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A NEW METHOD FOR THE SEISMIC DESIGN OF STRUCTURES WITH BILINEAR ISOLATORS USING INELASTIC SPECTRA

Arturo TENA-COLUNGA[1]

SUMMARY

This paper presents the concept of inelastic capacity design spectra for the design of base-isolated structures; particularly those structures using isolators with a bilinear hysteretic behavior when subjected to dynamic loading. The inelastic capacity design spectra relate peak nonlinear accelerations, velocities, displacements and effective isolated natural periods for bilinear systems with a given yield strength and post yield stiffness. Inelastic capacity design spectra could be useful for the design of base isolators with bilinear hysteretic behavior, as these devices can be designed for a fixed yield strength and post yield stiffness. The concept of inelastic capacity design spectra and its application for the design of base isolated structures is illustrated with the case study of a particular structure.

INTRODUCTION

Base isolation has emerged as a viable structural option in seismic zones during the last decade thanks to the great effort done by the structural community worldwide during the last thirty years, particularly in the United States, Japan and New Zealand. There has been extensive experimental and analytical studies in different types of base isolators that have allowed, among other issues, the development of design practices for specific base isolators and code procedures, for example, those established in the Uniform Building Code (UBC) since 1991 and the American Association of State Highway and Transportation Officials (AASHTO) since 1990. The growing interest on the use of base isolation in seismic zones in the United States seems to be related to the publication of these seismic code provisions. Other earthquake-prone countries with a long-time interest in base isolation, such as New Zealand, Japan and Italy, have constructed several base-isolated projects for buildings and bridges during this decade. In fact, Japan is the country that has more base isolated structures in the world nowadays. Many other nations that face the earthquake hazard have conducted research studies and/or build a few base-isolated structures, among others, Mexico, where the first steps directed to the development of seismic provisions for base isolation base upon the UBC guidelines and the regional seismicity of the country have been taken [i.e., Tena et al. 1997], and are still under way.

The seismic design of base isolators is generally controlled by the maximum allowable displacement of the isolators for dynamic stability rather than strength. Although this fact has been recognized before in the sizable literature on base isolation, the design practice on base isolation is currently based on a procedure where the design displacement is obtained indirectly from a given pseudo-acceleration design spectra specified for the design of conventional structures. The UBC code provisions (1991 to 1997 versions) share this design philosophy. A good design of base-isolated structures would require to have all relevant information at hand, and a pseudo-acceleration response spectra give only one third of the required information, as peak responses for velocities and displacements are not included. Therefore, the use of an inelastic tripartite design spectrum [Newmark and Hall 1982] would be potentially more useful, as the nonlinear action of base-isolated structures is concentrated on the isolators, and this spectrum gives all the needed information, as peak responses in acceleration, velocity and displacements are included. However, the inelastic design spectrum as presented by Newmark and Hall [1982] is based upon the concept of fixed displacement ductility demands, that is not the best

[1] *Professor, Departamento de Materials, Universidad Autonoma Metropolitana, Mexico, Email: atc@hp9000al.uam.mx*

concept for base isolators. For a given excitation, a displacement ductility demand can be associated to different yield strengths; this is, this ductility demand is not unique. Base isolators, particularly those with a bilinear hysteretic behavior, can be designed for a fixed yield strength and post yield stiffness. Therefore, constructing an inelastic capacity design spectra (ICDS) could be more useful for the design of base-isolated structures. The ICDS relate peak nonlinear accelerations, velocities, relative displacements and effective isolated natural periods for bilinear systems with a given yield strength and post yield stiffness. The use of ICDS could be useful for the design of base isolators with bilinear hysteretic behavior, as these devices are usually defined in this fashion. The construction and use of ICDS are presented in following sections

INELASTIC CAPACITY RESPONSE SPECTRUM CONCEPT AND COMPUTATION

The inelastic capacity design spectrum (ICDS) is basically a modification of the "modified response spectrum" (MRS) proposed by Newmark and Hall [1982], where the normalized yield strength (V/W) of a SDOF system is fixed rather than the displacement ductility demand (μ). The ICDS is obtained from inelastic capacity response spectra computed individually for specific ground motions and a given hysteretic model. An inelastic capacity design spectrum (ICRS) can be defined for any suitable hysteretic model; however, in this paper is defined for bilinear systems, as many commercial base isolators have this type of hysteretic behavior (among others, rubber bearings and steel hysteretic dampers). In particular, this paper presents ICRS for bilinear systems with a postyielding stiffness of 10% (k2/k1=0.10) as depicted in Fig. 1, a typical relation for most laminated rubber bearings and lead rubber bearings, as reported in the literature [i.e., Skinner et al. 1993, Kelly 1993]. An ICRS relates peak nonlinear accelerations, velocities and relative displacements with effective isolated natural periods for bilinear systems with a given yield strength and post yield stiffness.

To compute an ICRS for a given ground motion excitation, the following steps must be followed:

(1) Define the parameters of the hysteretic model. For a bilinear system, define V/W and k_2/k_i.

(2) Define the equivalent viscous damping ratio, the acceleration record, initial (T_i) and final (T_f) periods of interest, and the period increment (ΔT) for the computation of dynamic responses. The increments could be in arithmetic or logarithmic scales. The use of logarithmic increments is recommended, provided the characteristics of the tripartite plots.

(3) Do $T_j = T_{j-1} + \Delta T$, $T_i \leq T_j \leq T_f$

(4) For each period of interest T_j

   (a) Check that the integration time step (Δt) for the acceleration record is suitable for the computation of nonlinear problems. A rule of thumb is to check that $\Delta t \leq T_j/10$. Otherwise, interpolate the ground motion record. A selective interpolation algorithm should be defined, as there is not need to use very small integration time steps for long periods as they are needed, for example, for periods close to zero.

   (b) For each time step Δt, solve the equation of motion of a nonlinear SDOF system using a suitable numerical method (for example, Newmark-β method) given by:

$$m\ddot{x}(t) + c\dot{x}(t) + kx(t) = F(t) \qquad [1]$$

where m is the mass of the system, c is the damping coefficient of the system, k is the stiffness of the system associated to T_j, F(t) is the effective load at time t, and $\ddot{x}(t),\ \dot{x}(t)\ and\ \ x(t)$ are respectively the acceleration, velocity and displacement at time t, as defined in the literature.

   (c) Save the maximum responses in acceleration, velocity, displacement and nonlinear system force. Then, the effective isolated period T_I of the system can be computed as follows:

$$T_I = 2\pi\sqrt{\frac{m}{k_{eff}}}\ ; \qquad k_{eff} = \frac{F^-_{jmax} + F^+_{jmax}}{\Delta^-_{jmax} + \Delta^+_{jmax}} \qquad [2]$$

where F^-_{maxj} F^+_{maxj} and Δ^-_{maxj} Δ^+_{maxj} are respectively the maximum negative and positive forces and displacements *and* k_{eff} is the effective stiffness of the nonlinear SDOF system with an initial elastic period of interest T_j.

(5) Go to step 3 until $T_j=T_f$.

An average ICRS computed for a bilinear system with V/W=0.10, k2/k1=0.10 and ξ=0.05 when subjected to the set of ground acceleration records identified in Table 1 is depicted in Fig. 2. It can be observed that peak nonlinear responses in acceleration, velocity and displacement are not directly related, and there are period ranges where the nonlinear response is controlled by the displacements, but in other regions the velocities or the accelerations rule, as also illustrated with the MRS presented by Newmark and Hall [1982].

INELASTIC CAPACITY DESIGN SPECTRA

Inelastic capacity design spectrum (ICDS) could be defined for the design of base-isolated structures. The following items have to be defined for an ICDS: (1) the hysteretic model of interest and its parameters, (2) a set of representative ground motions records for a given seismic zone and soil type and, (3) a criterion to define the design curves. These three items have to be carefully assessed if the ICDS is intended for seismic guidelines, recommendations or design procedures for specific building codes. In this paper, ICDS is defined for representative strong ground motions recorded in the Mexican Pacific Coast during recent strong earthquakes using a crude statistical criterion for base isolators with bilinear behavior. The ICDS presented in this study were computed to assess their effectiveness for the design of base isolated structures, but they have not been developed yet to comply with the seismic code criteria of ruling Mexican seismic codes for the Mexican Pacific Coast. The specific criteria used for items 1 to 3 mentioned above are briefly described below

Selected Hysteretic Model

For the present study, a bilinear hysteretic model with a post to pre yielding stiffness ratio k_2/k_1=0.10 was selected (Fig. 1). As stated above, this was done because this is a typical ratio for most laminated rubber bearings and laminated lead rubber bearings, which are of particular interest for the author. Two normalized yield strengths were selected, V/W=0.05 and V/W=0.10, in order to cover the range where most elastomeric base isolators are designed in regions of severe ground shaking.

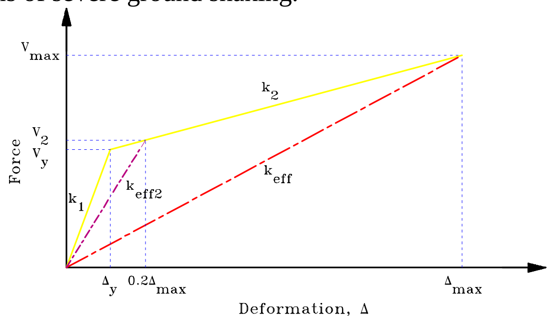

Figure 1. Design Envelope Curve for Bilinear Isolators

Selected Acceleration Records

Typical accelerograms for the Mexican Pacific Coast recorded during recent earthquakes were selected for the present study. The following earthquakes were considered: (a) the M_s=8.1 September 19, 1985 Michoacán earthquake, (b) the M_s=7.6, September 21, 1985 aftershock for the Michoacán earthquake, (c) the M_s=6.9, April 25, 1989 earthquake and, (d) the M_w=8.0, October 9, 1995 Manzanillo earthquake. A total of 42 accelerograms for the horizontal ground motions for 15 different stations were available; however, only the 16 strongest acceleration records corresponding to eight stations were selected for the reasons given in Tena *et al*. [1997]. The selected acceleration records and some of the characteristics for these records are summarized in Table 1. All stations are located on rock sites nearby the coast except ZACA and MANZ, where some site effects have been detected. Nevertheless, these stations were included because the acceleration records are among the strongest ever recorded in firm soils in the Mexican Pacific Coast, and this was an important criterion in this initial study to calibrate the use of ICDS. The records for station SMRZ have a strong pulse associated to an intermediate period, as a consequence of being an epicentral station for the 1989 earthquake.

Criterion to Define Design Curves

The criterion to define design curves for the ICDS was influenced by the selection of ground motions and the main objective of the present study, that was to assess the potential effectiveness of ICDS for the design of base-isolated structures rather than defining ICDS associated to specific building codes. The definition of ICDS for specific building codes would require complete seismic hazard analyses where further considerations should be made in the selection of ground motions, sizes of design earthquakes for different performance levels, exceedence rates, etc. In the present study, ICDS were defined for the mean plus a standard deviation ($\sigma + S_{dev}$) of the 16 selected acceleration records. This criterion was selected, among other considerations, as it was less conservative than defining an envelope curve for the 16 selected acceleration records, higher multiples for the standard deviation to have lower rates of exceedence or other more complex and complete probabilistic criteria.

Table 1. Characteristics of Selected Ground Motions

Event	Station	Duration (s)		Amax (cm/s2)		Dominant Site Period (s)	
		Record	Strong Phase	E-W	N-S	E-W	N-S
09/19/85	AZIH	71.8	20	162.	101.	0.12	0.30
	CALE	48.9	10	138.	138.	0.35	0.40
	PAPN	59.5	5	114.	157.	0.12	0.14
	PARS	52.6	16	89.	116.	0.12	0.13
	UNIO	62.7	25	147.	163.	0.23	0.35
	ZACA	90.0	45	271.	182.	0.36	0.20
04/25/89	SMRZ	30.5	4	127.	175.	0.19	0.30
10/09/95	MANZ	155	20	383.	363.	0.23	0.22

Procedure to Define Specific ICDS

For illustration purposes, this section presents the procedure used to define the ICDS for isolators with bilinear behavior with V/W=0.10 and k_2/k_1=0.10. The procedure follows the general criteria described in previous sections and was used for the other case study (V/W=0.05). The details of these studies are presented in Tena *et al* [1997]. The inelastic capacity response spectra corresponding to $\sigma + S_{dev}$ for the 16 selected acceleration records are depicted in Fig. 2. From the base isolation viewpoint, peak responses below an effective isolated natural period of 1.5 seconds (T_I<1.5s) are of little interest for the design of the base isolators, although they can be important for the design of the superstructure. Therefore, spectra are presented for the period range $1s \leq T_I \leq 10s$.

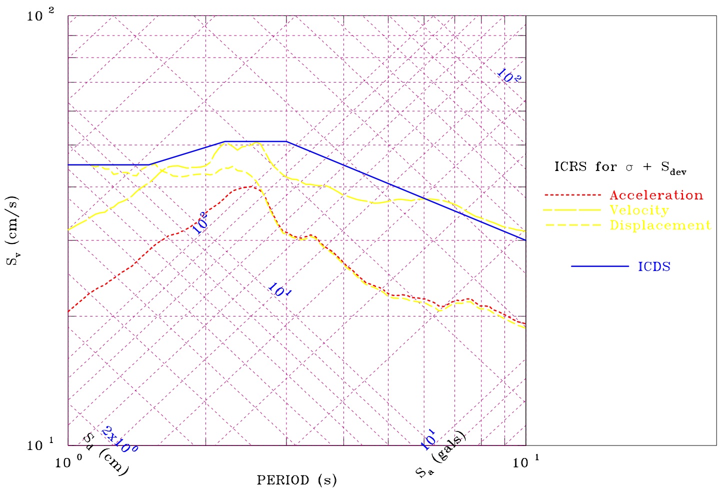

Figure 2. ICRS for $\sigma + S_{dev}$ and ICDS for Bilinear Isolators with Design Parameters V/W=0.10 and k_2/k_1=0.10

In order to define the design envelope shown with a thick, solid line in Fig. 2, the following considerations were made. It is recognized in the literature that base isolation is most appropriate when the effective period of the isolated structure is in the range 1.5s $\leq T_I \leq$3s. Skinner *et al.* [1993] proposes the lower limit and the upper limit is defined by the UBC code for using static design procedures and some options for dynamic design procedures ["Uniform" 1991]. To the author's knowledge, the highest effective period considered for a retrofit project with base isolators is the one considered for Los Angeles City Hall, close to 4 seconds. Therefore, the design envelope was defined in order to reasonably cover the period interval 1.5s $\leq T_I \leq$4s, being less conservative for periods longer than six seconds (T_I>6s) or lower than 1.5s (T_I<1.5s), as it can be observed in Fig. 2. An attempt was made to define the envelopes with few straight lines while still reasonably protecting the period range 1.5s$\leq T_I \leq$3s. This is why the flat part of the envelope depicted in Fig. 2 was extended up to T_I=3s. Because of this consideration, the period range 3s$\leq T_I \leq$5s is overly protected, as it was decided to define just one descending branch for the spectra (Fig. 2). The design envelope should cover at once the response maxima in terms of acceleration, velocity and displacement. It can be observed in Fig. 2 that the design envelope is ruled essentially by the peak responses for displacements (1s $\leq T_I \leq$1.6s) and velocities (T_I>1.6s). The same tendency was observed for the design envelope for V/W=0.05, although the period where velocity curves start to rule changes (T_I>2.1s for V/W=0.05).

Proposed ICDS

Inelastic capacity design spectra (ICDS) for V/W=0.05 and V/W=0.10 are depicted in Fig. 3. It can be observed in Fig. 3 that, for the period range of interest for most base isolation applications (1.5s $\leq T_I \leq$3s), it would be more convenient to design the isolators for lower normalized yield strength ratios (V/W=0.05), as peak displacements are smaller for this envelope. It can be observed from Fig. 2 that the acceleration curve is considerably surpassed by the displacement and velocity curves in the period range of interest. Therefore, it would be very conservative to design the superstructure using the accelerations associated to the ICDS presented in Fig. 3. The peak acceleration curve is proportional to the peak normalized strength curve (V_{max}/W). It is worth recalling that, for bilinear systems, the maximum force (V_{max}) should surpass the yielding force (V) if the response is indeed nonlinear. Therefore, it was considered convenient to define additional design spectra for the maximum normalized base shear transmitted to the superstructure (V_{max}/W), which is not shown for space constraints, but one can observe that shear forces transmitted to the superstructure decrease as the period increases, as a consequence that the nonlinear response of systems with long periods is smaller when subjected to ground motions for firm soil conditions

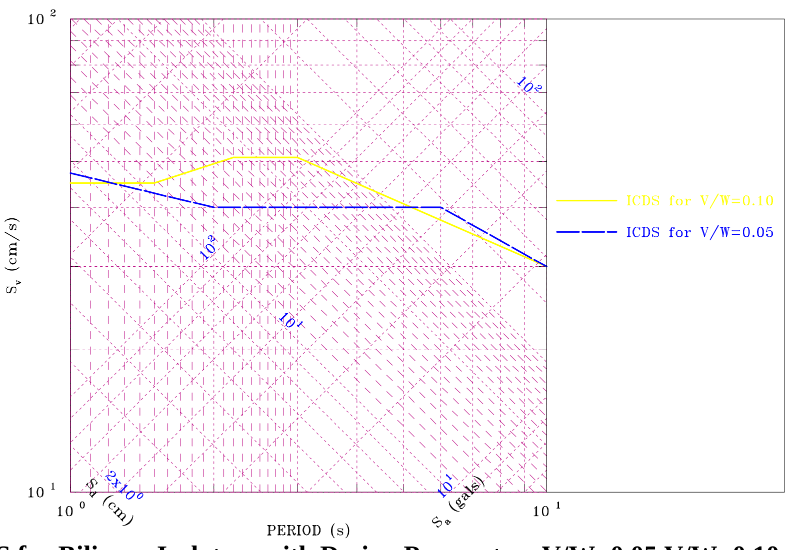

Figure 3. ICDS for Bilinear Isolators with Design Parameters V/W=0.05,V/W=0.10 and k_2/k_1=0.10

DESIGN OF BASE ISOLATORS USING ICDS

The proposed ICDS was calibrated for the design of the base isolators for three low-rise school buildings and an eight-story reinforced concrete (RC) building, studies which are presented in detail in Tena et al. [1997]. The school buildings are benchmark structures for the author, as his research team has previously used other strategies for the design of base isolators for these structures [i.e., Tena-Colunga 1996]. For these school buildings, a normalized yield strength ratio V/W=0.10 was selected, as done in previous studies. The eight-story RC office building was selected as an irregular structure where base isolation could be used. A normalized yield strength ratio V/W=0.05 was used for this building. The details of this structure, the design of the isolators and the nonlinear dynamic analyses conducted for this design are briefly presented in following sections and in detail elsewhere [Tena et al. 1997]. The details of the studies for the school buildings are not presented here for space constraints, but the interested reader is addressed to Tena et al. [1997], where it is reported that the design procedure was effective.

SUBJECT BUILDING

ECO1 is an eight-story, irregular office building composed of RC waffle flat-slab frame system and peripheral RC shear walls. Typical plan views, elevations and gross dimensions of the structure are depicted in Fig. 4. As it can be observed, the structure is irregular in plan and it has a major irregularity in frame 1 (Fig.4), where there are no waffle-slab for bay A-B up to the roof level, this is, there is an eight-story bay in frame 1. The typical cross section for columns is square. The columns vary from 70x70 cm in the first two stories to 60x60 cm in the remaining stories. The floor system is a RC waffle flat-slab 5 cm thick with 16 cm wide main ribs measuring 30 cm in depth. The "waffles" are formed by hollow lightweight concrete blocks. The thickness of the concrete walls is 20 cm. Yield strength of reinforcement steel is f_y=4200 kg/cm^2 (428.1 MPa) and compressive strengths for concrete are 300 kg/cm^2 (30.58 MPa) for the two first stories and 250 kg/cm^2 (25.48 MPa) for the upper stories. 3D elastic models for the building were made with ETABS assuming that the building was fixed at the base and using all representative modes that insure having at least the 90% of the total modal mass acting in each main direction. Young modulus for reinforced concrete was taken according to the concrete norms for Mexican codes. The remaining modeling assumptions for structural and nonstructural elements are described in Tena *et al.*[1997]. The dynamic characteristics for building ECO1 can be consulted elsewhere. The natural period for the structure is T=1.01s. Despite of the irregularities, the mode shapes are just lightly coupled. The total weight for the building is W=4793.5 Ton (47,024.2 kN).

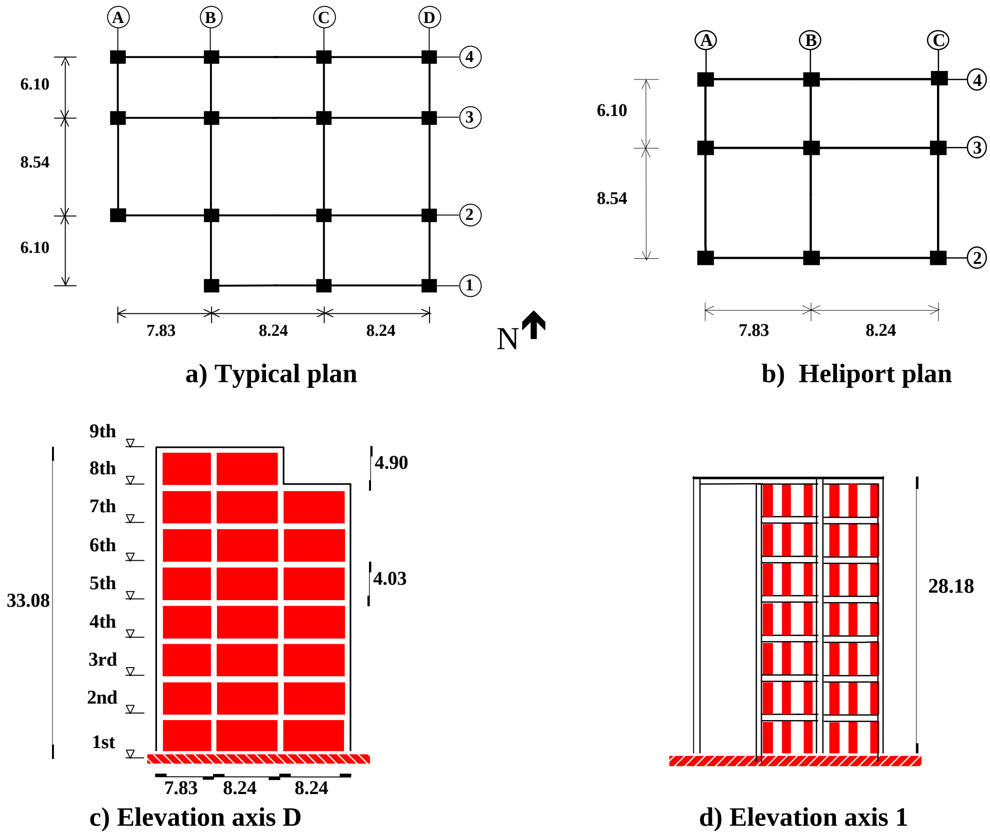

Figure 4. Plan Vews and Elevations for ECO1 Building (Dimensions in Meters)

Design of the Base Isolated Structure

Lead-rubber bearings (LRB) were designed for ECO1 building using the ICDS for V/W=0.05 depicted in Fig. 3. The design procedure involves an iterative process which is described in detail in Tena *et al.* [1997]; this paper only presents the key steps which illustrate the use of ICDS. The first step is to select a trial effective period for the isolated structure (T_I), considering the following restrictions: 1.5s $\leq T_I \leq$3s and $T_I \geq$2T, where T is the natural period for the fixed-base structure. Once T_I and the normalized yield strength (V/W) for the isolation system are selected, one can obtain the maximum design displacement for the isolation system, D, from the ICDS of Fig. 3. After defining D, one could propose the number of desired base isolators and define their individual characteristics to meet closely the design assumptions (V/W=0.05, k_2/k_1=0.10). In the design process, it was checked that the effective stiffness of the isolation system at the design displacement is greater than one third of the effective stiffness at 20 percent of the design displacement, as proposed by the UBC code (called here "UBC stiffness restriction", Fig. 1). This restriction is instrumental for the design of isolators and makes the design process iterative. Otherwise, if any unrestricted bilinear curve could be taken, there will be no need for an iterative procedure. For ECO1 building, one could take T_I>2.02s and get the smallest design displacement D (Fig. 3); however, the UBC stiffness restriction does not allow to use this design period. After some iterations, ECO1 building was designed for an effective isolated period T_I=3s and, therefore, using Fig. 3 and going to the displacement scales, for V/W=0.05, the design displacement is D=18.8 cm. Selecting 16 isolators, one below each column at the base level, the design procedure suggests to use LRB 56 cm in diameter and 40 cm in height, with a lead core 12.7 cm in diameter, for a maximum allowable isolator displacement for dynamic stability Δ_M=D=18.8 cm. Here, the design of the isolators is based on the assumption that roll-out instability controls the design displacement. Roll-out instability is typical of dowelled bearings [Kelly 1993]. Recent experimental research has shown that bolted bearings are capable of developing even higher allowable displacements, but this does not happen as a rule of thumb.

The design of the structural system was not done as ECO1 is a retrofit project and the building exists. However, the base shear coefficient for the design of the superstructure can be defined with the base shear curves (not shown). Thus, with an effective isolated period T_I=3s and V/W=0.05, the maximum normalized base shear transmitted to the superstructure for design was V_{max}/W=0.06, this is, V_{max}=287.6 Ton (2821.5 kN).

Nonlinear Dynamic Analyses

The proposed design for the isolation system for building ECO1 was tested with nonlinear dynamic analyses of the base-isolated model when subjected to bidirectional acceleration input using the 3D-Basis program [Nagarajaiah *et al.* 1991]. Twelve pairs of motions were selected, five for the 09/19/85 Michoacán earthquake, three for the 09/21/85 aftershock of the Michoacán earthquake, two for the 04/25/89 earthquake, one for the 05/31/90 earthquake and the only station available near the epicentral area for the 10/09/95 Manzanillo earthquake. Analyses were conducted considering that the E-W components corresponded to the long ("x") direction for the building and the N-S to the short direction ("x-y" quake), and viceversa ("y-x" quake). Some results obtained from the analyses are summarized in Table 2. In Table 2, Δ_i is the maximum dynamic displacement for a given isolator in an angle θ from the *x* axis, Δ_M=18.8 cm is the maximum allowable isolator displacement for dynamic stability, Δ_{xmax} and Δ_{ymax} are the maximum relative roof displacements with respect to the isolation system in the *x* and *y* directions respectively, V_{xe} and V_{ye} are the peak base shear forces transmitted to the structure in the *x* and *y* directions respectively, and V_{xi} and V_{yi} are the peak shear forces developed for the isolators in the *x* and *y* directions respectively, and W=4793.5 Ton (47024.2 kN), the weight for the structure.

Table 2. Peak Dynamic Responses for the Isolation Project, ECO1 Building

Station	Quake	Δ_{xmax} (mm)	Δ_{ymax} (mm)	Δ_i/Δ_M	θ	V_{xe}/V_{xi}	V_{ye}/V_{yi}	V_{xe}/W	V_{ye}/W
AZIH	y-x	20.9	9.1	0.47	294.09	0.88	0.88	0.044	0.046
CALE	y-x	21.5	6.8	0.75	11.75	0.89	0.88	0.045	0.040
UNIO	y-x	25.7	10.5	0.47	347.67	0.90	0.92	0.047	0.048
ZACA	x-y	30.7	8.1	0.69	327.44	1.07	0.96	0.052	0.041
SMRZ	x-y	19.0	12.4	0.65	318.14	0.86	0.96	0.045	0.042
MANZ	y-x	41.8	81.3	0.99	242.11	0.87	0.92	0.048	0.053

It can be observed from Table 2 that the proposed design is adequate for all ground motions, as the quotient Δ_i/Δ_M is always less than one. Maximum responses for the isolators are related to stations MANZ, ZACA and SMRZ. Relative roof displacements are very small for a building 33 m in height. The efficiency of the isolation system in reducing the base shear transmitted to the superstructure (V_{xe}/V_{xi} and V_{ye}/V_{yi} ratios) is between 86% to 96% for most stations, but it can be even 7% higher as it happens for station ZACA. Higher efficiencies in reducing the base shear transmitted to the superstructure have been observed for other buildings, among them, the school buildings of reference [Tena *et al*. 1997]. In addition, the maximum normalized dynamic base shear transmitted to the superstructure is obtained for station MANZ in the *y* direction (V_{ye}/W=0.053, Table 2), and is smaller than the maximum normalized base shear transmitted to the superstructure for design V_{max}/W=0.06 computed with the design spectra, so the proposed method seems safe enough for the design of base-isolated structures.

SUMMARY AND CONCLUSIONS

This paper presented the concept of inelastic capacity design spectra (ICDS) for the design of base-isolated structures; particularly those structures using isolators with a bilinear hysteretic behavior when subjected to dynamic loading. The ICDS relate peak nonlinear accelerations, velocities, displacements, and effective isolated natural periods for bilinear systems with a given yield strength and post yield stiffness. ICDS could be useful for the design of base isolators with bilinear hysteretic behavior as these devices can be designed for a fixed yield strength and post yield stiffness. In this paper, ICDS were defined for representative strong ground motions recorded in the Mexican Pacific Coast during recent strong earthquakes using a crude statistical criterion for base isolators with bilinear behavior. The ICDS presented in this study were computed to assess their effectiveness for the design of base-isolated structures, but they have not been developed yet to comply with code criteria of ruling Mexican seismic codes for the Mexican Pacific Coast. The development of ICDS associated to specific building codes would require complete seismic hazard analyses, where detailed considerations should be made in the selection of ground motions, sizes of design earthquakes for different performance levels, exceedence rates, etc., steps that would be taken in future works. The concept of ICDS and its application for the design of base isolated structures was illustrated with a subject building, but more case studies are available [Tena *et al*. 1997]. Nonlinear dynamic analyses conducted for ECO1 building and other structures suggest that the proposed ICDS are useful and reliable for the design of base-isolated structures, despite of the shortcomings of the study as described in previous sections, among them, using a limited strong ground motions data base and a crude statistical procedure. Therefore, the concept of ICDS seems to be a promising tool for reliable design of base isolators with bilinear hysteretic behavior. Further research is needed in order to define ICDS for specific building codes where, in addition to the items described above for seismic hazard analyses, a consideration must be made in order to incorporate the impact of bidirectional ground motions and the vertical component for the acceleration.

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