FORCE-BASED VS. DIRECT DISPLACEMENT-BASED DESIGN OF BUILDINGS WITH SEISMIC ISOLATION

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ABSTRACT:
A displacement-based design (DBD) procedure for buildings equipped with seismic Isolation Systems (IS's) is proposed. It has been derived from the Direct DBD (DDBD) method recently developed by Priestley and co-workers. The key aspect of the proposed procedure is the definition of a target displacement profile for the structure. It is assigned by the designer in order to accomplish given performance levels, expressed in terms of maximum IS displacement and maximum interstorey drift. The proposed design procedure has been developed for different idealized force-displacement cyclic behaviours, which may be used to describe the response of a wide variety of IS's, including: Lead-Rubber Bearings, High-Damping Rubber Bearings, Friction Pendulum Bearings and combinations of Flat Sliding Bearings with different re-centring and/or dissipating auxiliary devices. In this paper the background and implementation of the proposed design procedure are presented.

KEYWORDS: Direct Displacement-Based Design, Seismic Isolation Systems, Interstorey Drift

1. INTRODUCTION

It is widely recognized that the traditional Force-Based Design (FBD) approach cannot provide the appropriate means for implementing concepts of Performance-based Earthquake Engineering (Bertero and Bertero, 2002). Performance levels, indeed, are described in terms of displacements, as damage is better correlated to displacements rather than forces. As a consequence, new design approaches, based on displacements, have been recently implemented. One of such approach is the Direct Displacement-Based Design (DDBD), firstly proposed by Priestley (1993). The fundamental goal of DDBD is to obtain a structure which will reach a target displacement profile when subjected to earthquakes consistent with a given reference response spectrum. Figure 1 shows the fundamental steps in the application of the DDBD method for buildings.

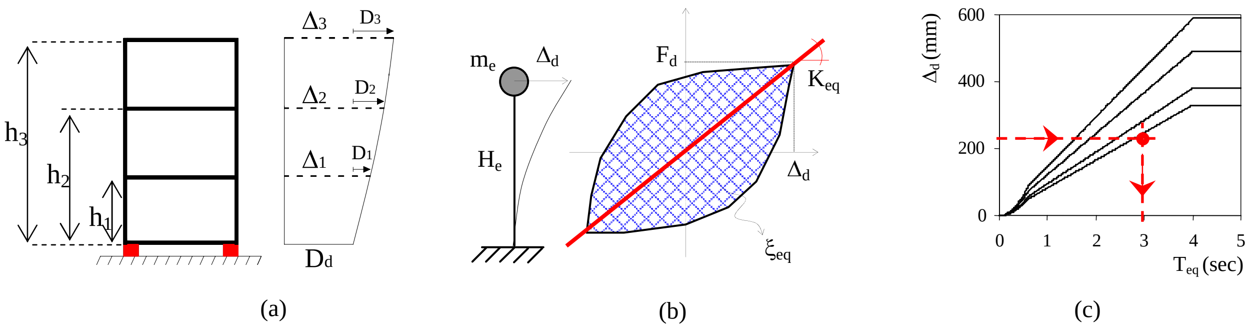

Figure 1: Schematic representation of the DDBD method for seismically isolated buildings.

The first two steps (Figs. 1(a) and 1(b)) highlight the most important differences between DDBD and FBD. In the FBD, the Base Isolated (BI-) building is modelled as a equivalent linear SDOF system with effective period of vibration T_{IS} and equivalent damping ξ_{IS}. The flexibility of the superstructure is neglected and the Isolation System (IS) is described by an equivalent visco-elastic model. Entering the ξ_{IS}-damping response spectrum with T_{IS}, the design acceleration of the BI-building is determined. It is then reduced by a behaviour modification factor (q in the Eurocode 8 (CEN, 1998)) to achieve the design base shear at the ultimate limit state. Interstorey drifts are checked by Linear Static Analysis (LSA) only at the end of the design, to verify damage limit state requirements. Basically, the FBD is an iterative design method. Indeed, iterations are needed both to obtain effective properties of the IS consistent with its maximum displacement (especially for strongly nonlinear IS's) and to accomplish with given limit values of interstorey drifts.

In the DDBD method, the MDOF model of the BI-building (see Fig. 1(a)) is replaced by an equivalent linear SDOF system whose properties (K_{eq} and ξ_{eq} of Fig. 1(b)) correspond to the equivalent lateral stiffness and equivalent viscous damping of the real structure at the peak displacement response. The equivalent properties (K_{eq} and ξ_{eq}) of the SDOF system considered in the DDBD method differ from the effective properties (K_{IS} and ξ_{IS}) of the SDOF system considered in the FBD, due to the flexibility of the superstructure. The target displacement profile of the building (Δ_i in Fig. 1(a)) is set by the designer at the beginning of the analysis, to ensure a specified performance level of the structure, for a given level of seismic excitation. No iterations are needed in the DDBD method and the attainment of the seismic performances of the BI-building are guaranteed by the control of structural displacements (both IS displacement and interstorey drifts).

In this paper, a DDBD procedure for BI-buildings is presented. It has been implemented in MATLAB considering four different types of IS's: (1) High Damping Rubber Bearings (HDRB), (2) Lead Rubber Bearings (LRB), (3) Friction Pendulum Bearings (FPB) and (4) combinations of Flat Sliding Bearings (FSB) and SMA-based re-centring auxiliary devices. The performance levels of the structure are governed through the selection of suitable values of the maximum IS displacement (D_d) and maximum interstorey drift (θ_d). As output, the design procedure provides the basic mechanical properties of the IS that achieves the required performance level. In the next paragraphs the basic modelling assumptions and the step-by-step procedure of the proposed design method are described.

2. MODELING AND SCHEMATIZATION OF BUILDINGS WITH SEISMIC ISOLATION SYSTEMS

The proposed design procedure is specifically addressed to frame buildings characterized by a shear-type behaviour. In the current version, the procedure has been developed for regular multi-stories buildings with uniform mass and stiffness distribution over the height of the building (see Figure 1(a)). Under these hypotheses the maximum interstorey drift is attained at the first floor. As a consequence, it can be expressed, in percentage terms, as $\theta_d = 100\ D_1 / h_1$. As known, the key aspect of the DDBD method is the target displacement profile of the structure, for a given level of seismic excitation (Priestley et al., 2007). It is specified by assigning a suitable displacement pattern and a target displacement amplitude. In the proposed procedure, a concave deformed shape of the superstructure (see Fig. 1(a)) is assumed:

$$\Phi_i = cos\left[\left(\frac{1}{I_r}\right)\cdot\left(1-\frac{h_i}{H}\right)\cdot\frac{\pi}{2}\right]-cos\left[\left(\frac{1}{I_r}\right)\cdot\frac{\pi}{2}\right] \tag{2.1}$$

where h_i is the height of the i-th storey, H is the total height of the building and I_r represents the ratio between the IS effective period (T_{IS}) and the fundamental period of vibration of the fixed-base building (T_{fb}).

The target displacement amplitude is expressed in terms of a limit value of the maximum IS displacement (D_d) and maximum interstorey drift (θ_d). Finally, the target displacement profile of the BI-building is obtained:

$$\Delta_i = D_d + \theta_d \cdot c_1 \cdot \Phi_i \tag{2.2}$$

where c_1 is equal to $h_1/(100*\Phi_1)$. It can be noted that $\theta_d*c_1*\Phi_i$ coincide with D_i of Fig. 1(a).

The design displacement (Δ_d) and effective mass (m_e) of the equivalent SDOF system are then derived based on the characteristic equations of the DDBD method (Priestley et al., 2007):

$$\Delta_d = \sum_{i=0}^{n}\left(m_i \cdot \Delta_i^2\right) \Big/ \sum_{i=0}^{n}\left(m_i \cdot \Delta_i\right) \tag{2.3}$$

$$m_e = \sum_{i=0}^{n} \left(m_i \cdot \Delta_i \right) \Big/ \Delta_d \tag{2.4}$$

Five different force-displacement models have been considered to capture the cyclic behaviour of the most currently used IS types. They are shown in Figure 2, with the associated mechanical parameters. The first model (Fig. 2(a)) represents a visco-elastic behaviour. It can be used to describe the cyclic response of HDRB and LDRB. The second model (Fig. 2(b)) represents an elasto-plastic with hardening behaviour. It can be used for HDRB, LRB (Skinner et al., 1993) and Steel Yielding Devices. The third model (Fig. 2(c)) represents a rigid-plastic with hardening behaviour, which can be exploited to describe the cyclic behaviour of FPB (Al-Hussaini et al., 1994) or FSB+LDRB. The forth model (Fig. 2(d)), referred to as double flag shaped model, derives from the combination of a bilinear elastic behaviour, modelling the typical F-d cycles of SMA-based re-centring devices (Dolce et al., 2000), and a rigid-plastic behaviour, reproducing the schematic F-d cycles of FSB (Dolce et al., 2005). Finally, linear (α = 1) or nonlinear (1 < α < 0.2-0.3) viscous models (Fig. 2(e)) are used to take into account possible auxiliary viscous dampers (Constantinou et al., 1993).

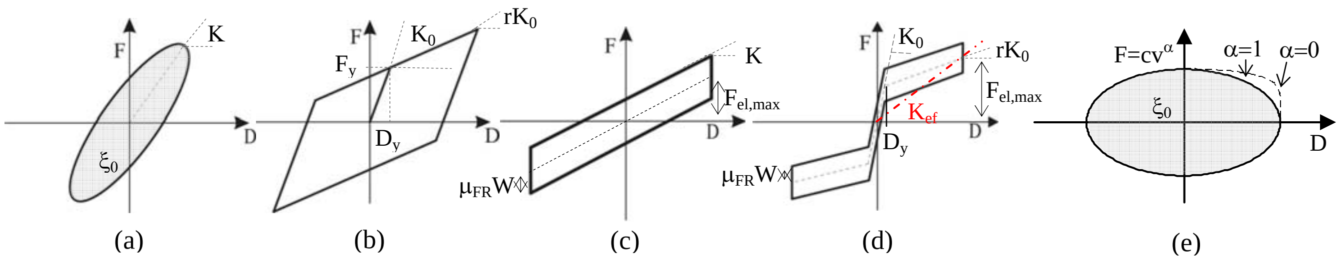

Figure 2: Schematic cyclic behaviour of: (a) HDRB, (b) LRB, (c) FPB, (d) FSB+SMA and (e) VD.

In the proposed procedure, the effective damping ratio of the displacement-dependent IS's (Figs. 2(b)-2(d)) is calculated based on the well-known Jacobsen's equation (Chopra, 1997):

$$\xi_{IS} = \frac{W_d}{4\pi \cdot W_s} = \frac{W_{hysteresis} + W_{friction}}{2\pi \cdot F_d \cdot D_d} \tag{2.5}$$

in which W_d is the total energy dissipated by the IS in the cycle of maximum amplitude, W_s is the strain energy stored at the maximum displacement D_d and F_d the force in the IS at the maximum displacement. The aforesaid general expression of the effective damping ratio (ξ_{IS}) is particularized to each IS, making use of its basic mechanical parameters. The specification of practical values for such IS mechanical parameters is fundamental both for helping the designer in the selection of the model parameters at the beginning of the analysis and for evaluating typical values of damping ratio for each IS. A detailed discussion on this topic can be found in (Cardone et al. 2008). In any case, it is important to emphasize that:

- for the visco-elastic IS's (Fig. 2(a)), the damping ratio (ξ_{IS}) does not depend on the IS displacement. This implies a great flexibility in the selection of the design IS displacement (D_d), as long as the necessary IS damping ratio falls within suitable ranges (Cardone et al, 2008).
- for the elasto-plastic IS's (Fig. 2(b)), ξ_{IS} depends on D_d through the ductility and post-yield stiffness ratio. In principle, chosen a given D_d, it is possible to realize a great variety of damping ratios through a proper selection of the IS yield displacement (D_y) and post-yield stiffness ratio.
- for FPB and FSB+SMA IS's (Figs. 2(c) and 2(d)), instead, ξ_{IS} depends on the friction coefficient (μ_{FR}), design IS displacement (D_d) and effective period of the BI-building (T_{IS}). Unfortunately, in the DDBD method, T_{IS} also represents the main output of the design procedure. As a consequence, for these IS's, an iterative design process is in principle required, since input and output are mutually correlated through T_{IS}. In other words, the target IS displacement D_d cannot be arbitrarily selected, otherwise the design procedure could not converge to any solution.

In this study, a preliminary design procedure has been implemented, in order to assist the designer in the optimal selection of target displacements of the BI-buildings. Such a preliminary procedure also permits to avoid iterations within the DDBD method for friction-based IS's.

3. DIRECT DISPLACEMENT-BASED DESIGN OF BUILDINGS WITH SEISMIC ISOLATION

Two different approaches can be followed within the proposed DDBD procedure for BI-buildings. They differ in the performance level required to the superstructure. With the first approach, the performance objective is to prevent or limit damage to non-structural elements. The performance objective is then expressed by means of a target value of the maximum interstorey drift (θ_d), which shall be lower than a suitable threshold value for the protection of non-structural members (e.g. θ_{lim} = 0.2-0.3%). The superstructure is supposed to respond within its elastic range ($\theta_d<\theta_y$). With the second approach, limited inelastic deformations are supposed to occur in the RC frame, according to a strong-column/weak-beam mechanism. The performance objective is to limit the ductility demand ($\mu = \theta_{max}/\theta_y$) below a given value. The yield drift θ_y is defined using the semi-empirical equation proposed by (Priestley, 2003):

$$\theta_y = 0.5\varepsilon_y\, l_b / h_b \tag{3.1}$$

where ε_y is the steel yield strain, l_b the beam length and h_b the beam depth.
The performance objective for the IS is expressed by means of a target value of its maximum horizontal displacement (D_d), which shall not exceed the IS displacement capacity. As a basic assumption of the method, the structural configuration, including floor masses, interstorey heights and beam/column sections, is assumed to be known at the beginning of the design process, resulting from functional/aesthetic requirements and non-seismic load conditions. A graphical procedure for the preliminary selection of IS type, target IS displacement (D_d) and target interstorey drift (θ_d) has been implemented. It is illustrated in Figure 3, separately for elastomeric-based (Fig. 3(a)) and friction-based (Fig. 3(b)) isolation systems.

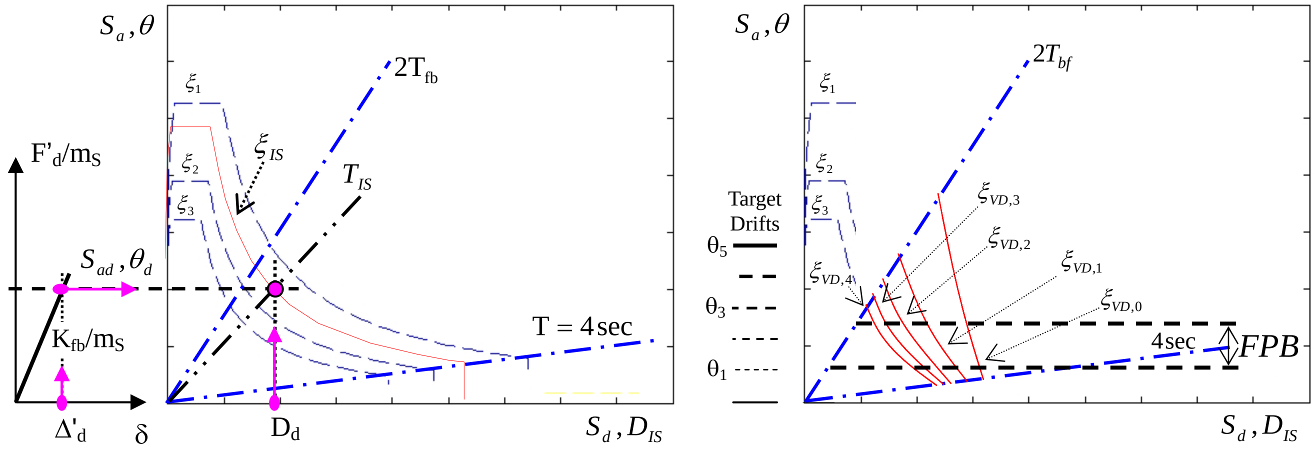

Figure 3: Graphical tools for the preliminary selection of IS type, target IS displacement and target interstorey drift for (a) elastomeric-based and (b) friction-based IS's.

The diagrams of Figure 3 show a number of high-damping elastic spectra ($\xi_1<\xi_2<\xi_3$) in the so-called ADRS (Acceleration-Displacement-Response-Spectra) format. Reference is made to the effective period of vibration (T_{IS}) and equivalent viscous damping (ξ_{IS}) of the BI-building modelled as a SDOF system with lumped mass (M_{tot}) equal to the total mass of the building (ground floor included) and stiffness equal to the effective stiffness of the IS at its target displacement (D_d). Basically, each IS type is characterised by a different damping level (Cardone et al, 2008). As a consequence, each IS type can be associated to a different group of response spectra. The dashed lines passing through the origin of the axis correspond to two limit values of the effective period of vibration of the building with seismic isolation (T_{IS}), equal to $2T_{fb}$ (being T_{fb} the fundamental period of vibration of the building w/o seismic isolation) and 4 sec, respectively.
On the left hand side of the ADRS diagram of Fig. 3(a), the schematic displacement vs. acceleration relationship

of the Fixed Base (FB-) building is reported. In this case, reference is made to a SDOF system with lumped mass (m_S) equal to the mass of the superstructure (ground floor excluded) and elastic stiffness (K_{fb}) equal to the lateral stiffness of the FB-building. This latter is derived from the well-known expression:

$$K_{fb} = m'_e \cdot \left(2\pi / T_{fb}\right)^2 \tag{3.2}$$

where T_{fb} is the fundamental period of vibration of the FB-building, calculated by a height-dependent code expression (e.g. $T_{fb} = 0.075 * H^{3/4}$ for regular RC frame buildings, according to (CEN, 1998)) and m'_e is the first-mode participating mass of the FB-building, calculated through Eq. (2.4) assuming in Eqs. (2.1)-(2.2) $I_r = 1$ and $D_d = 0$. It should be noted that the aforesaid FB-building and BI-building refer to the same structure, characterized by the same displacement profile. The expression FB-building is used to indicate that reference is made to the relative displacements D_i rather than to the absolute displacements Δ_i (see Fig. 1(a)), as made for the BI-building. The FB- and BI-building under consideration are then characterized by two different equivalent design displacements (Δ'_d and Δ_d, respectively) while by the same design acceleration (S_{ad}). The target displacement (Δ'_d) calculated with Eq. (2.3), assuming $I_r = 1$ and $D_d = 0$, therefore, does correspond to the attainment of the target drift (θ_d) in the superstructure. The interception between Δ'_d and the line schematizing the force-displacement behaviour of the superstructure (see Fig. 3(a)) identifies the design acceleration level for the isolated structure (S_{ad}). From an analytical point of view, this latter can be calculated as follows:

$$S_{ad} = \Delta'_d \cdot \left(K_{fb} / m_S\right) = \theta_d \cdot c_1 \cdot \left[\sum_{i=1}^{n} \left(m_i \cdot \Phi_i^2\right) \Big/ \sum_{i=1}^{n} \left(m_i \cdot \Phi_i\right) \right] \cdot \left(m'_e / m_S\right) \cdot \left(2\pi / T_{fb}\right)^2 \tag{3.3}$$

where m'_e/m_S represents the first-mode participating mass coefficient (λ) of the superstructure in its "fixed-base" configuration. Equation (3.3) can be used to convert the target drift (θ_d) in the corresponding target acceleration S_{ad} (and vice-versa). As a matter of fact, based on Eq. (3.3), spectral accelerations and interstorey drifts can be equivalently used to enter the ADRS diagrams, as shown in Fig. 3.

As can be observed, for the elastomeric-based IS's, it is possible to choose any target point (D_d and θ_d) falling within the domain defined by the two T-lines corresponding to $T_{IS} = 2T_{fb}$ and $T_{IS} = 4$ sec, and the response spectra associated to the upper and lower bound values of the damping ratio of each IS type (Cardone et al., 2008). Indeed, this always results in a feasible preliminary configuration of BI-building, identified by T_{IS} and ξ_{IS}. The equivalent viscous damping ratio of the friction-based IS's (i.e. FPB, FSB+LDRB and FSB+SMA), instead, depends on the target IS displacement (D_d) and effective period of vibration of the BI-building (T_{IS}), obviously, in addition to the friction coefficient (μ_{FR}) of the sliding bearings. The target interstorey drift (θ_d), moreover, is associated to a defined design acceleration (S_{ad}), expressed by Eq. (3.3). As a result, for the friction-based IS's, the target displacements (D_d, θ_d) cannot be selected arbitrarily. They must satisfy given conditions, implicitly expressed by the following relationship:

$$S_{ad} = S_a\left(T_{IS}\right) \cdot \eta\left(\xi_{IS}\right) \tag{3.4}$$

in which $\eta\left(\xi_{IS}\right)$ represents the damping reduction factor, taken equal to $\sqrt{7/\left(2+\xi_{IS}\right)}$, as suggested by (Priestley et al., 2007). Basically, Eq. (3.4) defines a curve in the ADRS format, which provides the IS configurations (identified by the values of T_{IS} and ξ_{IS}) and the corresponding target displacements that can be actually realized, relying upon a given friction coefficient. An example of "applicability" curve is identified with $\xi_{VD,0}$ in Fig. 3(b). The label $\xi_{VD,0}$ is used to indicate that no additional Viscous Dampers (VD) are used. If a VD with $\xi_{VD,i}$ is adopted, the "applicability" curves change as shown in Fig. 3(b). In particular, they progressively move towards the origin of the axis, also reducing their slope, as the additional viscous damping increases ($\xi_{VD,1}<\xi_{VD,2}<\ldots$). As a consequence, the values of possible target displacements (D_d and θ_d) progressively reduce while increasing the additional viscous damping. In the proposed procedure, the "applicability" curve for friction-based IS's is univocally identified once a given response spectrum, seismic intensity, friction coefficient (μ_{FR}) and auxiliary viscous damping (ξ_{VD}) are specified. For each applicability curve, the T-lines associated to the limit period values of $2T_{fb}$ and 4 sec, assumed at the beginning of the analysis, define the upper and lower bound values of the target displacements D_d and θ_d.

For the FPB system, further limitations apply. As a matter of fact, indeed, the horizontal displacement capacity of FPB is conditioned by the acceptability of the corresponding vertical displacement and residual horizontal displacement. Both are a function of the radius of curvature R of the device. As a consequence, limitations to the ratio between the design IS displacement (D_d) and the radius of curvature (R) are needed to limit vertical and residual displacements. Reasonable values of the ratio D_d/R are between μ_{FR} (of the order of 5% for lubricated interfaces) (Dolce et al., 2005) and 15% (Priestley et al., 2007). The limitations on the ratio D_d/R lead to restrictions to the values of the design spectral acceleration (S_{ad}), hence target interstorey drift (θ_d), that can be selected. The maximum and minimum values of the design acceleration for FPB can be computed with the following expression:

$$S_{ad}^{min(max)} = F_{IS}^{min(max)} / M_{tot} = g \cdot \left[(D_d / R)_{min(max)} + \mu_{FR} \right] \tag{3.5}$$

where g is the standard gravity constant. In Fig. 3(b) the maximum and minimum values of the design acceleration are identified by means of two horizontal dashed lines. The segments of the "applicability" curves comprised between the two aforesaid dashed lines provide the target displacements D_d and θ_d that can be suitably considered for FPB.

The graphical tools presented in Fig. 3 can be used for the preliminary selection of D_d, θ_d and/or IS type. After that, the DDBD method can be applied to determine the IS characteristics that allow to achieve the required performance objectives, as well as the corresponding design base-shear (V_b) and inertial force distribution for the Linear Static Analysis of the building (Priestley, 2003):

$$F_i = V_b \cdot (m_i \cdot \Delta_i) \Big/ \sum_{i=0}^{n} (m_i \cdot \Delta_i) \tag{3.6}$$

As said before, the proposed design procedure can be applied assuming for the superstructure either an elastic or inelastic behavior. When the superstructure is supposed to respond within its elastic range, an equivalent viscous damping (ξ_S) equal to 5% can be adopted. When plastic hinges are expected to occur, instead, the equivalent viscous damping is evaluated as a function of the global displacement ductility of the RC frame (μ), through the semi-empirical relationship proposed by (Priestley et al., 2007):

$$\xi_S = 5 + 120 \cdot \left(\left(1 - \sqrt{\mu}\right) / \pi \right) \tag{3.7}$$

Basically, the proposed DDBD procedure can be divided in eight steps.

In **Step 1**, the input data are defined. They include the geometry (h_i and m_i) and the basic characteristics (T_{fb} and θ_y) of the building. For what concerns the yield drift (θ_y) and the lateral stiffness (K_{fb}) of the superstructure, reference is made to the Eqs. (3.1)-(3.2). Step 1 also includes the selection of IS type, target IS displacement (D_d) and target interstorey drift (θ_d), by means of the graphical tools described before (see Fig. 3).

In **Step 2**, the design acceleration (S_{ad}) associated to the selected θ_d is derived through Eq. (3.3). Actually, I_r is unknown at beginning of the analysis, as it depends on T_{IS}. A trial value of I_r is then assumed, based on the results of the preliminary design process (see Fig. 3). This also permits to determine the deformed shape of the superstructure (Φ_i) and then the absolute storey displacements (Δ_i) of the BI-building through Eqs. (2.1) and (2.2), respectively. Usually, no iterations on I_r are needed, as the errors in the estimate of the relative storey displacements (D_i) are limited to a few percents.

In **Step 3**, the MDOF model of the BI-building (see Fig. 1(a)) is converted into an equivalent SDOF system (see Fig. 1(b)) whose equivalent design displacement (Δ_d) and effective mass (m_e) are given by Eqs. (2.3) and (2.4).

In **Step 4**, the equivalent damping ratio (ξ_{eq}) of the SDOF system is derived, combining the equivalent damping of IS and RC frame in proportion to the respective displacements:

$$\xi_{eq} = \left[\xi_{IS} \cdot D_d + \xi_S \cdot (\Delta_d - D_d) \right] / \Delta_d \tag{3.8}$$

In **Step 5**, the period of vibration of the equivalent SDOF system (T_{eq}) is obtained, entering the displacement response spectrum at ξ_{eq} damping, with the design displacement Δ_d obtained in step 3. The equivalent stiffness is then derived through the well-known relationship $K_{eq} = m_e (2\pi/T_{eq}^2)$. Finally, the design base shear of the BI-building is computed as $V_b = K_{eq} \Delta_d$. The effective stiffness of the IS (K_{IS}) at the target displacement D_d is then calculated as $K_{IS} = V_b/D_d$.
In **Step 6**, the mechanical characteristics of the IS are fully specified, based on their equivalent linear characteristics (K_{IS}, ξ_{IS}) and the mechanical parameters (friction coefficient, post-yield hardening ratio, viscous damping ratio, etc.) assumed at the beginning of the analysis.
In **Step 7**, the design base shear V_b is distributed over the height of the structure according to Eq. (3.6). With the lateral force distribution thus obtained, a Linear Static Analysis (LSA) of the building is performed (**Step 8**), modelling the IS through its effective stiffness K_{IS} at the target displacement D_d. Based on the LSA results, the design strengths of all the structural elements are determined, following the seismic code requirements for BI-buildings (e.g. EC8, 1998).
Nonlinear Time-History Analyses (NTHA) have been carried out by SAP2000_Nonlinear, in order to evaluate the accuracy of the proposed procedure in achieving the performance objective of the design. Three RC framed building models, differing in the number of storeys (3, 5 and 7, respectively) and IS type (HDRB, LRB, FPB+VD and FSB+SMA+VD, respectively) have been examined. All the IS's have been designed according to the proposed procedure, assuming different target IS displacements (D_d = 150-350mm) and interstorey drifts (θ_d = 0.1-0.3%). Seven accelerograms, compatible with the EC8 displacement response spectrum for soil type BCE (CEN, 1998), have been used in the NTHA. For the sake of brevity, the results of these analyses are not reported in this paper. Herein, only the most important findings are summarized.
The maximum IS displacements provided by NTHA result in good agreement with the target IS displacements adopted in the DDBD (percent differences lower than 10%), regardless the IS type used. Similar considerations can be made for the maximum interstorey drifts, for which the differences between NTHA results and DDBD predictions are lower than 15%. The NTHA results, however, have also pointed out that, in order to get an accurate estimation of the maximum storey shear forces over the height of the building, the lateral force distribution for LSA must reflect the mechanical behavior of the IS. A distribution of lateral forces proportional to the storey masses (like that suggested in the standard formulation of the DDBD method (Priestley, 2003)) may be suitable for (quasi-)elastic isolation systems (e.g. LDRB, HDRB and LRB with low degree of non linearity) while a distribution proportional to the product of storey masses and storey heights would be more reasonable (and conservative) for strongly nonlinear IS's (e.g. FPB, FSB+SMA and LRB with high degree of non linearity). An extensive parametric investigation of NTHA is being carried out with the aim of defining more accurate distributions of equivalent static forces, specific for each IS, which account for the actual mechanical behaviour of the IS and the ratio between the effective period of the BI-building (T_{IS}) and the fundamental period of the FB-building (T_{fb}). Comprehensive results on this matter will be presented in an upcoming publication.

As final remark, it can be noted that the modern seismic codes prescribe to perform an upper and lower bound analysis, assuming the most unfavourable IS characteristics for accelerations and displacements, respectively, in order to take into account the effects of the variability of the IS mechanical behaviour with air temperature, loading rate and magnitude of vertical load, as well as the changes in the IS mechanical properties due to ageing and differences within the same production lot.
Generally speaking, accelerations, inertial forces and interstorey drifts should be evaluated taking into account the maximum expected value of effective stiffness ($K_{IS,max}$) and the minimum expected values of effective damping ($\xi_{IS,min}$) and friction coefficient ($\mu_{FR,min}$) (upper bound analysis). On the contrary, IS displacements should be evaluated taking into account the minimum expected values of effective stiffness ($K_{IS,min}$), effective damping ($\xi_{IS,min}$) and friction coefficient ($\mu_{FR,min}$) (lower bound analysis).
In practice, if the variability of the IS mechanical behaviour is expected to be relatively low (say extreme – maximum and minimum- values of K_{IS} and ξ_{IS} differing less than 20% from the corresponding mean values), the step-by-step procedure described before can be applied referring to the mean values of the IS mechanical properties. On the contrary, if the variability of the IS mechanical behaviour is expected to be more significant (say percent variations of K_{IS} and ξ_{IS} between 20 and 50%), the DDBD approach shall be applied two times consecutively, first to design the IS, referring to its lower bound extreme working conditions (i.e. assuming $K_{IS,min}$, $\xi_{IS,min}$ and $\mu_{FR,min}$), then to verify that the maximum interstorey drifts generated by the earthquake

considering the upper bound values of the IS mechanical properties (i.e. $K_{IS,max}$, $\xi_{IS,min}$ and $\mu_{FR,max}$) are compatible with the selected design value (θ_d). Normally, some iterations are needed to get a suitable solution.

4. CONCLUSIONS

A Direct Displacement-Based Design (DDBD) procedure for RC framed buildings with different Isolation Systems (IS's) has been presented. The procedure has been specialized for five different force-displacement models of IS, which can be used to describe the cyclic behaviours of a wide variety of IS's, including: (i) High Damping Rubber Bearings, (ii) Lead Rubber Bearings, (iii) Friction Pendulum Bearings and (iv) combinations of Flat Sliding Bearings with different auxiliary devices. The key parameters of the proposed procedure are the target IS displacement (D_d) and the target maximum interstorey drift (θ_d), which are assigned by the designer to accomplish either an "Operational Building" (FEMA, 2000) Performance Level (PL), characterised by minimal or no damage to the building structural and non-structural components, or a "Damage Control" (FEMA, 2000) Structural PL, with limited ductility demand to the structural members. At the moment, the design procedure has been fully developed and implemented for the first PL. The implementation for the second PL is still in progress.
Results of Nonlinear Time-History Analyses (NTHA) on different configurations of BI-buildings (for the sake of brevity, not shown in this paper) confirmed the accuracy of the DDBD procedure in the attainment of the performance objective of the design (i.e. $D_{IS} = D_d$ and $\theta_{max} = \theta_d$). The NTHA results, however, also pointed out that some refinements to the method are still needed. Basically, they include an improved formulation of the lateral force distributions for the Linear Static Analysis of the BI-building, which should be specific for each IS type, accounting for its actual mechanical behaviour and isolation ratio T_{IS}/T_{fb}.

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