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Seismic behaviour of base isolated structures with nonlinear behaviour

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ABSTRACT: A study to estimate the ductility demands of base isolated structures with non-linear behaviour when subjected to seismic action is presented and the influence of base isolation systems on the performance of these structural systems is examined. The results of this parametric study allow the construction of design diagrams for base isolated structures containing the behaviour coefficients to be used for a given structure and base isolation system, as a function of the structure's allowable ductility. These design diagrams are presented as a function of the relation between the structure's characteristics and those of the base isolation systems and allow an immediate perception of the adequability of the base isolation option.

1 INTRODUCTION

Although still not generally accepted by design engineers due to the lack of experience in its use, base isolation is becoming a promising alternative to the current practice of safety measures for earthquake design.

The uncoupling of the structure from the ground is accomplished by the use of specially designed devices, placed at the base of the structure, that simultaneously provide an increased capacity to dissipate the energy input by the earthquakes and confer an additional flexibility and a consequent frequency shifting which usually causes a decrease in the seismic forces.

Among the available base isolation systems, the most utilized consist in reinforced rubber blocks or elastomeric bearings associated to energy dissipation devices, such as lead infills (Buckle, 1990). More recently, has increased the use of high damping steel-laminated elastomeric bearings which do not require special provisions for energy dissipators, as the elastomers already guarantee an adequate level of energy dissipation (Martelli and al., 1991).

To justify the use of base isolators a comparison between the performance of base isolated structures and non-isolated structures needs to be made. This comparison, at least in terms of the earthquake design for ultimate stage level, needs to assume that the structure can undergo into nonlinear behaviour even if base isolated.

The assessment of the nonlinear behaviour of base isolated structures subjected to seismic action is presented in this study, where particular attention is given to the structural required ductility and to the influence of the characteristics of the base isolators in the structural performance. Comparisons between the behaviour of structures with and without base isolators is presented.

2 STRUCTURAL MODELS AND ANALYZED PARAMETERS

2.1 Structural model

To simulate the seismic behaviour of base isolated structures, the response of single degree of freedom oscillators with frequencies between 0.6 and 2.4 Hz is analyzed. This frequency range corresponds to the interval where lay most of the structures that are affected by the earthquake motion. The variation of the natural frequency of the oscillator is obtained through the variation of its stiffness, thus keeping the mass unchanged.

The use of single degree of freedom systems is justified due to the fact that previous studies (Guerreiro, 1989) have shown that, at least for linear response of base isolated structures, the influence of the first mode is preponderant in the global response.

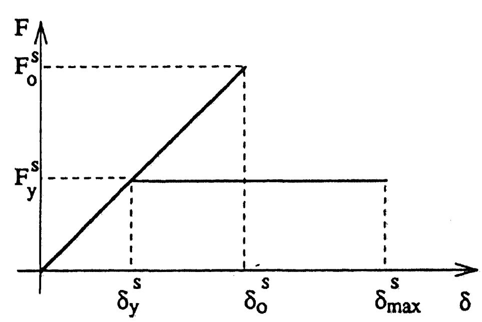

Figure 1. Model of structural behaviour.

The nonlinear behaviour of the structure is modeled by means of an elasto-plastic model (fig. 1). For each natural frequency, four different yielding levels are considered, each corresponding to a given value of an equivalent q factor (behaviour coefficient). The equivalent q factor is defined, according to figure 1, as the ratio between the maximum elastic force for the non isolated oscillator under consideration (F_o^s) when subjected to a given seismic action and the yielding force for the same oscillator when assuming an elasto-plastic model (F_y^s).

$$q = \frac{F_o^s}{F_y^s} \quad (1)$$

Four q values were adopted:

q = 3.5; 5.0; 6.5 and 8.0

and interpolation was performed when analyzing the results for intermediate values.

To simulate the seismic action, four different time histories were generated based on the power spectral density function according to the Portuguese code for actions. The simulated ground motion corresponds to a medium magnitude and small epicentral distance earthquake (type 1) on a hard soil (type I). The maximum elastic force was defined as the average of the maximum response values for each of the four time histories.

2.2 Base isolation model

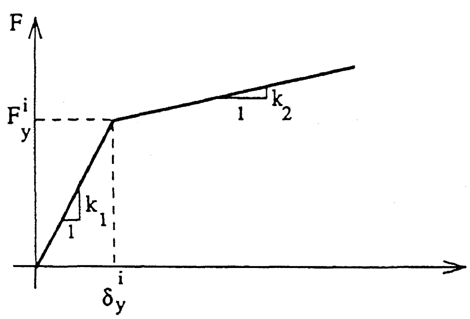

Figure 2. Model of base isolation.

The simulation of the base isolation system is performed by a bilinear model shown in fig. 2. Two main parameters characterize its behaviour:

$$\alpha = \frac{1}{2\pi}\sqrt{\frac{k_2}{m}} \quad (2)$$

representing the equivalent frequency of an oscillator which mass is the mass of the structure (m) and which stiffness is the stiffness of the base isolator above yielding (k_2). It also represents the natural frequency of the global system if the structural stiffness is considered infinitely higher then the stiffness of the base isolator above yielding. Eight different α values are considered in this study, varying from 0.2 to 1.6.

$$\eta = \frac{F_y^i}{F_o^s} \quad (3)$$

representing the yielding level of the base isolator when compared to the maximum elastic force in the non-isolated elastic structure. Three different values of η are considered in this study (5%, 10% e 15%).

In all cases the initial stiffness of the base isolator (k_1) is considered ten times higher than the stiffness above yielding ($k_1 = 10\, k_2$).

The response of the base isolated models is analyzed by means of the following parameters:

δ_{max} - maximum top displacement of the structure relative to the ground.

δ_{max}^i - maximum base displacement of the structure (deformation of the base isolator) relative to ground.

δ_{max}^s - maximum top displacement of the structure, relative to base isolator.

d - maximum ductility required for the structure.

$$d = \frac{\delta_{max}^s}{\delta_y^s} \quad (4)$$

3. EFFECTIVENESS OF BASE ISOLATION

3.1 Methodology for the assessment of effectiveness

To assess the effectiveness of base isolation systems, the results obtained for the various chosen configurations can be analyzed from different perspectives.

Let us assume, as probably is the perspective of the design engineer, that the natural frequency of the non-isolated structure (f) and its ductility (d) are parameters that can be known in advance. The design engineer has then to choose the appropriate base isolation system, both in terms of its yield level (η) and stiffness or vibration frequency (α), so that the equivalent behaviour coefficient (q) that can be adopted for structural design can be maximized, while controlling the relative displacements both for the structure (δ_{max}^s) and the base isolation system (δ_{max}^i).

Even if it is assumed that the natural frequency (f) and the available ductility (d) of the structure are known values, it is difficult to present by a simple equation or by a design chart, a relation between the assumed values of α and η and the obtained q factor.

Thus, the assessment of the effectiveness of a base isolation has to be made in terms of the equivalent behaviour coefficient (q factor) and relative displacements obtained for each possible situation, because, due to the multiplicity of involved parameters, there is not a unique way to accomplish the analysis in global terms.

3.2 q factor control

Despite of the difficulties of having a general view of the interdependence of the several parameters influencing the equivalent q factor, the analysis of a wide range of different situations and possible base isolation solutions, allow for some conclusions, based on the results obtained for the response of base isolated structures subjected to the four time histories.

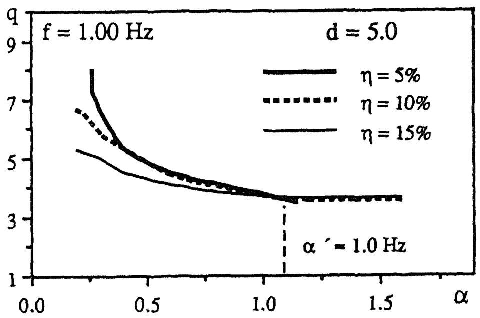

Figure 3. q factor as a function of α (f=1.0 Hz, d=5.0)

In figure 3 the relation between the q factor and α is presented, for three η values and a given ductility level (d=5.0).

It can be observed that, for the lower values of α, it is possible to allow for higher q factors. In this range of α values, the higher values of the q factor are obtained for the lower values of η.

It is important to note that the range of values that allow for higher q factors, are the values that lead to more flexible solutions. Thus, it is important to control simultaneously the maximum displacement values as will be discussed later.

For values higher than a certain α (α', in the present case $\approx$ 1.0 Hz), the q factor becomes independent from α. In this range, despite the chosen α value, the q factor values tend to the ones that would be obtained for a non-isolated structure, and thus no advantage is obtained in the use of a base isolation system with those characteristics.

It is also visible that the influence of η is larger for lower α values, while for $\alpha > \alpha'$ there is no influence of η on the q factor, confirming the lack of effectiveness of base isolators with large α.

In fig. 4 the relation between q and α is shown for different ductility values.

It is possible to observe that the value of α' is independent on the level of assumed ductility. For all ductility values, the q factor becomes independent on α for $\alpha > \alpha'$ ($\alpha' \approx$ 1.0 Hz in this case).

Also visible is the fact that despite the assumed α value, for higher available ductility values, higher q factors can be assumed.

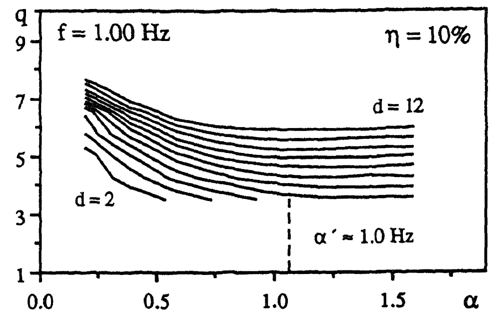

Figure 4. q factor as a function of α (f=1.0 Hz, η=10%)

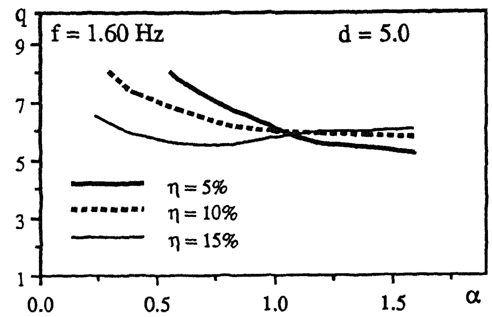

Figure 5. q factor as a function of α (f=1.6 Hz, d=5.0)

The value of α' depends on the characteristics of the structure to be isolated. For stiffer structures the value of α' is higher than for more flexible ones as can be seen from fig. 5, showing a graph similar to the graph presented in fig. 3 but for a structure with higher frequency (f = 1.6 Hz).

It can be seen that the evolution of α' follows the evolution of the structural natural frequency f.

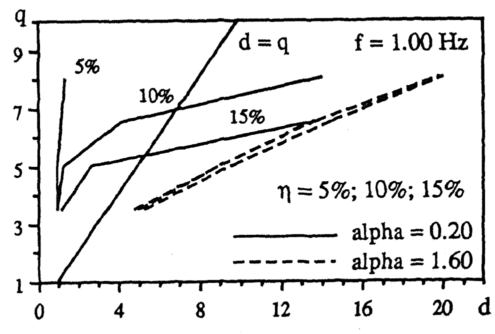

Figure 6. q factor as a function of ductility
(f=1.0 Hz, α= 0.2 and 1.6)

The relationship between the obtained q factor and the assumed available ductility can be examined from fig. 6, where only the extreme analyzed values of α are displayed. It is visible that an increase in the ductility level leads to an increase in the q factor as could already be seen in fig. 4. Yet, the most important conclusion that can be taken from fig. 6 is that the effectiveness of base isolation in terms of allowing for high q factors without large demands on ductility, corresponds to the adoption of low α values and low η values. This may not be the case in terms of displacement control as will be seen further on.

Also from fig. 6 it can be seen, as should be expected given the conclusions from figs. 3 and 4, that while for α = 0.20 (< α', in this case) the q factors obtained for a given ductility are very sensitive to the η value, for α = 1.60 (> α') the q factors are almost independent on η.

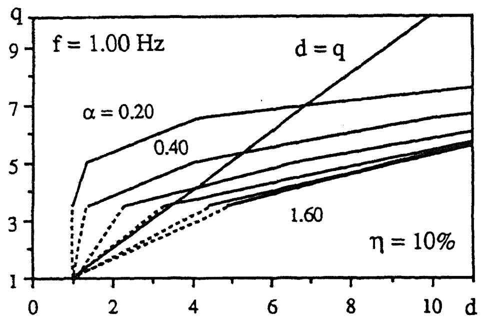

Figure 7. q factor as a function of ductility (f = 1.0 Hz)

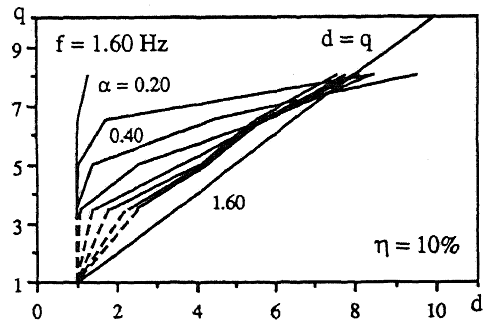

Figure 8. q factor as a function of ductility (f = 1.6 Hz)

In figures 7, 8 and 9, diagrams of q versus d are represented for three different frequencies (f = 1.0, 1.6 and 2.0 Hz), a given η value (η = 10%) and the entire range of studied α values.

In all figures the same tendency for the variation of q with d and α can be observed. The shown diagrams contain good qualitative indications and, if available for various η values and the proper natural frequency f, can constitute relevant diagrams for design purposes.

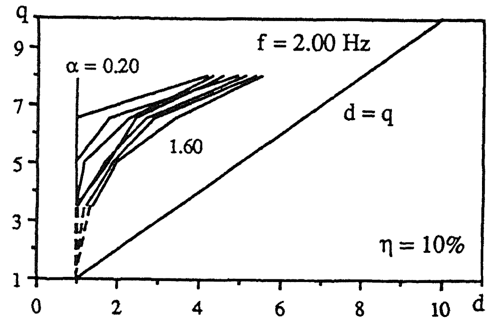

Figure 9. q factor as a function of ductility (f = 2.0 Hz)

In all figures, as was the case of fig. 6, a line indicating d=q is represented. This line, according to a criterium established by Ballio to determine q factors (Ballio, 1985), separates two zones in the diagram with distinct behaviour. One, where the q factor is larger than the required ductility and that represents a safe zone, and other where the needed ductility exceeds the obtained q factor, and thus represents an unsafe zone.

According to this philosophy, while for the case shown in fig. 9 (f = 2.0 Hz), any α value can be adopted, because q is smaller than d, for the case shown in fig. 7 (f = 1.0 Hz) only α values lower than α ≈ 1.0 Hz could be adopted, and still with an additional limitation to the assumed ductility and consequently to the q factor. Perhaps even more important than avoiding crossing the d=q line is the fact that a zone in the diagram corresponding to large variations of d for small variations of q should be avoided, for it represents a less stable situation where a small overestimation of q may mean a very high increase in ductility demand. For this reason, and due to the shape of the q-d curves, the d<q zone is confirmed to correspond to a safer design.

The comparison between figures 7, 8 and 9 further allows the conclusion that for very low α values the isolated structure can remain totally elastic even for large q values (as high as 6.5 for α = 0.20). As should be expected, this is evident for stiffer structures (higher f values) that thus benefit more from the base isolation solution. One should not forget that the equivalent q factors under consideration correspond to the ratio between the maximum force in the linear non isolated structure and the maximum force in the nonlinear isolated structure, and thus q factors larger than one may occur even if the structure behaves linearly on top of the base isolation.

To show that the previous results (average values of the response to the four time histories) are very sensitive to the earthquake motion, diagrams of q versus d for the individual time histories are presented in fig. 10 with the average value. As can be observed large variations occur, showing that the variability in the seismic input is a factor that can not be neglected.

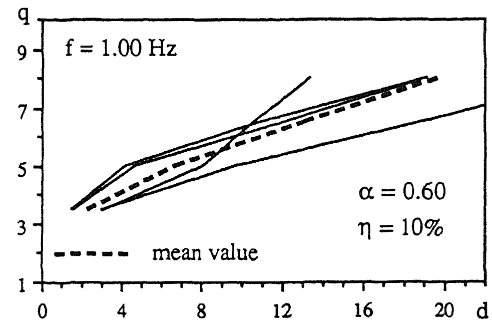

Figure 10. Influence of the ground motion on the obtained q factors.

3.3 Displacement control

The complete control of a base isolation solution can only be achieved if displacement control is guaranteed. Assuming low α and η values may represent a large reduction in the seismic forces but may increase displacements to non admissible values.

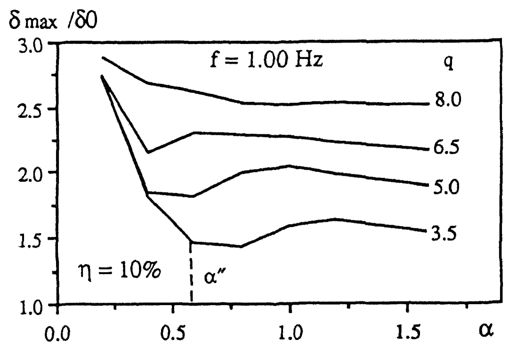

Figure 11. Maximum displacements as a function of α (f=1.0 Hz)

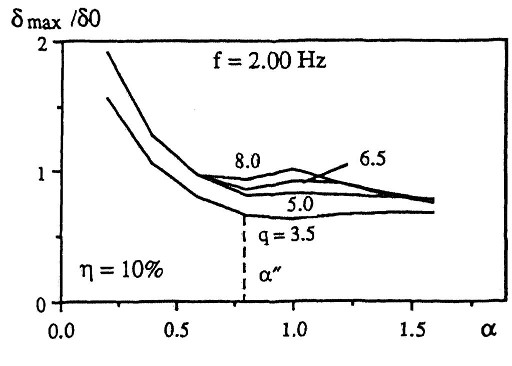

Figure 12. Maximum displacements as a function of α (f=2.0 Hz)

Relations between displacement increase, with respect to the linear non isolated situation (δ_{max}/δ_0), and α are presented for an assumed η value (10%), different q factors and two different values of the structural natural frequency (fig. 11 - f = 1.0 Hz; fig. 12 - f = 2.0 Hz).

As expected, it can be observed in both cases, that displacements increase for small α values. Very small values of α should be avoided for they represent a zone where a small variation in α may cause large variations in the top structural displacements relative to ground. It is also visible that there is a range where variations in α do not cause a variation in the displacements. There is an α value, α'', such that for α > α'' there is no significant increase in the total displacements (structure and base isolation system). It should be noted that in the analyzed situation , α" is always lower than α'.

A good criterium is thus to choose α and η values that allow for the higher possible force reduction, simultaneously guaranteeing acceptable displacements. This can be achieved selecting values situated in the zone between α" and α'. The simultaneous use of diagrams such as those in fig. 3 and figures 11 and 12 are thus necessary for a correct design of base isolation systems.

It should be noted that the recommendation stating that α values corresponding to α < α'' and α > α' should not be adopted, is not a restrictive rule. α values outside this interval can be used, bearing in mind that for α < α'' there has to be a strict control on the deformation of the base isolator and for α > α' there may be no great benefit from the use of base isolation.

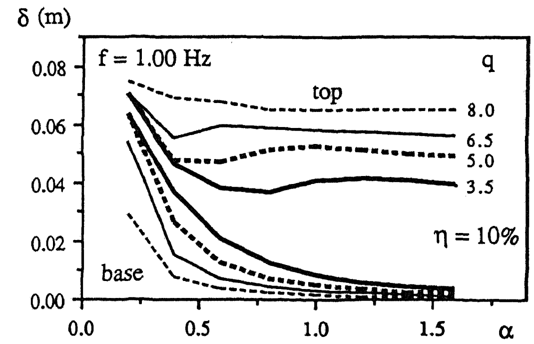

Figure 13. Top and base displacements (f = 1.0 Hz)

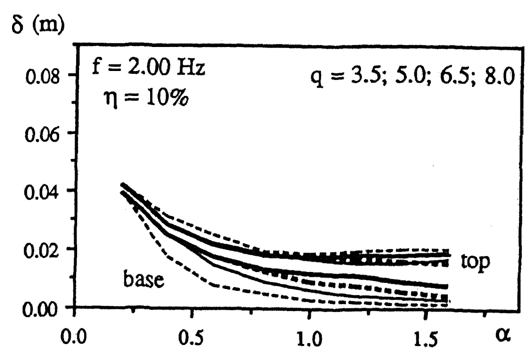

Figure 14. Top and base displacements (f = 2.0 Hz)

To further understand the characteristics of the displacements, diagrams such as those in figures 13 and 14 should also be available for design purposes. They represent for the two previously mentioned situations ($f = 1.0$ Hz; $f = 2.0$ Hz), the decomposition of the total displacements into structural displacements and base isolation displacements. The top curves represent the top displacements of the structure relative to ground. The bottom curves represent the base displacements also relative to ground which relate to the base isolation deformation.

It is visible that small α values ($\alpha < \alpha''$) cause large deformations of the base isolation system, while for larger α values the top displacements correspond almost entirely to structural deformation, turning the base isolation unnecessary.

The structural displacements can be obtained, for each q factor, by the difference between a top and a corresponding bottom curve in figs. 13 and 14. It can be seen that these displacements, which are related to the ductility and the base shear in the structure and thus to the q factor itself, tend to increase with increasing α and also increase, as should be anticipated, with the increase in q. This shows that the displacement control for base isolated structures is mainly a problem of controling the deformation of the base isolator, because the larger displacements that can occur in the structure are always the ones that correspond to very stiff base isolation systems (large α values) and thus similar to the displacements for the non-isolated structure.

A final conclusion that can be drawn from figures 13 and 14 is that design of base isolation systems aiming primarily to displacement control can also be achieved using diagrams as the ones shown in the mentioned figures. The use of base isolators with low α values, do not significantly increase the top global displacements because the structural displacements are reduced in the same order of magnitude of the base isolation displacements.

4. FINAL REMARKS

The design of base isolation systems to diminish the forces and/or displacements in structures subjected to seismic motion can use basic concepts similar to the ones utilized for the design of non-isolated structures.

The control of forces and displacements, both in the structure and the base isolator, depends on the availability of design rules, allowing the selection of the appropriate characteristics of the base isolation system, together with the corresponding design q factors.

The results presented in this study, although not general for all the possible situations, already allow for some important qualitative conclusions regarding the effectiveness of base isolation solutions.

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