting, whenever possible, the amount of energy transmitted to the structure through Seismic Isolation and eliminating that which inevitably penetrates through appropriate dissipative seismic devices inserted in appropriate points of the structure itself.
Although basic concepts and general guidelines for retrofit of structures have been formulated in the recent years, the proper design strategy for a given facility is a unique problem requiring a customised solution.

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