8th Canadian Conference on Earthquake Engineering / 8ième Conférence canadienne sur le génie paraséismique
Vancouver – 1999

Simplified seismic evaluation of existing structures

Tena-Colunga, Arturo[1]

ABSTRACT

One of the major concerns in the structural engineering practice is to assess the nonlinear response of new or existing structures for moderate or strong earthquake motions in a simple way. This can be done using what the author defines as displacement ductility demand spectrum. This displacement ductility demand spectrum is a variation of the well-known nonlinear response spectrum for single degree of freedom (SDOF) systems with fixed displacement ductility demands. For illustration purposes, a sample seismic evaluation of an existing structure using the proposed spectra is presented and compared with a seismic evaluation using more rigorous methods.

INTRODUCTION

Damaging earthquakes occurred during the last 14 years in Chile, México, Armenia, The United States, Japan, Perú, Bolivia, Egypt, Turkey, Iran, Philippines and Colombia, among other affected nations, have warned the engineering community worldwide about the vulnerability of existing structures. Several research projects have been conducted during the last decade with the same final goal: to mitigate the seismic hazard in the built environment. Among other issues, many research efforts have been directed from the structural engineering perspective to: (1) evaluate and improve existing guidelines available in seismic codes, (2) study and develop modern technologies to improve the seismic performance of structures subjected to earthquakes, for example, base isolation, passive energy dissipation and active control, (3) study and develop strategies for the seismic retrofit of structures, (4) improve methods for seismic analysis and design, (5) develop general guidelines for the seismic evaluation of existing structures and, (6) develop simple procedures to define the seismic hazard and vulnerability of the built environment of a region using seismic-hazard maps.

The seismic evaluation of existing structures is an issue of paramount importance in earthquake engineering practice. The evaluation of existing structures is not only important to assess the vulnerability of specific structures, but also to complement strategic plans directed to mitigate the seismic hazard in the built environment of a given region. However, available methods for the seismic evaluation of existing structures have not evolved significantly during the past decade, particularly when the expected nonlinear dynamic response of structures for moderate or strong earthquakes and the uncertainties associated to it have to be assessed in a simple way. This paper presents an integral method for the seismic evaluation of existing structures, using what the author defines as displacement ductility demand spectrum (DDDS). This DDDS is equivalent to the constant strength response spectrum (CSRS) formerly studied by other authors with other purposes (i.e., Mahin and Bertero 1981, Pal *et al.* 1987) and discussed in greater detailed in following sections.

INELASTIC DESIGN SPECTRA (IDS)

The concept of inelastic design spectra (IDS) can be traced back to the late 1960′s and it has been used for many years for the design of special structures such as nuclear power plants (i.e., Newmark and Hall, 1982). In fact, these spectra and their variations (i.e., strength spectra) have also been used to define the design spectra for building structures of many seismic codes worldwide, where a basic elastic pseudo-acceleration spectrum can be reduced for inelastic behavior to primarily account for tolerated ductility demands and overstrength, based upon studies conducted for nonlinear SDOF systems, in addition to the experience and judgment of building code developers.

Inelastic spectra can be understood as a family or curves, and depending on the parameters that are fixed, these spectra have been named in different ways by many authors. When peak nonlinear response quantities are primarily assessed for a target displacement ductility demand, the resulting spectra have been called constant ductility response spectra, CDRS. On the other hand, constant strength response spectra (CSRS) are obtained when maximum displacement ductility demands and displacements are primarily assessed for a constant strength or strength ratio.

The concept of CDRS has been used widely by most researchers interested in inelastic spectra. Based upon the concept of CDRS, pseudo-acceleration design spectra have been defined for different seismic building codes worldwide and strength

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[1] Emilio Rosenblueth Professor, Departamento de Materiales, Universidad Autónoma Metropolitana Azcapotzalco, Av. San Pablo #180, 02200 México, D.F., MÉXICO, e-mail: atc@hp9000a1.uam.mx

reduction factors (R, R_μ, etc) have been computed and proposed by different researchers using SDOF systems considering different hysteretic models, primarily bilinear hysteretic models (i.e., Riddell and Newmark 1979, Miranda 1993b, Ordaz and Pérez-Rocha 1998). On the other hand, few researchers have studied the use of CSRS (i.e., Mahin and Bertero 1981, Pal *et al.* 1987). The works of reference have primarily used CSRS to evaluate inelastic design spectra proposed in the literature at the time, such as the well-known Newmark-Hall and ATC methods (Mahin and Bertero 1981), and/or to study the variation of the ductility demand using a set of ground motions (Mahin and Bertero 1981, Pal *et al.* 1987).

DISCUSSION ON IDS AND THE SEISMIC EVALUATION OF EXISTING STRUCTURES

The concept of CDRS is widely accepted and has been useful in design practice; however, it is quite debatable that the structural community (primarily outside academic practice) would know or assess better the global ductility capacity of a structural system rather than other significant parameters, i.e., strength capacity. In addition, the use of a constant ductility value is not as practical as one may think from the computational viewpoint.

For example, it is well known that there are some computation deficiencies with this approach, among them, that it is possible to have multiple yield strengths that produce the same target ductility, as illustrated, for example, in Miranda (1993a). Besides, it has also been shown that there could be important variations in the strength demands required for structural systems for a constant ductility in the period range where most structural systems are designed in practice, independently of the soil conditions (i.e., Miranda 1993a). These variations could be particularly important for the design of buildings located in soft soil sites, such those found in Mexico City. These variations in the strength demands for constant ductility values are not necessarily well represented with the R_μ curves presented by others (Tena 1997).

Despite the shortcomings mentioned above associated with the use of CDRS, and the fact that the nonlinear response of structural systems is not always well represented by equivalent SDOF systems (particularly for irregular or special structures), the concept of IDS based upon CDRS and the study of more rational strength reduction factors for the design of structures are very valuable, because it is easier and faster to study general trends with this approach than using more complex models. This is particularly true for the design of new structures. However, the use of CDRS is not practical for the seismic evaluation of existing structures and/or the design of suitable retrofit schemes for such structures.

For example, it will be unrealistic to evaluate an existing structure using smooth curves computed from a set of ground motions recorded worldwide for different earthquakes associated to different fault mechanisms, ignoring more relevant information as, for example, the dynamic characteristics of the site and the nature of earthquakes that affect the region where the structure is located. To the author's knowledge, the only R_μ rule that is starting to take care of this shortcoming is the one recently proposed by Ordaz and Pérez-Rocha (1998).

For the evaluation of existing structures, however, the author considers that one should provide the engineering community with methods that are more suitable to their needs and professional practice. Therefore, as most practicing engineers are used to estimate lateral load capacities, structural displacements and natural periods, it would be convenient to provide a version of inelastic spectra that practicing engineers can use with confidence and where they can get a feeling of the parameters that are involved. For this purpose, constant strength response spectra (CSRS, called here displacement ductility demand spectra, DDDS) are closer to the needs of engineering practice to evaluate existing structures than CDRS, as structural engineers can compute and feel the required parameters to build a DDDS for each specific structure. Whereas the proposed DDDS is a variation of the CSRS studied by other authors with other purposes, to the author's knowledge, no one has used a DDDS (CSRS) for the seismic evaluation of existing structures before.

DISPLACEMENT DUCTILITY DEMAND SPECTRA (DDDS)

Concept

A displacement ductility demand spectra (DDDS) relates peak displacement ductility demands (and other important response quantities, i.e., displacements) with structural periods of nonlinear SDOF systems with given yield strengths, as shown in Fig. 1 for structural systems with an elastic-perfectly-plastic hysteretic behavior for a yield strength ratio V/W=0.15 for the well-known SCT-EW accelerogram recorded during the 1985 Michoacán earthquake. Thus, the DDDS are constant strength response spectra (CSRS).

The main difference between a DDDS and a CDRS is that the strength is fixed rather than the displacement ductility. This variation offers some advantages from the computational viewpoint. The computation of a DDDS is simpler and faster as no iterations are needed to target the fixed strength value, as is needed, for example, in the computation of CDRS to achieve the target ductility demand. In addition, there are no uniqueness problems in the definition of DDDS, as there are for CDRS, because the yield strength is defined and fixed *a-priori*.

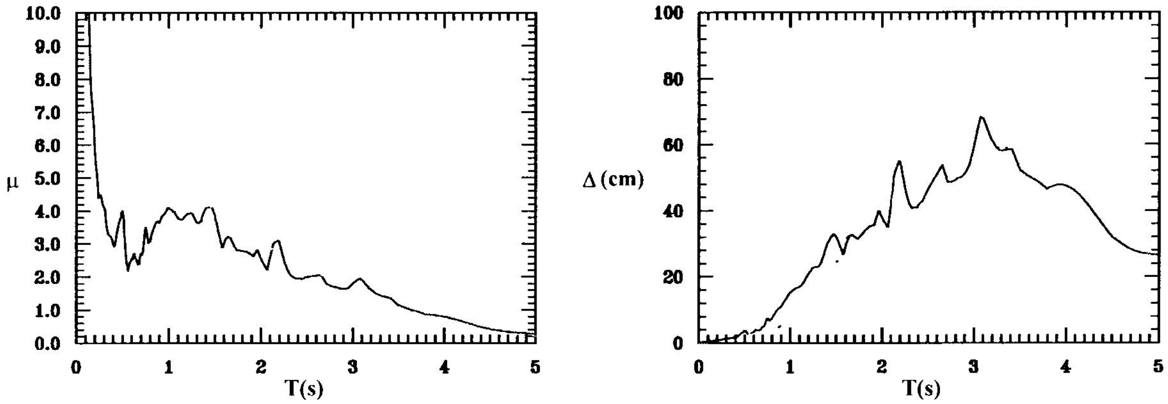

Figure 1. DDDS for a structural system with V/W=0.15 subjected to the 1985 SCT-EW record

Application for the seismic evaluation of existing structures

The concept of a DDDS offers some advantages for the seismic evaluation of existing structures with respect to CDRS. It is "easier" for most structural engineers to estimate the lateral load capacity of an existing structure rather than defining its ductility demand capacity, although none of these parameters can be assessed with any precision. Nevertheless, the lateral load capacity of a structure could be estimated using conventional methods of analysis (limit analysis, pushover analysis, etc) together with the information from blue prints or experimental data. If no blue-print information or experimental data is available at the time of a preliminary seismic evaluation, then, crude estimates of the minimum lateral load capacity could be done for structures if the date of construction is known, the structural system is recognized and is assumed that the structure was designed to comply with the requirements of a ruling building code. In addition, the uncertainties associated to the assessment of the lateral strength capacity can be evaluated by computing additional curves for other strength values considering overstrength sources and/or the possibility that the computed strength was overestimated.

A suitable hysteretic model can be selected for the structural system to define DDDS, not only the well-known elastic-perfectly-plastic behavior for all structures. For example, for structural steel systems, the DDDS can be computed using hysteretic models that would take into account representative post-yield stiffnesses, among others, the bilinear or the Ramberg-Osgood hysteresis models; for reinforced concrete structures one may pick stiffness degrading hysteresis models such as Clough or Takeda models; and for masonry structures one can use stiffness and strength degrading models, for example, the one proposed by Kwok and Ang (1987).

Estimates of dominant periods (frequencies) of response for subject structures could be done from *ad-hoc* analytical models or experimental methods (i.e., ambient vibration tests, forced vibration tests, analyses of recorded motions in seismically instrumented buildings, etc). The use of experimental methods to estimate vibrational characteristics of real buildings is not uncommon in Mexico City. The implications on the uncertainties associated to the estimates of dominant structural periods can be easily evaluated with the DDDS, as the impact of underestimates and overestimates in structural periods on peak ductility demands and displacements can be directly evaluated with the DDDS curves (Fig. 1).

Therefore, once the lateral load capacity and the dominant structural periods for the structure are estimated, a suitable hysteretic model or a set of hysteretic models have been chosen, and a set of representative or "critical" ground motion records have been selected for the site, then, DDDS can be defined for simplified seismic evaluations. Peak ductility demands and displacements can been assessed with the DDDS, as well as the uncertainties that one may have on the estimates of strength, stiffness (period) and hysteretic characteristics. Then, one may judge if the displacement ductility demands obtained from the DDDS can be developed by the structural system depending on its characteristics and seismic detailing, if the lateral displacements could be accommodated without damaging nonstructural components, favoring structural pounding with neighboring structures or creating panic in the users of the building. In addition, from the peak inelastic displacement defined by the DDDS one can compute the lateral displacements of a building (and, by extension, story drift ratios) using procedures already available in the literature. With a preliminary evaluation of a structure using a DDDS, one could decide whether further detailed analyses are needed or not for a subject structure. Thus, the use of DDDS could be potentially useful for the seismic evaluation of existing structures because structural engineers could: (a) assess the vulnerability of structural systems to different earthquake scenarios in a simple fashion, (b) study retrofit design strategies that would lead to good solutions for a particular structure before conducting detailed studies and, (c) incorporate these methods and/or some of these concepts into seismic building codes to improve design practices.

Differences with other methods for the seismic evaluation of existing structures

The DDDS involves strength concepts in a consistent way and, in that fashion, it offers several advantages from some old evaluation strategies that were done in the past. For example, a common evaluation procedure used in the past was to verify if an existing structure satisfied the requirements and criteria of the ruling building code (intended for new construction) and, based upon these studies, decide whether the structure needed: (a) no retrofit, (b) to be retrofit or, (c) to be demolished. In many instances, the retrofit plan must be designed to satisfy the strength and deformation requirements of a building code that did not have specific provisions for existing buildings. Many structural engineers worldwide in earthquake-prone areas consider this procedure an odd strategy, as there is no warranty that it would lead to good retrofit plans. Fortunately, this old practice is not longer accepted as "good practice", and some efforts have been directed to develop code procedures to evaluate existing structures in the past two decades, particularly after the 1989 Loma Prieta Earthquake. It is worth noting the efforts made by the ABK group for the evaluation of existing masonry structures outlined in the ABK Methodology that impacted the appendix C of the UCBC code, and the efforts directed to develop the NEHRP Guidelines for the Seismic Rehabilitation of Buildings (FEMA 273).

SEISMIC EVALUATION OF STRUCTURES USING DDDS: AE2 BUILDING CASE STUDY

The subject building, located near Alameda Park in downtown Mexico City, was a ten-story office building that was built in the 1950's according to the provisions of Mexico's 1942 Federal District Code. The total height of the structure from the ground level was 33.5 m, with typical story heights of 3.5 m, except at the first floor, which has a height of 5.5m. The original steel structure consisted of ordinary moment resisting frames (OMRF) in both orthogonal directions. All original connections are riveted. The original foundation system is mixed and consists of a 4.8 m deep box foundation over point-bearing piles. The original structure was later modified by adding three stories with elements similar to the original sections for stories eight to ten. At the time of the 1985 Michoacán earthquake, the structure consisted of thirteen stories and a total height of 44 m. The structure under these conditions experienced moderate structural damage during the earthquake, due to its flexibility and torsional response. Because of the poor performance during the 1985 Michoacán earthquake, the building was retrofitted in 1990 by removing the three-story addition and by adding stiff "macro" braced frames (MBF) as depicted in plan and in elevation in Fig. 2.

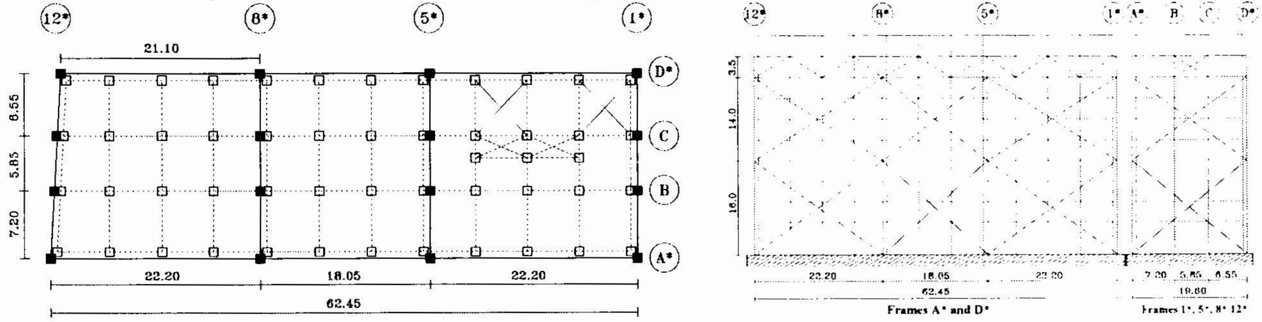

Figure 2. Plan and elevation for AE2 building (dimensions in meters)

The seismic evaluation of the original structure (ORIG), the building in its condition at the time of the 1985 Michoacán earthquake (APEN), the existing retrofit with MBF (MACRO) and an alternate retrofit plan with Added Damping and Stiffness (ADAS) energy dissipation devices have been subject of detailed studies which are summarized in Tena-Colunga and Vergara (1997). The artificial N-S accelerogram for the Alameda Park site (ALAM-NS) for a M_s=8.1 earthquake and its associated response spectrum for 2% viscous damping used in that study is depicted in Fig. 3.

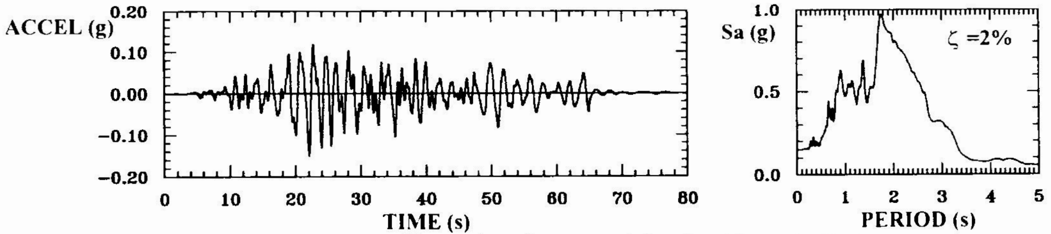

Figure 3. Artificial ALAM-NS acceleration record for the Alameda Park Site

For this building, it will be only shown what could be concluded from DDDS computed for the ALAM-NS record for a 2% viscous damping to evaluate the global response of the two retrofit models (MACRO and ADAS) in the N-S direction, assuming that the lateral load capacity of each models was computed from limit analyses, the elastic dynamic characteristics were defined from 3-D frequency analyses (Tena-Colunga and Vergara 1997) and that the ductility capacity could be assessed from visual inspections of the building and our own engineering knowledge and experience. The computed DDDS are depicted in Fig. 4 for the retrofit models (MACRO and ADAS). Two hysteretic models have been considered in the study, an elastic-perfectly-plastic model (ELP) and the Ramberg-Osgood model (ROS). The lateral base shear capacities computed from limit analyses in the N-S direction were V/W=0.352 (MACRO model) and V/W=0.191 (ADAS model), where W is the weight of each model. The dynamic characteristics of each model are presented in detail elsewhere (Tena-Colunga and Vergara 1997), but the natural periods in the N-S direction for the MACRO (T=0.90s) and ADAS (T=1.19s) models are depicted with broken vertical lines in Fig. 4.

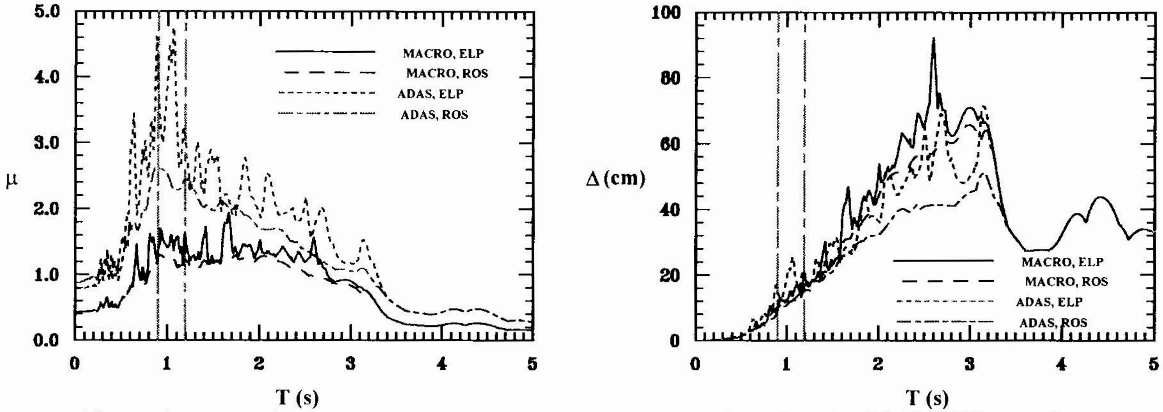

Figure 4. DDDS for the retrofit models of AE2 building subjected to the ALAM-NS record.

If one studies the expected nonlinear dynamic behavior with the DDDS for the existing retrofit using macro braced frames (MACRO model, Fig. 4), then, it can be concluded that the substantial increment in the lateral stiffness (the natural period for the unretrofit structure was 2.64s) and strength (strength of the unretrofit structure was V/W=0.074) is beneficial to improve the overall seismic behavior of AE2 building, as the building is led to reduced ductility and deformation demands, with a small nonlinear action. The predicted global response with the DDDS correlates well with the results obtained from a nonlinear dynamic analysis of representative frames; however, the DDDS does not show a potential problem that can occur with the MBF retrofit, as the nonlinear action is due primarily by column yielding and dynamic brace buckling (Tena-Colunga and Vergara 1997), effects that can only be observed using more detailed nonlinear dynamic analyses. If the alternate retrofit plan is evaluated using the DDDS (ADAS model, Fig. 4), it can be concluded that the ADAS retrofit is also a suitable solution, but that this solution leads to higher displacement and displacement ductility demands with respect to the MACRO retrofit.

If the results of the DDDS presented in Fig. 4 are compared with those computed from nonlinear dynamic analyses of representative frames presented in Tena-Colunga and Vergara (1997), the following observations can be done: (1) Certainly, the story displacement ductility demands for the ADAS retrofit are higher than for the MACRO retrofit; however, the ductility demands for the ADAS model are associated almost exclusively to the yielding of the ADAS energy dissipation devices, whereas in the MACRO retrofit the ductility demands are associated to column yielding and brace buckling. These yielding mapping cannot be deducted with the DDDS alone, (2) Although the story drift angles are slightly higher for the ADAS retrofit than for the MACRO retrofit for most stories, the peak story drift angle occurs for the MACRO retrofit, (3) The peak story displacement ductility demand for the ADAS retrofit (μ=3.8, not shown) is underestimated using a DDDS with an ELP model (μ=3.19, Fig. 4) and substantially underestimated using a ROS model (μ=2.44, Fig. 4). In addition, the DDDS cannot evaluate that the ADAS devices work in the desired ranges of deformation, (4) The shape of the global hysteresis curves associated to the DDDS differ from those obtained using representative frames, where singularities associated to the distribution of structural members affect the shape of the hysteresis curves, particularly for the MACRO retrofit model (see Tena-Colunga and Vergara 1997), (5) The DDDS do not show that the ADAS retrofit leads to lower shear and axial forces at the base than the MACRO retrofit.

Therefore, it can be concluded that the DDDS are useful to estimate with, an acceptable level of approximation, peak displacement ductility demands and lateral displacements of complex structural models such as the ADAS and MACRO retrofits; however, one cannot infer the details of how the nonlinear action takes place and, sometimes, these details can be very important. Thus, if one takes a decision for a given structural system based exclusively on the results of a DDDS, then, there is a risk that this decision might not be the best from the structural viewpoint.

CONCLUDING REMARKS

One of the major concerns in the structural engineering practice is to assess the nonlinear response of new or existing structures for moderate or strong earthquake motions in a simple way. This could be done using displacement ductility demand spectra (DDDS). A DDDS relates peak displacements and displacement ductility demands with structural periods of nonlinear SDOF systems with given yield strengths. The main difference between DDDS and traditional constant ductility response spectra (CDRS) is that the strength is fixed rather than the displacement ductility. This variation offers several advantages for the seismic evaluation of existing structures as explained in this paper.

The use of DDDS could be potentially useful for the seismic evaluation of existing structures as one could: (a) assess the vulnerability of structural systems to different earthquake scenarios in a simple fashion and, (b) study retrofit design strategies that would lead to good solutions for a particular structure before conducting detailed studies. The DDDS involves strength concepts in a consistent way and, in that fashion, it offers several advantages from some old seismic evaluation strategies that were done in the past. For space constraints, the concept of a DDDS and one sample seismic evaluation of an existing structure was presented, but more examples are already available (i.e., Tena 1997). The case study presented herein allows one to conclude that the DDDS are very useful to obtain reasonable estimates of peak displacement ductility demands and lateral displacements of structural systems where one can assess, with some precision, their lateral strength, natural periods (or range of periods) and hysteretic characteristics. If these can be done, one can evaluate the implications of uncertainties in the estimate of strengths, stiffnesses, hysteretic characteristics and those of the ground motions in the global response of structures, and relate these responses with the seismic detailing of structures. Nevertheless, the DDDS do not allow one to visualize the details of the nonlinear response of the structure and often, these details can be very important, particularly for complex structures or structural systems, so one should not rely on the use of a DDDS alone for the seismic evaluation of an existing structure. In fact, the DDDS should be regarded as an additional tool in the seismic evaluation of existing structures that could lead us to good solutions based upon our engineering background, judgment and ethical conduct. With the DDDS, one can decide when more complex nonlinear analyses should be done and when this is not necessary, for example, when elastic responses are detected with the DDDS. For the latter case, one can use, depending on the complexity of the structure, suitable elastic models with confidence.

ACKNOWLEDGEMENTS

This research was carried out at Centro de Investigación Sísmica, México City, when the author was serving as the Coordinator of the Structural Research Program.

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