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The evolution of seismic devices for bridges in Italy

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ABSTRACT: The idea of protecting structures from damaging effects of earthquake by the use of purposely designed and properly installed mechanical devices is over a century old, but its practical applications are relatively recent, probably due to the lack of suitable and reliable devices.
The first Italian use of an seismic device on a road bridge dates back to 1974; since then, a large number of bridges have been protected, particularly, with the base isolation system.
The paper, though a review of a few significant examples, describes the historical evolution of the conception and design of seismic devices in Italy, from the original purely elastic devices to the most modern elasto-plastic or dissipating devices.

1 INTRODUCTION

Suitable design strategies to protect civilian edifices were proposed more than a century ago, but strange as it may seen, very few practical applications have been seen until the very recent past.

This fact may be explained on the one hand by the requirements of existing seismic codes that, at least in certain countries, hinder or make difficult their adoption; and, on the other hand, at least in the past, by the lack of adequate devices which allow the reliable and efficient creation of a seismic protection system.

In other words, the actualization was prevented by the lack of both seismic "hardware" and "software".

As it regards the latter, it is worthy of note to mention that Italy has been actively involved, since 1989, in the process of drafting a national Standard for a seismic devices which may one day serve as guideline for a similar European Standard.

In Italy, the first mechanical devices deliberately designed and installed on a bridge in order to create a suitable auxiliary system to protect the structure from seismic actions dates back to 1974, well before the earthquake of May, 1976 on the Friuli region prompted great interest in the seismic problem in our country.

In fact, during that year, two different Road Administrations trusted the design of seismic devices to FIP Industriale, Selvazzano, Italy, quite different one from the other, to be installed, respectively, on the Savio viaduct on the E47 Expressway and the Somplago viaduct on the A23 Highway.

Perhaps, one could date to that year the birth of the sometimes called "Italian approach" to bridge seismic design.

Essentially, this "approach" consists in the creation of an efficient auxiliary system active against lateral and specifically seismic forces, quite distinct from the classic "structural system" which resists vertical loads through the use of bearings arrangement.

In other words, specific devices are installed in order to prevent the disastrous effects of an earthquake, thus relieving the bearings from having to resist seismic horizontal forces (i.e.: the bearings are all of the "free" or "multidirectional" type.)

In fact, eventhough one realizes that it is always possible to design bearings capable of absorbing relevant horizontal forces, their connection to the superstructure is nonetheless precarious, above all, when prefabricated beams are used.

However, special bearings with seismic features have been developed for use in zones of low to medium seismicity ($S = 6$ and $S = 9$), which have met with some success in the retrofitting of existing structures.

The choices in the conception of structures that meet seismic criteria opted by design engineers since 1974 are numerous. Said choices, notwithstanding their relevant variety, can be grouped into roughly two main types; to be more precise, into those structures that, in the event of an earthquake, tend to:

a - Make the structural members work together (thus creating temporary restraints that become automatically active during the earthquake itself).

b - Limit the accelerations transmitted to the bridge deck and, therefore, reduce inertial forces (in practice, the base isolation system).

Two groups of seismic devices correspond to these two classes of solutions, and they are:

- the viscous type (commonly known as oleodynamic).

- the elastic and elasto-plastic type. (or energy-absorbing devices)

Obviously, a great variety of possibilities exist as it regards the combination of different types of seismic devices. The future Italian Seismic Standard will deal, amongst other things, with these combination devices.

2 OLEODYNAMIC DEVICES

The superior seismic behavior of hyperstatic structures and bridges in particular is well known as they call upon all the structural elements to work together at a critical moment.

However, construction techniques (e.g.: prefabricated beams) and the risk of occurrence of dangerous states of stress subsequent to differential settling of the foundations often suggest the choice of isostatic arrangements.

The advantages of the two concepts can be maintained through the adoption of oleodynamic devices.

In point of fact, the latter allow slow displacements (i.e.: due to thermal variations) but prevent those of sudden onset due to earthquake or braking actions.

In other words, given the conditions of normal use, the structure remains isostatic - with all the practical advantages the design concept entails - while it becomes hyperstatic during an earthquake, thus preventing, at the same time, relative movements that may produce damage to the bearings, joints, and other adjacent structural members, and - in the case of railroad bridges - to rails and ties.

The first oleodynamic device was mounted on the previously cited Savio viaduct, (see Fig. 1) while the most recent and worthy of note applications of the concept are mounted on the Direttissima Rome-Florence Rail Line, the Trafori Highway, and the covering (short side) of the nuclear power plant at Montalto di Castro, Italy.

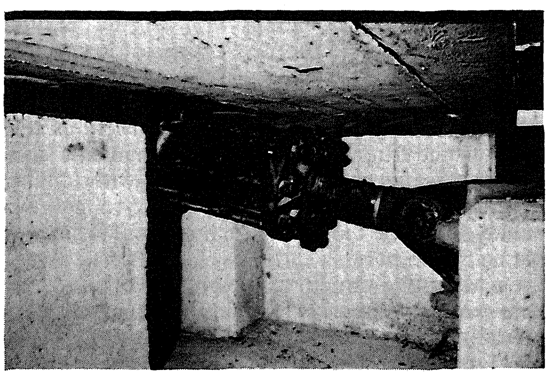


Fig. 1 - Oleodynamic seismic device

All the above devices have successfully passed the dynamic tests simulating actual seismic actions. (see Fig. 2)

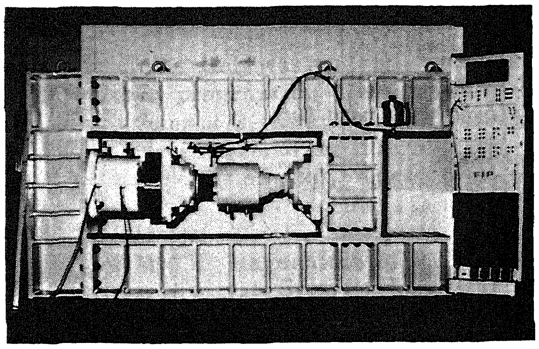


Fig. 2 - Testing rig for oleodynamic devices

3 ELASTIC AND ELASTO-PLASTIC DEVICES

The devices of elastic or elasto-plastic characteristics were developed in order to allow the creation of the "Base Isolation System", that is, the design strategy based on the assumption that a structure can be decoupled from damaging ground motion during an earthquake through the use of devices that prevent, or at least reduce, the transmission of horizontal accelerations into the structure itself.

This concept first saw the light, as far as we know with certainly, in 1909, when a patent was issued in England [1], surprisingly, to a medical doctor who in a letter to a Cilean engineer, stated to have perfected a Japanese design of 25 years before.

However, as it is known, the theoretical solution of simple decoupling is not practicable as the structure would not be able to support any lateral forces, as it conversely is needed in its normal use (i.e.: wind, braking, centrifugal force in bridges, etc.).

It is also known that the most obvious remedy to this inconvenient would be to use an elastic connection between structure and ground which acts as a self-centering device but at the same time creates an oscillating system consisting of the said device (the "spring") and the structure (the "mass").

Selecting opportunely low values for the rigidity of the spring, it becomes possible to obtain resonance periods sufficiently elevated ($T > 2$ sec), and therefore, centered in a zone of the seismic spectrum characterized by low energy components. The result is an appreciable reduction in seismic response.

The first example of an elastic device is that of the already mentioned Somplago viaduct (Udine-Carnia Highway) constructed with the assembly of four discs of neoprene vulcanized to steel plates (see Fig. 3a)

With a double system of tension rods, affixed respectively to the abutment and the bridge deck, it was possible to obtain the double effect stressing the discs always in compression, also during the phase of separation between the abutment and the bridge deck.

The whole device was conceived in such a way as to allow on-site assembly and eventual replacement.

The characteristic load vs. deformation curve ob-

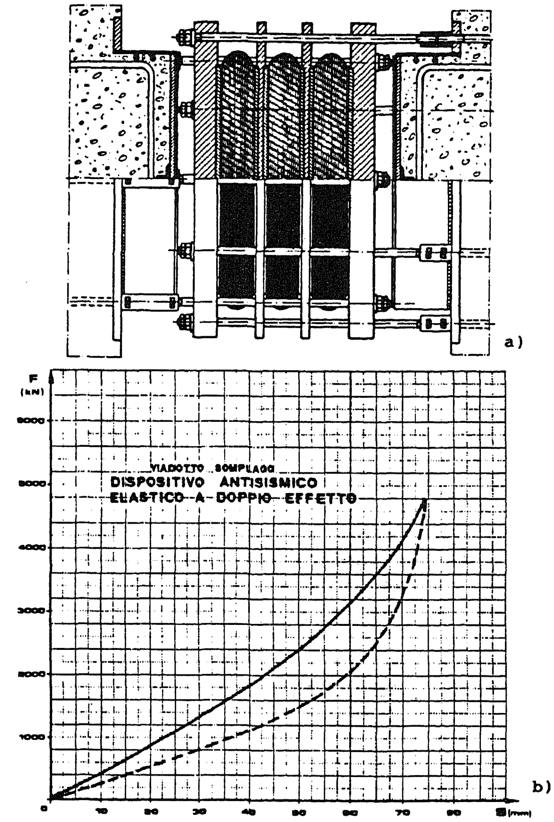


Fig. 3 - Elastic seismic device

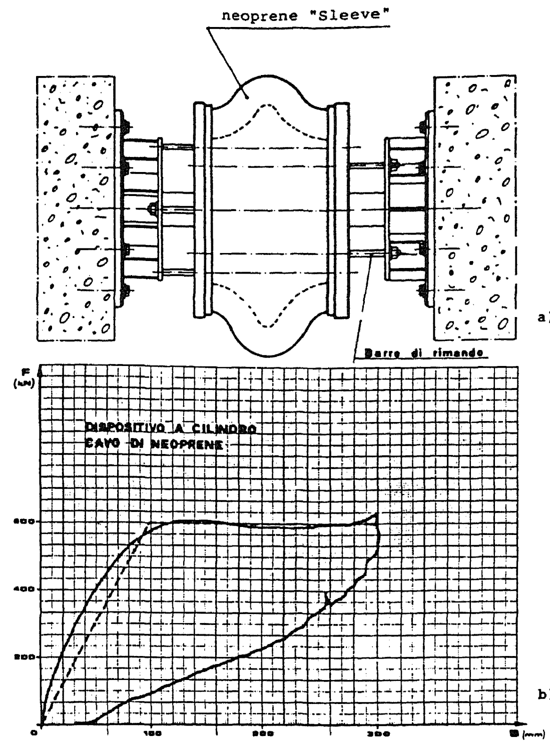


Fig. 4 - "Sleeve type" elastic seismic device

served is of the increasing slope type. (see Fig. 3b)

This aspect is also common to other elastic devices, therefore, it may be concluded that the control of relative displacement (which normally still remains elevated) may be reached, although not so that of the forces at play.

The Somplago viaduct is believed to be the first example of a bridge intentionally base isolated at the design stage. Preceeding examples are known, but they are cases of retrofitting [2].

It is worth mentioning that four elastic devices were installed at one end of each of the two decks comprising the viaduct. The length of both decks is 1.2 Km. (approx. 3/4 mile).

No provisions were made for transverse seismic actions.

Before its completion, the viaduct was exposed to the May, 1976 earthquake (magnitude 6.4 and peak acceleration 0.35 g.) and no damages were reported.

For the subsequent section of the same highway, the design engineers prescribed devices with characteristic curve force vs. displacement of the type shown in Fig. 4b.

This curve shows a first phase of proportionality between force and displacement (elastic phase), followed by a phase of constant force independent of displacement.

In such a way, the maximum force transmitted from the abutment to the bridge deck is limited to a desired value.

This is equivalent to the introduction of a load limiting device in series with the "spring".

The author proposed a device in which the deformable element is made up of a hollow cylinder (a sort of huge sleeve) in neoprene, which allowed by itself, when adequately proportioned and axially loaded, to obtain the required characteristic curve. (see Fig. 4a)

In fact, on the initial phase of compression, the cylinder assumes the shape of a barrel with an external curvature completely convex, the load vs. deformation curve being almost linear ("elastic" behavior).

After approximately 15-20% deformation, there appears a counterflexion in the vicinity of the cylinder borders, and these align themselves perpendicularly to the load transmission plates; the slope of the curve is diminished, may be annulled, and even become negative as a function of the adopted geometric parameters, with the appearance of a phenomenon of elastic instability in radial symmetry.

An opportune system of restraints allowed the double effect, that is, to work under compression even during the phases of separation between the abutment and the bridge deck.

Fig. 4b, shows the optimal approximation to the theoretical curve. Even the dissipation (not mentioned in the specifications) was good and that allowed some limitation of the relative abutment-bridge deck displacements.

With respect to other proposed solutions, the major advantage of this device consisted, however, in a significant reduction of the axial overall dimension so as to allow its installation between the bridge deck and the abutment, with obvious advantages as it regards inspection and maintenance.

Notwithstanding, the radial overall dimension was considerable after the bulging.

The viaducts equipped with the "sleeve-type" device were also seismically isolated transversally. The relevant devices were simply neoprene disks.

For the first time, the problem of utilizing a yet more compact element of seismic restraint - and above all, of a more dissipating nature - was posed by the Passarella viaduct and the Carnia-Tarvisio Highway.

The bridge deck of this structure is in fact made up of 4 steel girders which exclude the installation of sleeve-type seismic devices.

As it regards energy dissipating capacity, it should be noted that the Italian bridge design engineers became aware, at the end of the 70s, that damping properties of seismic devices are a powerful tool in their hands to control relative displacements between ground and structure.

Studies conducted to satisfy the new specifications led to the manufacture of an oleodynamic-type device with high dissipating characteristics, schematically assimilable to a double action hydraulic cylinder, in which each chamber is connected to the other, and connected to a membrane-type hydropneumatic reservoir, pre-loaded with inert gases. (see Fig. 5 and 6)

The two chambers are connected by two overpressure adjustable valves - one for each direction of movement.

Both extremes of the seismic device are equipped with spherical joints that guarantee a rotation of ± 5° so as to allow its installation even in cases when the alignment of the anchor plates affixed respectively to the bridge deck and the abutment is not perfect.

The device operates in the following manner:

- With mounting forces and up to reaching the preload pressure of the accumulators, modest displacement is observed. This is due to the elasticity of the system and the compressibility of the hydraulic oil; (O-A portion of the curve of Fig. 5b).
- Upon exceeding the pre-load pressure, the gas in the reservoir reduces its volume in relation to the rise in pressure (and therefore, that of the force acting upon the piston rod) according to a change that approximates an adiabatic process (portion A-B).
- Upon reaching the adjusted pressure of the overpressure valve, the transfer of fluid from one chamber to the other begins. Said valve guarantees a differential pressure (and therefore, also a force) almost constant, independent of the flow rate of the fluid, i.e.: of the velocity of displacement of the piston rod (portion B-C).

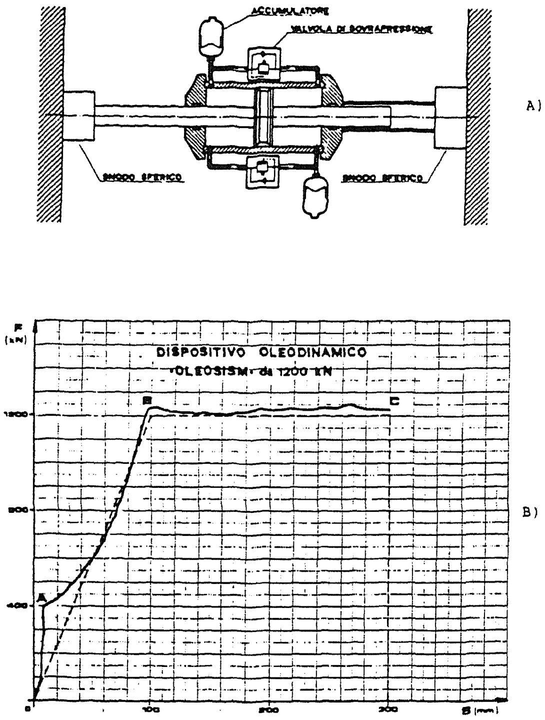


Fig. 5 - Oleodynamic energy-absorbing device

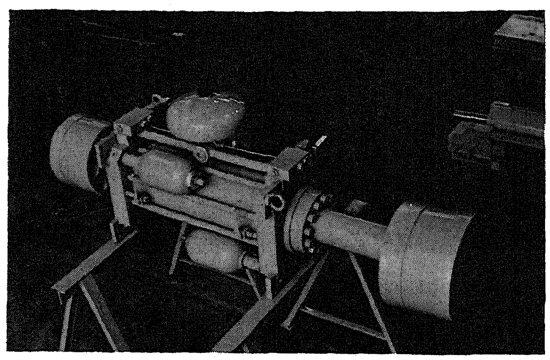


Fig. 6 - Oleodynamic energy-absorbing device

The geometry of the cylinder and the piston being equal, this device permits to adjust at will the characteristic curve force-displacement by modifying the volume in the reservoir, its pre-load pressure, and the pressure of the overpressure valve.

Amongst the advantages that accrue through the use of this oleodynamic device, the following are worthy of note:

- High reliability and constant characteristics in time and independent from both temperature and velocity, when compared to earlier solutions which utilized elastomers.

- Ease of placement and inspection due to their compactness nature, their capability to vary geometric length (through the oil intake in one of the two chambers i.e. by means of a simple hand pump) and the presence of spherical joints at the ends.

- Ability to move the bridge deck to correct possible launching errors, excess of shrinkage, post-seismic residual displacements, etc. - as the same can operate as common double-action jacks.

- Possibility of an unlimited number of complete cycles to take place.

- Ability to provide a "rigidity" zone (portion O-A of the curve) adjustable at will through the pre-load pressure of the reservoirs - in such a way, the forces of normal function (bearing friction, brakings, wind as well as minor earthquakes) do not produce displacements of the bridge deck.

An alternative to the above are the "Sacrificial restraint devices", i.e.: rigid components designed to fail at a given level of load. These devices need to be replaced after each earthquake.

Eventhough the oleodynamic line appeared very promising due to the variety of characteristic curves that can be obtained thanks to the use of a single, relatively simple and proven mechanism, owing to the perplexity of some civil bridge engineers - reluctant to use devices that may seem like veritable "machines" - most recent studies are aimed at the research for simpler solutions based upon mechanical devices which make use of the plastic deformation of mild steel.

Amongst several elements tested - all of the elasto-plastic type - the three reported in Fig. 7 have shown themselves to be particularly promising.

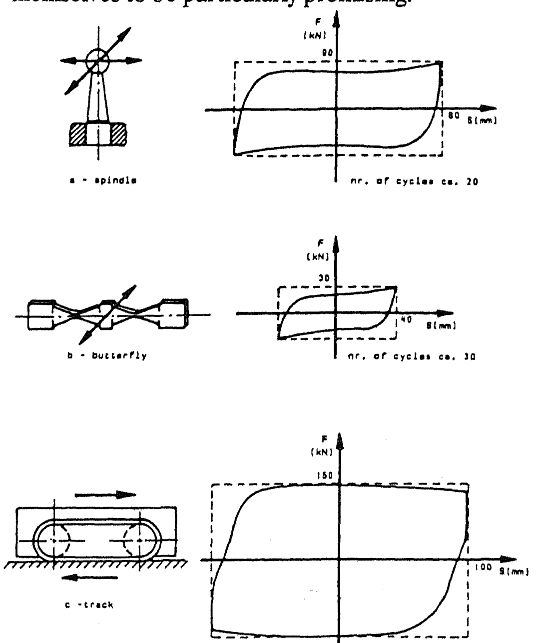


Fig. 7 - Some mechanical energy-absorbing devices

These dissipators have already found practical application either in combination with classical PTFE bearings or in particular arrangements suitable to create fully seismic bearings.

Fig.8 shows a practical case in which a combination of classical PTFE spherical bearings (designed to transmit only the vertical loads) and some dissipating elements on the "spindle" type is trusted with the task of absorbing lateral forces and dissipating seismic energy with significant plastic displacements.

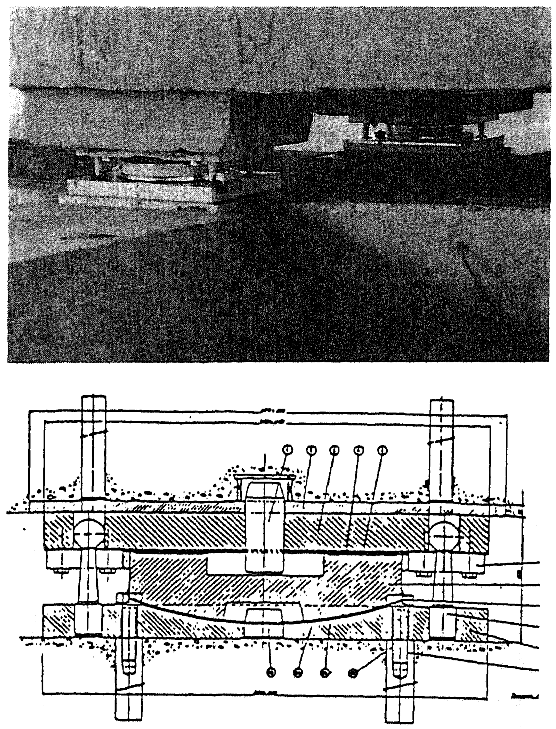


Fig. 8 - Seismic PTFE bearing

The device in question is manufactured in the "fixed" and "mobile" versions. ("fixed" and "mobile" with respect to the normal life of this structure: in case of an earthquake both became mobile)

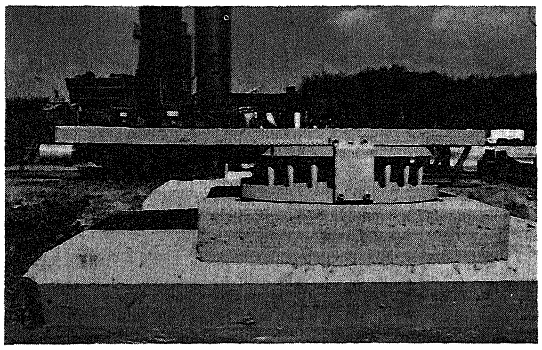
In the mobile type, a hydraulic device as described in par. 2 is placed in series with the dissipating elements in order to ensure continuous coupling of the bridge deck and the dissipating elements thus avoiding stresses induced by thermal expansion during the normal function of the bridge.

The shape of the dissipating elements has been specifically studied so that the displacements transmitted to their heads generate a state of uniform stress along their total length without zones of dangerous concentration of strains, above all, in the phase of plastic deformation.

Once the design engineers and the manufacturers had started on the way to mechanical devices which use the plastic deformation of steel, the Italian imagination broke loose.

Dozens of inventive and innovative solutions were proposed and the majority of them have found a practical and successful application today.

Fig. 9 shows a recent type using "crescent moon" elements as hysteretic energy dissipators.



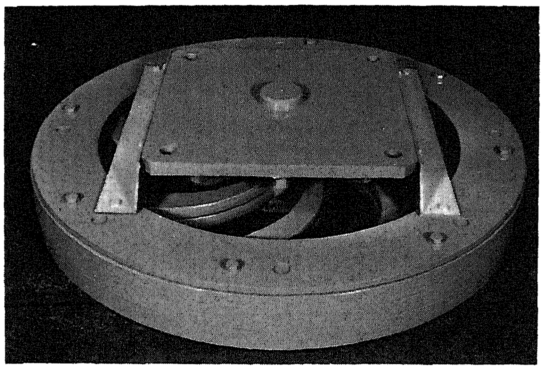


Fig. 9 - Multi directional energy-aborbing devices

Installed between two "free" PTFE bearings, this seismic device provides seismic protection to the bridge deck in all directions even with different behavior in longitudinal and transverse directions.

At present, it's safe to assert that almost all new bridges in Italy are equipped with seismic devices and certainly all those constructed in seismic zones.

There is also a great deal of retrofitting in progress to existing bridges.

At the end of 1991, a national survey has shown that over 155 bridges and viaducts are seismically protected.

The above gives an enviable record to Italy.

4 CONCLUSIONS

After almost two decades of study and practical applications, seismic devices for bridges and viaducts have reached such a level of development and degree of reliability as to dispell any doubts over the validity of their use.

If properly designed and correctly inserted in the structure, seismic devices have the potential for providing protection against all earthquake exposure.

According to the Italian Seismic Code, they must:

- avoid any structural damage in the occurrence of the "design earthquake" , i.e.: an earthquake with a period of return equal to the useful life of the structure; (100 years for bridges)
- avoid the collapse of the structure, with the acceptance of some structural damage, for the "most disastrous earthquake" foreseen at that specific site, i.e.: the earthquake with a period of return greater than 500 years.

It is not just the advent of reliable seismic devices (the "hardware"), what has made structural seismic protection a practical reality.

Other parallel but independent "software" developments have also contributed to the acceptance of the above design strategies, the most important being the well known Base Isolation System.

Amongst these, we should note:

- the development of reliable software for the computer analysis of structures to predict their performance;
- improvement in the estimation of ground motion at a particular site by seismology engineers; and last, but not least,
- the drafting of suitable seismic codes.

The devices' cost effectiveness is amply justified by the benefits they secure - which can be quantified [3].

However, beyond purely economic considerations, it behooves one to consider the vital importance of bridge survivability which enhances or makes possible rescue operations following a disastrous seismic event.

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