Earthquake Engineering, Tenth World Conference © 1992 Balkema, Rotterdam. ISBN 90 5410 060 5

# Seismic isolated bridges structures in Italy

Marco Mezzi & Alberto Parducci
*Perugia University, Italy*

ABSTRACT: A large number of Italian bridges built in seismic areas have been provided with special isolating devices in order to achieve a suitable seismic protection. These apparatuses have been used both in the construction of new bridges and in retrofitting of existing ones. Because of the current use of continuous deck structures, some particular isolating configurations have been designed. A general description of the isolating systems and design criteria is presented in the report.

## 1 INTRODUCTION

A large number of Italian highways bridges, built in seismic areas, have been provided with various kind of seismic isolating devices. Up to this time, more than a hundred bridges (both new and retrofitted structures) have been built, while the design of an equal number of structures is carrying out, in which the use of aseismic devices is foreseen. Medeot (1991) presented a list of more than 150 Italian bridges in which various kind of particular aseismic restrainers systems were used, in order to reduce the seismic input.

In Table 1 (new bridges) and Table 2 (retrofitted bridges), synthetic lists of the main isolated structures are represented. In Table 3 and Table 4 comparative estimations of the costs of the most recent works are reported. (for Table 3 and Table 4 see the last page of the report).

Table 1. New isolated bridges in "Autostrade", "SAT" and "ANAS" networks.

| Sections (see Figure 1) | No. |
|---|---|
| [A] Udinė - Carnia | 32 |
| [B] E.45 (Perugia - Cesena) | 5 |
| [C] Raccordo autostradale (Roma) | 22 |
| [D] Vittorio Veneto - Pian di Vedoia | 9 |
| [E] Livorno - Civitavecchia | 5 |
| [F] Variante appenninica (to be designed) | ≈ 30 |

The main goal in seismic isolation is to improve the seismic performances of structures, reducing their response if they will be attacked by the "maximum earthquake" expected on the site. From this fundamental point of view, two different performance levels can be considered in the design.

At the higher performance level, the responses of all the structural elements (except the isolating devices) are requested to remain below their elastic limits. Therefore, the main structures are not stressed in the plastic range and no structural damages are foreseen, neither in the case of the "maximum expected earthquake". This is the performance level, defined as "Integral Seismic Protection" (ISP), which was usually considered in the design of new isolated bridges.

Table 2. Bridges in "Autostrade", "SAT" and "ANAS" networks which have been retrofitted using seismic isolation systems.

| Sections (see Figure 1) | No. |
|---|---|
| [G] Napoli - Bari | 22 |
| [H] Firenze - Bologna | 2 |
| [I] Roma - Napoli | 12 |
| [J] Salerno - Reggio Calabria | ≈ 50 |

At a lower level, it can be accepted that some structural members, in addition to the isolating devices, may be engaged in the plastic range by the "maximum expected earthquake", but within the limits of low admissible ductilities. This is a lower performance level, defined as "Limited Seismic Protection" (LSP), which was accepted in the design of some retrofitted existing bridges.

## 2 ISOLATING SYSTEMS

Most of the isolating systems used in the Italian bridge designs were based on the use of special connecting restrainers by which the lateral forces acting between the superstructure and the piers are transmitted. Generally, in the field of bridge constructions, these devices are characterized by an elastic-plastic (EP) behaviour. With this kind of behaviour the maximum values of the transmitted forces can be controlled in order to limit them below assigned values which takes into account the yielding resistance of the main structural members. Furthermore, a large energy dissipation can be attained, due to the hysteretic paths of the EP cycles.

A reduction of seismic response was also obtained using low-stiff connectors (elastomeric bearings). Then, the reduction is due to the increase of the natural period of the structure, which grows up to the range in which the seismic input has a lower power. The devices can also be arranged in order to obtain high damping systems with a further decrease of the response (lead rubber bearings).

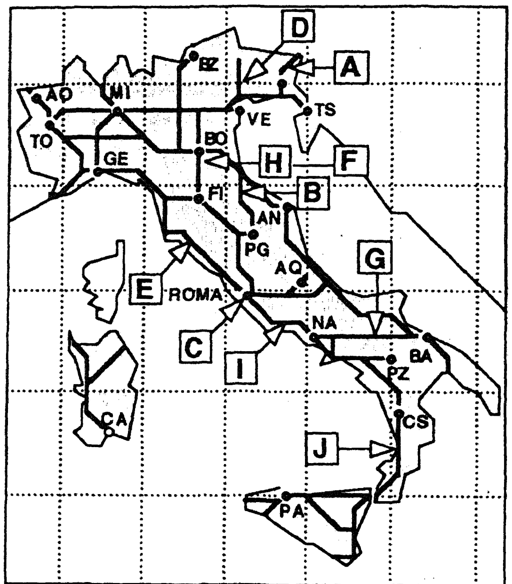

Figure 1. General layout of the Italian highway network

These high-flexible and high-damping devices were not frequently used in Italy in the design of main bridge structures. Therefore, only the bridges isolated with apparatuses having an EP behaviour are considered in this report.

## 3 STRUCTURAL SCHEMES

Usually in Italy, new bridges are built by means of continuous multi-span girders. These schemes, which mainly derives from constructive procedures, can also be suitably considered from the seismic point of view, because a monolithic behaviour of the whole deck-structure under seismic actions can be attained. Furthermore, the paving joints between the consecutive single-span girders are eliminated, so improving the durability of the structure and avoiding all the troubles deriving by the defaults of the joints.

The longitudinal schemes of a continuous deck structure were often reproduced in retrofitting existent bridges, built 20-30 years ago, which were built by means of single-span girders. The continuity was then obtained by the insertion of flexible new slabs connecting two consecutive girders. The static scheme for the vertical loads (pinned single-span beams) remains as the previous one, but the deck structure behaves as a continuous girder against horizontal forces.

Sometimes, in order to increase the flexibility of the connecting slabs, a special joint, which realises a horizontal hinge, was also used (Figure 2).

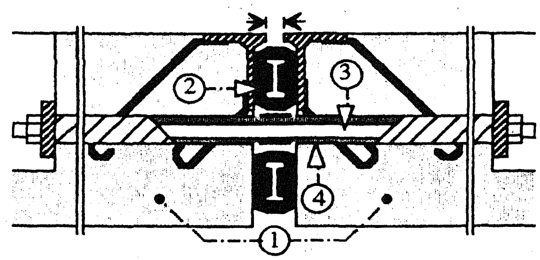

Figure 2. Hinged slab joint. (1) Connecting slab. (2) Elastomeric pads. (3) Prestressing bar. (4) Elastic grout (Fip-Industriale system)

## 4 GENERAL LAY-OUT OF ISOLATED BRIDGES

A continuous section of a multi-span superstructure can be isolated from the substructures (piers and abutments) in various ways, fundamentally as it is described below.

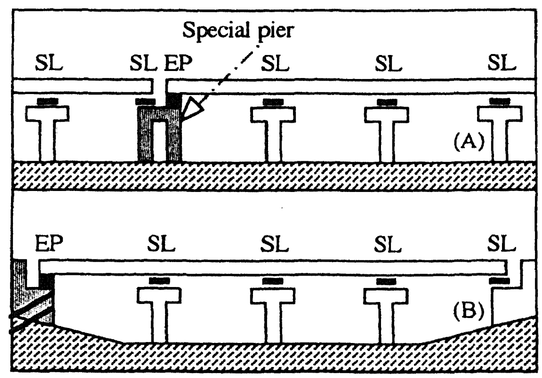

Figure 3. Typical configurations with one EP device.

### 4.1 Only one EP device is acting

With respect to the longitudinal seismic inputs, an isolated configuration can be obtained inserting sliding supports between the girder and all the piers but one. In this single position a dissipating EP device must be placed. So, the piers having sliding supports are not engaged by longitudinal forces due to the inertia of the girder masses.

Obviously, the single supporting structure on which all the longitudinal forces are applied must be designed (new bridges), or must be reinforced (existent bridges), strong enough to resist the whole seismic forces (Figure 3).

This solution was suitably used when the bridge had only one continuous section. The deck was restrained to an abutment, which was designed to resist the whole longitudinal seismic force. Sometimes, in retrofitting works, the existent abutment was reinforced by means of sub-horizontal rod-ties inserted in the back ground (Figure 3.B).

These are simple isolating configurations, because all the bearings can be designed as usual sliding supports and only one special restraining device has to be provided for each continuous section.

### 4.2 All the supports acting as EP devices

Another isolated configuration can be obtained connecting the continuous superstructure to all the piers by means of bearings devices which behaves in EP way when longitudinal forces are transmitted. In this case, all the substructures are engaged in seismic resistance and the inertia force of the deck masses is distributed between all the piers. The maximum force transmitted to each pier is limited by the assigned plastic threshold of the EP device placed on it.

The plastic thresholds may be designed in such a way that the maximum stresses in the piers do not reach the elastic limits (ISP), or the maximum required ductility (LSP). Particularly, in retrofitting existent bridges, the plastic thresholds of the devices placed on each pier were often be designed according to the actual resisting moments of the column, so that strengthening works of this structural element could often be avoided.

Unfortunately, significant problems arise from these configurations due to their consistency with the volumetric variations of the deck structure. The provisions used in Italian bridges are illustrated in a subsequent point of the paper.

### 4.3 Transversal isolation

In both the previous configurations, the transversal isolating system could be designed considering the usual EP behaviours of the horizontal connectors, placed on all the piers. In fact, the sliding supports can easily be guided in the longitudinal direction, while in the transversal direction usual behaviours of EP devices could be performed.

## 5 SEISMIC ISOLATION AND VOLUMETRIC VARIATIONS

Volumetric variations of the girder structures may occur, due to thermal effects, shrinkage of the concrete structures and creep of the prestressed elements. Currently, in the practice of continuous beams design the resulting longitudinal deformations are freely allowed.

Considering the two isolating schemes described in the previous section, these deformations can be freely permitted only in the former configuration where all the supports but one are designed as sliding ones.

On the contrary, the latter configuration, in which all the piers are connected to the girder via EP devices, can originate troubles and particular expedients have to be designed.

Fundamentally, there are to ways of dealing with this problem, as it is illustrated below.

### 5.1 EP devices separated by gaps

In order to design continuous bridges, particular configurations were previously examined in which all the piers were equipped with EP devices, but only one of them was fixedly connected to the deck. The other piers were provided with lateral gaps equal to the drift due to thermal effects. Because creep and shrinkage shifts cannot be included in the gaps, the devices had to be arranged with adjusting apparatuses in order to allow these deformations free and leave the gaps serviceable only for thermal excursions.

Due to the gaps, during seismic quakes the devices are differently engaged. Then, different plastic thresholds and different lateral resistances of the piers were to be designed. Therefore, this configuration was not considered as an ideal solution of the problem and it was improved as it is described in the following point.

### 5.2 Use of shock-transmitters

A more efficient configuration can be attained inserting an "oleodinamic" apparatus between the deck and the EP devices (Figure 4).

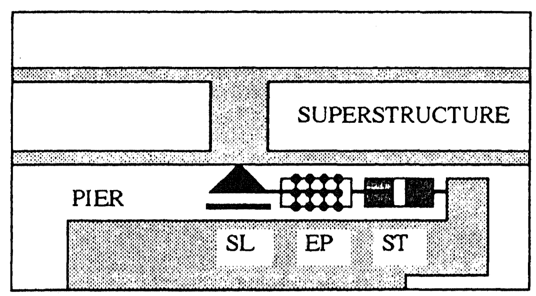


Figure 4. Arrangement of a bearing system with a shock transmitter. (SL) = sliding support; (EP) = EP device, (ST) = shock transmitter.

Because the oloedinamic device behaves as a highly viscous mechanism, it can be used as a "shock-transmitter" (ST). When a rapid deformation is requested, as during an earthquake, it actually behaves as a fixed restrainer and the full transmission of the seismic forces across the EP device is guarantied. When quasi-static slow deformations are requested, as those due to volumetric variations, drifts are permitted without significant horizontal forces.

A configuration in which all the EP devices are engaged during a seismic attack was then reached. Generally, an uniform distribution of plastic threshold of all the devices was designed, but different distributions, according to the actual pier resistances, was also be designed.

### 5.3 Special applications of ST devices

Seismic isolation of a bridge is commonly intended as the partial separation of the deck displacements from those of the piers, in order to limit the transmitted forces by means of plastic connecting devices. On the contrary, in particular situations, a fixed stiff connection between some piers and the deck, in order to optimize the global seismic response, could be suitably designed. This can occur when, in a multi-span section of a continuous bridge, there are some piers having very different slenderness; for example, when the height of one pier is much greater than the others.

In these configurations, using EP devices, too large displacements could be performed by the highest columns during a severe seismic attack. Therefore, the use of only a ST device, without the EP one, can be a suitable solution in order to obtain a stiff connection between the highest column and the deck, working only during a seismic attack (Figure 5). This arrangement makes the thermal drifts free. The inertial forces of the deck structure, together with those of the non-isolated piers, must be resisted by the EP devices placed in the remaining structures.

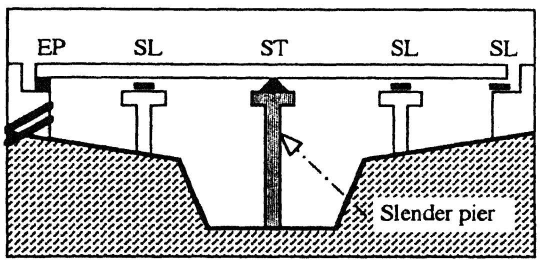


Figure 5. A ST application on slender piers.

ST devices were suitably used also for connecting the second abutment (for example, the right abutment in Figure 3.B) of a single continuous deck section designed with sliding supports on all the piers and EP dissipating devices on both the abutments.

## 6 GENERAL DESIGN CRITERIA

The plastic behaviour of an EP device has to be performed only if the structure is attacked by a major earthquake. Therefore, the plastic threshold must be designed high enough that only its elastic behaviour will be engaged when the structure is stressed by horizontal service loads (braking and centrifugal forces, wind and moderate seismic inputs). Two different intensities of design earthquakes were then considered for design purposes.

Conventional elastic calculation were carried out in order to evaluate the current responses of the structures under service loads. At this design level the seismic input can be reproduced by equivalent static forces or using a modal analysis with an assigned spectrum. A conventional check of the elastic resistance of the various members was then carried out, like for an usual non isolated structure.

In addition, seismic analyses were performed considering the maximum expected earthquake. Particularly, in the design of the bridges which are described in the following sections, the maximum earthquakes were simulated by artificially generated accelerograms derived by assigned response spectra and peak ground accelerations (PGA), in accordance with the Italian GNDT regulation. The shapes of the response spectrum depended on the local characteristics, while the PGA depended on the seismicity of the site.

Dynamic direct analyses was carried out, by a step-by-step procedure, taking into account the non linear behaviour of both the isolating devices and the main structural members. The DRAIN-2D code was used.

Two different digital models were considered, in order to simulate the seismic behaviour in both longitudinal an transversal directions. For design purposes the following parameters were calculated:

- maximum plastic deformations of the EP devices,
- maximum displacements of the deck structure,
- maximum displacements of the piers,
- maximum stresses in the structural elements,
- maximum local deformations of all the elements which could behave in plastic range.

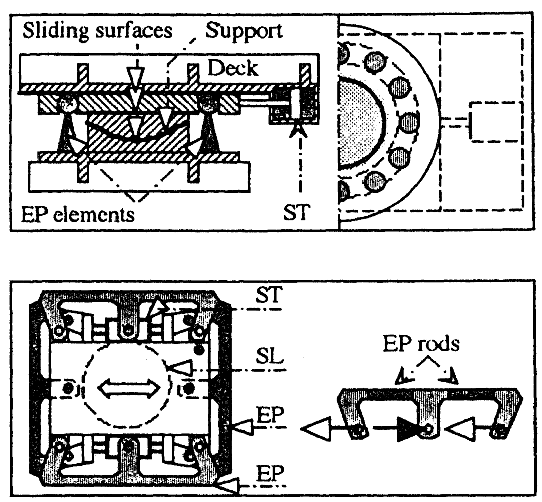


Figure 6. Schemes of the two types of EP devices used in the Mortaiolo Bridge.

The calculated maximum deformations of EP devices had to be consistent with their actual allowable ductilities which were measured by means of experimental tests.

With reference to the structural members, the checking criteria of their seismic behaviour were related to the requested protecting level:

Table 3. Estimated costs for recent new isolated bridges in Italian highway network (Figure 1) [1986-91]

| Section | Total length (km) | Structure (US $) x $10^6$ | Supports (US $) x $10^6$ | Isolation (US $) x $10^6$ |
|---|---|---|---|---|
| [C] | 6.5 | 120 | 1.8 | 2.5 |
| [D] | 3.3 | 64 | 2.3 | 5.2 |
| [E] | 13.1 | 223 | 8.1 | 9.0 |
| | 22.9 | 407 | 12.2 | 16.7 |

Table 4. Estimated costs for recent retrofitted bridges in Italian network (Figure 1) [completed works 1986-91]

| Section | Total length (km) | Structure & Isolation (US $ x $10^6$) |
|---|---|---|
| [G] | 4.7 | 4.8 |
| [H] | 0.5 | 0.5 |
| | 5.1 | 5.3 |

Table 5. Characteristics of the bridge "Mortaiolo"

New structure under construction

Highway: Livorno - Cecina [E]
Continuous deck made by prestressed RC slabs

Total length: 10 km Typical span length: 45 m
Typical continuous length: 432 m
RC piers - height: 5-12 m

Design parameters for the typical continuous section:
PGA = 0.25 g (20 seconds)
Isolated deck mass: 10'000 t

Isolating system (Figure 6):
EP devices (long & trans) on all the piers + ST
Stiffness: Ke = 150 MN/m (each pier)
Total yielding force: Fy = 11 MN
Max displacement: Su = 80 mm

- when the ISP performance was required for the design of a new bridge, ultimate resistance checks of all the members were carried out;
- when the LSP performance was required for the retrofitting of an existent bridge, ductility checks were performed in order to control the maximum plastic deformations of all the critical resistant sections of the structure.

The ductility checks of the reinforced concrete structural elements were carried out considering the following hc lengths of the Mattock plastic hinges:

$$hc = 0.5\,d + 0.05\,z$$

where:
- d is the transversal dimension of the resistant section,
- z is the distance of the controflexure point (high of the column).

The main characteristics of three typical examples of seismic isolated new and retrofitted structures are illustrated in Table 5 ("Mortaiolo Bridge"), in Table 6 ("Ponte nelle Alpi" Bridge) and in Table 7 ("Salso" bridge). The references of the highway sections are shown in Figure 1.

Table 6. Characteristics of the bridge "Ponte nelle Alpi"

Design of a new structure

Highway: V.Veneto - Pian di Vedoia [D]
Continuous steel beam (+ RC ramps)

Total steel length: 310 m Spans lengths: 95+120+95 m
RC piers - height: 18-24 m

Design parameters: PGA = 0.318 g (20 seconds)
Isolated mass: 2700 t

Isolating system of the continuous steel section:
EP devices (long & trans) on all the piers + ST
Stiffness: Ke = 60 or 120 MN/m
Total yielding force: Fy = 5.4 MN
Max displacement: Su = 85 mm

Table 7. Characteristics of the bridge "Salso"

(Design of a retrofitted structure

Highway: Salerno - Reggio Calabria [J]
Single-span prestressed beams retrofitted using connecting hinged-slabs

Total length: 320 + 200 m Span length: 33 m
RC piers - height: 22-67 m

Design parameters: PGA = 0.338 g (20 seconds)
Isolated mass: 5400 t

Isolating system in longitudinal direction:
EP device on the abutment
Longitudinal sliding supports on the current piers
Longitudinal ST on the higher piers.
Stiffness: Ke = 900 MN/m
Total yielding force: Fy = 9.0 MN
Max displacement: Su = 100 mm

## 7 EXPERIMENTAL AND ACCEPTANCE TESTS

When EP devices are to be used for seismic isolation of a bridge, severe experimental tests procedures must be performed. Generally, quasi-static tests were requested and the inelastic behaviours at given values (maximum alternate deformations and number of repeated cycles) of the experimental performances were evaluated. A typical test procedure, which was prescribed for the construction of the Mortaiolo Bridge, is described below.

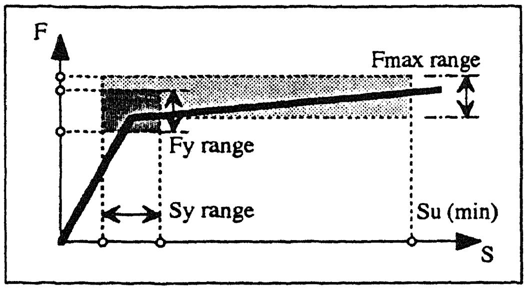


Figure 7. Ranges for acceptance tests.

### 7.1 Preliminary tests

Primarily, the actual behaviours, on which the design hypotheses were based, were defined. The behaviour of an EP device was usually reproduced by bi-linear relationships between forces and displacements. The design values of the following mechanical parameters were then derived by preliminary experimental tests:

- Ke = stiffness of the elastic branch
- Kp = stiffness of the post-elastic branch,
- Fy = yielding force,
- Sy = yielding deformation,
- Su = ultimate deformation

### 7.2 Acceptance tests

The actual performances of the apparatuses used in the constructions were prescribed according to the results of the calculations. For acceptance procedures, their mechanical parameters were checked carrying out tests both in the elastic and plastic range. Generally, the following parameters were specified (Figure 7):

- minimum and maximum values of Fy and Sy;
- minimum value of Su;
- minimum and maximum value of the force up to the Su displacement;
- number of alternate cycles to be performed (10 cycles between the nominal elastic limits and 10 cycle in the maximum plastic range).

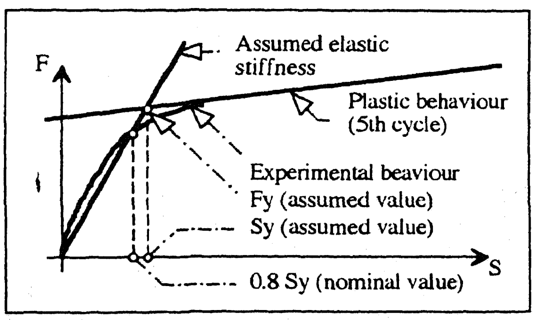


Figure 8. Practical criterion for the evaluation of the characteristic parameters from experimental tests.

Generally, during an experimental test the yield point (Sy-Fy) cannot be exactly estimated, due to the round path of the diagram. In order to achieve an unified criterion, the procedure illustrated in Figure 8 was assumed.

Furthermore, the actual plastic behaviour cannot be estimated as an absolute value, because it depends on the progressive number of cycles. Therefore, the maximum deformation of an element was defined with reference to an assigned number of repeated cycles (5th cycle).

## 8 CONCLUSIONS

Usual situations of structural configurations and typical isolating systems were described with reference to the Italian experience.

The criteria used in the design of new isolated bridges and in retrofitting existing ones were illustrated.

Characteristic data of some realizations of seismic isolation were reported as a sample of Italian practice.

## 9 ACKNOWLEDGEMENTS

The bridges described in the report are in the "Autostrade" and "SAT" and "ANAS" Italian network. Most of their isolating designs were performed by the authors.

The isolating devices have been manufactured by Italian firms (Fip-Industriale, Alga, Tesit, Asfalto Ansani, Tis).

## 10 REFERENCES

Medeot, R. Seismic isolated bridges in Italy. *International Conference on bridge supports.* Toronto (Canada).

Mezzi, M. & Parducci, A. 1990. Optimum behaviour for seismically isolated buildings. *9th European Conference on Earthquake Engineering.* Moscow.

Parducci, A. 1989. Isolamento sismico e sistemi dissipativi. *International Meeting on Base Isolation and Passive Energy Dissipation.* Assisi (Italy).

Parducci, A. 1989. Considerazioni sui criteri di progetto delle strutture da ponte con impalcato sismicamente isolato. *International Meeting on Base Isolation and Passive Energy Dissipation.* Assisi (Italy).

Parducci, A. 1991. Design strategies and economical benefits in seismic isolation. *Pacific Conference on Earthquake Engineering.* Auckland (New Zealand).

Parducci, A. & Mezzi, M. 1991. Seismic isolation of bridges in Italy. *Pacific Conference on Earthquake Engineering.* Auckland (New Zealand).