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Retrofit through base-isolation: S. Pietro-Frigento

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ABSTRACT: The design of a base-isolation system for the seismic retrofit of a small existing Church is pointed out. The Church is placed in the area affected by the seismic event of 1980 (IRPINIA EARTHQUAKE). The design also includes the strengthening of masonry and the stiffening of the whole structure. HDS-LRB (High damping steel-laminated Rubber bearing) are adopted. Eventually, a deterministic and reliability analysis of the structural behaviour is accomplished.

1. Historical buildings and base-isolation

A new application of base isolation is the seismic retrofit of historical buildings. This field is very promising in Italy, since many historical towns are in seismic areas. In the provinces of Avellino and Salerno there are about 600 historical hazardous buildings. For many of them, heavily damaged by the hearthquake, base isolation may prove to be the only means of preservation. As a matter of fact, masonry structure are characterized by specific high frequencies, very similar, therefore, to those of the harmonics of the seismic motion generally carrying the most part of energy. The introduction of a base isolation system takes away from the structure the most dangerous frequencies and, together with the necessary stiffening of the "wall box", is the safest method of seismic protection .

2. S. Pietro's Church in Frigento

The first example of retrofitting an historical building through seismic isolation in Italy is foreseen in Frigento (South Italy) in the masonry church dedicated to S. Peter.(Sparacio et al. 1991). The examined structure is very common and extremely simple: it is a "box" with a lenghtened plan, slightly trapezoidal (fig. 1,2). The masonry of the external walls is made from unsquared stone blocks of calcareous stone and poor-binder mortar. The wooden roof is not an effective connection for the walls, because of its lack of stiff elements in the horizontal layer, that would close and stiffen the box-shaped complex; the plant measures are: m 22.00 x m 8.00; the thickness of the walls varies from a minimum of 0.75m. to a maximum of 1.15m, with an average value of 0.85m. The height of the structure, from the Church floor, is about 6.50m. The building body is placed in a "moderate seismicity" area, according to a classification made by G.N.D.T. in 1984; the site has some steepness. The project is possible thanks to the "Soprintendenza ai Beni Artistici e Architettonici" of Avellino and Salerno, which showed itself to be interested in the progress of restoration technologies, promoting studies and researches of the seismic behaviour of masonry buldings (Soprint. BB.AA.AA.AA.SS., 1983).

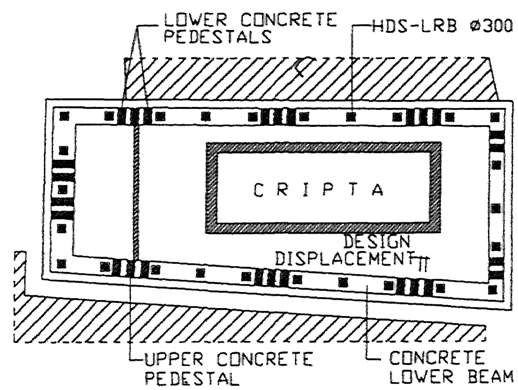

Fig.1: S.Peter's church in Frigento -plan

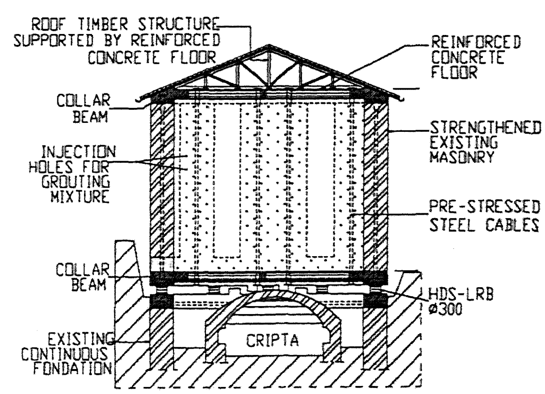

Fig.2: S.Peter's church in Frigento -section

3. Design procedure

According to ENEAS DESIGN GUIDE-LINES (Martelli et alii,1991), the design procedure has been divided in three steps: selection of seismic input based on the knowledge of the site geology, design of the base-isolation system, trough the computing of design displacement and horizontal stiffness, using linear elastic hypotesis about HDS-LRB behaviour, dynamic analysis of a 3-D model involving isolation system and structure, with the help of a non-linear modelling of HDS-LRB behaviour. As a final check, a sensitivity analysis of the structural behaviour is accomplished.

3.1 Selection of seismic input

A good knowledge of the site-geology was reached through "in-situ" Geophysical exploration (down-hole proofs) and penetration tests. "P" and "Sh" wave velocities were measured at the mean depth of each ground layer of the foundation, reaching the bed-rock to 30 m. In tab. 1 is represented the wave velocity variation by depth. The choice of a "Local Elastic Response Spectrum" (LERS) is the next step to take.

Table 1. P-waves velocity

Depth(m)	Velocity(m/s)
0-2	285
2-20	1000
20-30	2000

Some good Italian works (Serino,De Luca, 1991), (Sabetta,Pugliese, 1989) have pointed out the substantial agreement of Displacements LERS proposed by EUROCODE 8 (CEE, 1988) with Displacement Spectra of the most destroying Italian earthquakes. It has been shown that time histories, recorded during these events, produce steady normalized displacement spectra in the range of periods greater than 2.0 s. Instead, when 0.4<To<2.0s, displacement spectra demonstrate a linear variation in good agreement with EC8. This is the analytical expression of EC8 - LERS for specific site.

$$S_a(T) = A_g \beta_e(T) S \left(\frac{5}{\eta}\right)^{\frac{1}{2}} \qquad 1)$$

where: Ag is the peak ground acceleration (referred to the bed-rock in the same seismical area), $\beta_e(T)$ is the elastic response spectrum, normalized to the peak ground acceleration defined below, S is the parameter inserted by the code to consider the local site conditions (variable from 0.8 to 1) and η is the structural damping percentage, different from 5%. The expression used for $S_a(T)$:

$$a) S_a(T) = A_g \left(\frac{5}{\eta}\right)^{\frac{1}{2}} 0.8(1+5T) \qquad T \in [0;0.3]$$

$$b) S_a(T) = A_g \left(\frac{5}{\eta}\right)^{\frac{1}{2}} 2.0 \qquad T \in [0.3;0.8] \qquad 2)$$

$$c) S_a(T) = A_g \left(\frac{5}{\eta}\right)^{\frac{1}{2}} \frac{1.60}{T} \qquad T \in [0.8;+\infty]$$

3.2 Design of isolation system

The most important parameters needed to design the base isolation system are: "design displacement" D, which the bearing must be able to absorbe without damages, and the maximum lateral force Fmax acting on the bearings during the earthquake. The ratio between Fmax and D expresses the isolation system stiffness. The design procedure is dependent on the value assigned to the maximum shear force (Fmax) transmitted to the superstructure. Two criteria may be followed: the first one is to assign to Fmax the value obtained from an elastic analysis; the second one allows the superstructure to pass the elastic limit and therefore the value of Fmax is calculated through a limit-state bcomputation. For the seismic retrofit of existing monuments the first one is obviously more suitable, leading to the value of 200 tp. Therefore, it is convenient to use the isolation factor c=Fo/W (Mostaghel,Kelly, 1987), expressing the ratio between the above-defined force and the global weight of the structure. Following this procedure, it is possible to define the period of the isolated structure. The response spectrum, in terms of displacements, can be expressed as:

$$S_d(T) = \frac{S_a(T)}{\omega^2} \qquad 3)$$

The previously defined "isolation factor", c, leads to write a second equation between displacement and period:

$$c = \frac{F_0}{W} = \frac{KD_0}{W} \qquad 4)$$

where Do represents the bearing system displacement, when Fmax = Fo , so that
equating the expressions of K, from definition of c and the definition of s.d.o.f. period, we finally have the needed equation between Do and T :

$$D_0 = cg\left(\frac{T}{2\pi}\right)^2 \qquad 5)$$

Equating 1) and 2) (see fig.3):

$$T = \frac{1}{c} 1.6 A_0 \left(\frac{5}{\eta}\right)^{\frac{1}{2}} \qquad 6)$$

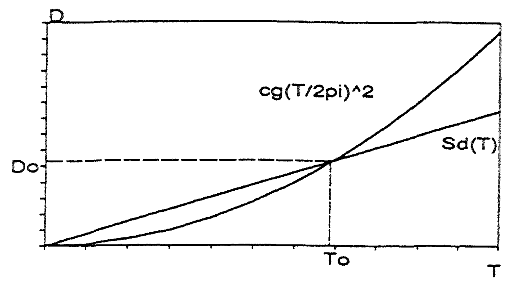

Fig.3: determination of design period

Since the structure weights 1330t, we have c=0.15. The most recent reports on laboratory testing of HDRB(E-NEA) already in use (Martelli et al., 1991), (Serino, 1991), assign to η an average value of 13%. From (6) : T=2.30 s where we have set Ao=0.35. From (4) : Do = 0.20 m and, finally, from (3) : K = 990 t/m.

3.4 Strengthening of masonry

The first step consists in improving the mechanical characteristics of the masonry. The aim is not only to improve the final behaviour of the structure increasing its resistance and elastic modulus, but also to facilitate operations related to the bearings insert, giving compactness and monolithic property to the walls, during the cutting operations. This aim is surely achieved with proved stiffening procedures such as injections of grouting mixture, placed in vertical and horizontal strips and in particular areas, if necessary, reinforced with small stainless steel bars, to fasten wall-joints. In this phase, aligned with the vertical cemented strips, housings for steel strands are provided with small drillings (Sparacio, Avramidou, 1986), (Giangreco,Russo Spena, Sparacio,1984), (Sparacio, 1987). These original techniques have been widely used in repair and retrofit of masonry buildings, without base isolation, but they are especially suitable when base isolation is introduced. To create a chamber to put and serve the rubber bearings, the removal of flooring and covering of the hypogeum vault is indicated. At the same time, along the external perimeter of the Church, a trench is dug for the isolation of the surrounding buildings. As soon as both underground faces of the external walls are laid bare, the cutting in fields will follow. Starting from the end of the Church and proceeding in parallel with the long side of the plan, we will construct, in strips, a connecting horizontal diaphram, reinforced by massive edges, within the masonry walls. The external edge of the diaphram, coupled with the partition beam (beneath the pre-existing continous foundation) allows to spread properly the reaction of the bearing on the old masonry, avoiding concentrations of stress. The insertion of the bearing is performed after the setting of the concrete, recovering under adequate monitoring, all the eventual deformations which may have been caused by decompressions in the overhanging masonry. Anchor plates for vertical strands (which inserting will contribute in giving, at the same time, ductility to the masonry and rigid body behaviour to the isolated structure) are placed in intrados of superior beams. The procedure ends with another horizontal diaphram for the roofing, for a complete closure of the box cell. The reinforcement of the isolation system beams, to simplify operative procedures, is obtained by means of simple pre-compression cables strung in sheaths previously arranged in the casting. See in fig. 8 a detail of "stops", whose finality is only "psichological" : they must be totally unrelated to the motion forseen in the dynamic analysis.

4. Deterministic analisys

A non-linear dynamic analisys has been performed to compute maximum values of Relative displacement (Dr) and Absolute acceleration (Aa) for the isolated structure. Isolated structure was modelled with a SDOF dynamic system. HDS-LRB non-linear behaviour has been simulated through a 3-parameters mathematical expression. Bonacina, Serino and Spadoni (1992) have found, in good agreement with experimental tests, the following equation between Rubber-Shear Tangent Modulus (Gt) and Rubber-Shear Strain γ:

$$G_t(\gamma) = G_\infty + a e^{-b(\gamma-\gamma_{min})} \qquad \textit{loading} \qquad 7)$$

$$G_t(\gamma) = G_\infty + a e^{-b(\gamma_{max}-\gamma)} \qquad \textit{unloading} \qquad 8)$$

where $G_\infty = 0.631 MPa$, a=1.61 MPa and b=6.30. Four different ground motions were adopted to study the dynamic response of isolated system. Each input time history was scaled using the EC8 expressions for Sa(T) (a,b,c). In table 2 are listed the principal time history parameters vs. isolated system response.

Table 2. Time history input and system response.

Event	PGA	Aamax	Drmax
Tolmezzo	1.70	0.34	0.03
Calitri	1.70	0.94	0.12
Sturno	1.70	1.10	0.16
Brienza	1.70	0.35	0.04

where PGA and Aamax are expressed in $\frac{m}{s^2}$ and Drmax is expressed in m.

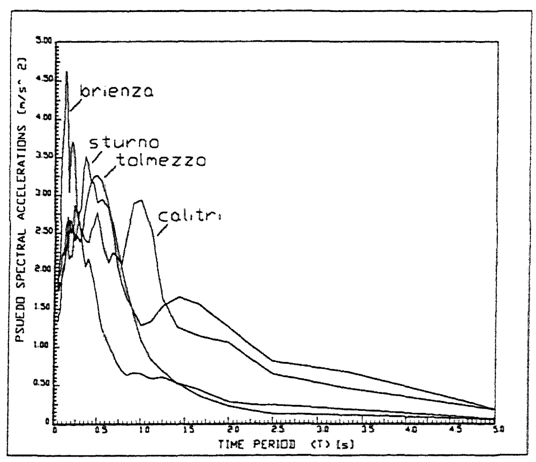

Fig.4: Input spectra

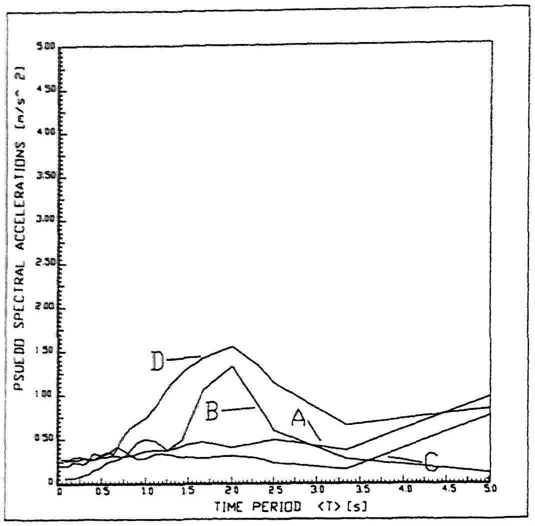

Fig.5: Response spectra

In figs. 4) and 5) are shown the input and response spectra for a linear system with an equivalent secant stiffness and a viscous damping of 13%. It may be interesting to compare the results of the latter analysis with those obtained from the non linear one (table 2).

5.Sensitivity analysis

The parameters entering the design and check procedures have been assumed as deterministic quantities, except for the earthquake excitation which has been made to vary in a space of real recorded accelerograms. Although, the character of random variables needs to be recognised for most of the quantities in the computation (weights, stiffnesses, damping, earthquake excitation..). Therefore, a complete sensitivity and reliability analysis of the isolated system should consider all the uncertainties. This is not the aim of the present study and, since the biggest uncertainties are related to the eartquake excitation, a sensitivity analysis indagating the relationship between the latter and the response of the s.d.o.f. system in terms of displacement, has been performed. The earthquake excitation has been considered as a zero-mean stationary gaussian random process and therefore completely characterized by its Power Density Spectrum, defined through the Kanai-Tajimi form, calibrated so as to match the PDS of the elastic response spectrum of EC8. Only the central frequency of the motion has been considered as a r.v., disregarding the influence of the peak ground-acceleration, since the level of protection provided by the isolation system, given a particular value of a_g, is the aim of the study. The hysteretic behaviour of the isolator has been modelled with the expression:

$$f = c\dot{x} + \alpha k x + (1-\alpha)kz \qquad 9)$$

where f is the force, x the displacement and z an auxiliary variable defined by:

$$z = A\dot{x} - \nu |x|^n \dot{x} - \gamma |z|^{n-1} z |\dot{x}| \qquad 10)$$

The latter is the expression proposed by Bouc(1967), graphed in fig.6) together with the force-displacement relationship of the designed isolator.

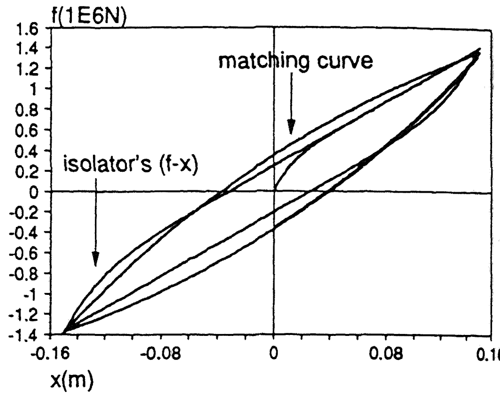

Fig.6: force-displacement diagram of the isolator and matching curve

The equation of motion of the s.d.o.f. gets:

$$m\ddot{x} + c\dot{x} + \alpha k x + (1 - \alpha k z) = -m\ddot{y}_0 \qquad 11)$$

where $\ddot{y}_0$ is the earthquake excitation process. Through the use of statistical linearization it is possible to compute the fractiles of the peak response x for any given probability p. The results are shown in fig. 7) as function of the central frequency of the earthquake excitation ω_g, for p=0.5.

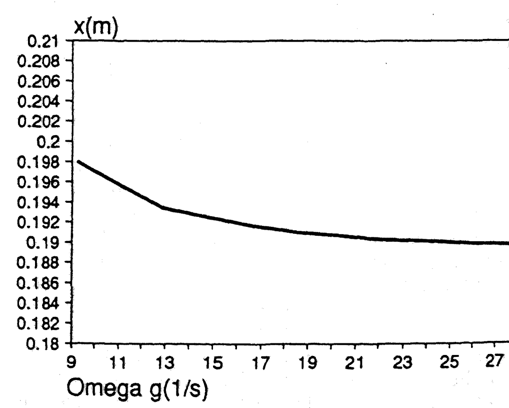

Fig.7: response of the isolated system versus ω_g

From fig.7) two considerations may be drawn: the first one is that the response of the isolated system is not much influenced by the change in the central frequency of the motion; the second one is that the peak responses are bigger than those obtained from the deterministic analysis.

REFERENCES

Bonacina,G. , Serino,G. , Spadoni, B. 1992.Implications of shaking table test results in the analysis and design of base isolated structures. *10th W.C.E.E.*. Madrid. Spain

Commissione Della Comunita' Europea. 1988. *Eurocodice 8, Strutture in zone sismiche: Progetto.* Maggio.

Giangreco, E., Russo Spena, F., Sparacio, R. 1984. Stress Analysis and Strengthening techniques of Masonry. *8th WORLD CONF. ON EARTH. ENG.*, S.FRANCISCO.

Mostaghel, N., Kelly, J.M., 1987. *Design procedure for R-FBI bearings.* EERC, REPORT UCB/EERC-87/18, Berkeley.

Pinto, P.E., Vanzi I. 1992. Base isolation: reliability for different design criteria.*10th W.C.E.E.*.Madrid. Spain

Sabetta, F., Pugliese, A. 1989. Stima di spettri di risposta da regist. di forti terremoti italiani. *Ingegneria Sismica*, anno III.

Serino,G., De Luca,A. 1991. La definizione degli spettri di progetto nelle strutture isolate alla base. *5th Ntnl Conference of ANIDIS.* Vol. II. Palermo. Italy. September.

Serino, G. 1991. *Modelli analitici per l'analisi della risposta dinamica di una struttura isolata sottoposta a prove di rilascio.* ISMES S.p.A.

Soprintendenza per i BB.AA.AA.AA.SS. di Salerno ed Avellino. 1983. *Programma di ricerca e sperimentazione del patrimonio Architettonico - Artistico danneggiato dal sisma del 23.XI.80.* Voll. I,II,III,IV - Salerno. Italy.

Sparacio, R., Avramidou, N. 1986. Additional prestressing for repair strengthening purposes. *IABSE Symposium.* Tokyo.

Sparacio, R. 1987. Restauro di edifici a struttura muraria in zone sismiche".(Cours intensit european, Ravello,DEC) in PACT; *Journal Of The European Study.* Group On Phis.,Chem., Math. and Biol. Tech. Appl. To Archael = n.18 HACKENS. Rixensart.

Sparacio, R., Cavuoto, F., Martelli, A., Pugliese, A., Sano', T. 1991. Report on first experience on seismic retrofitting by use of Base Isolation. *Proc. Intnl. Meet. Earthq. Protec. Bldngs.* Ancona. Italy.