Pushover Analysis of Masonry Infilled Reinforced Concrete Frames for Performance Based Design for Near Field Earthquakes

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***Abstract*—**Non-linear dynamic time history analysis is considered as the most advanced and comprehensive analytical method for evaluating the seismic response and performance of multi-degree-of-freedom building structures under the influence of earthquake ground motions. However, effective and accurate application of the method requires the implementation of advanced hysteretic constitutive models of the various structural components including masonry infill panels. Sophisticated computational research tools that incorporate realistic hysteresis models for non-linear dynamic time-history analysis are not popular among the professional engineers as they are not only difficult to access but also complex and time-consuming to use. In addition, commercial computer programs for structural analysis and design that are acceptable to practicing engineers do not generally integrate advanced hysteretic models which can accurately simulate the hysteresis behavior of structural elements with a realistic representation of strength degradation, stiffness deterioration, energy dissipation and 'pinching' under cyclic load reversals in the inelastic range of behavior. In this scenario, push-over or non-linear static analysis methods have gained significant popularity, as they can be employed to assess the seismic performance of building structures while avoiding the complexities and difficulties associated with non-linear dynamic time-history analysis. "Push-over" or non-linear static analysis offers a practical and efficient alternative to non-linear dynamic time-history analysis for rationally evaluating the seismic demands. The present paper is based on the analytical investigation of the effect of distribution of masonry infill panels over the elevation of planar masonry infilled reinforced concrete [R/C] frames on the seismic demands using the capacity spectrum procedures implementing nonlinear static analysis [pushover analysis] in conjunction with the response spectrum concept. An important objective of the present study is to numerically evaluate the adequacy of the capacity spectrum method using pushover analysis for performance based design of masonry infilled R/C frames for near-field earthquake ground motions.

***Keywords*—**Nonlinear analysis, capacity spectrum method, response spectrum, seismic demand, near-field earthquakes.

I. Introduction

PERFORMANCE based seismic engineering has emerged as the new paradigm in the earthquake resistant design of structures. Earthquake engineering experts believe that performance based design [PBD] principles and procedures [1] will be at the core of the new generation of standard codes of practice for earthquake resistant design of structures. The textbook edited by [1] refers to several completed and on-going research efforts to develop and embody PBD methodologies [2]-[4]. However, each of these documents [2]-[4] was prepared with limited objectives. One of the documents [3] is applicable to new steel moment resisting frames only. The other two documents [2], [4] provide guidelines for performance-based evaluation and retrofit of existing buildings; the former is limited to the performance based evaluation of existing reinforced concrete [R/C] buildings. The latter document, [4], considers all types of buildings and it is, therefore, referred to as a pre-standard that resembles the model of a PBD code. The document, however, does not allude to masonry infilled R / C frames.

Limited number of research studies have been reported in the literature on the performance based seismic engineering [PBSE] of building structures [5], [6]. A few research studies on PBSE documented in the literature have concentrated on performance-based design of building structures with structural control schemes [7], [8]. A comprehensive literature review on PBSE of building structures till 2007 is reported by [9]. However, none of the reported studies treat masonry infilled R/C frames. [10] implemented various available performance based seismic evaluation procedures including non-linear dynamic time-history analysis for simulating the observed seismic performance of typical samples of R/C buildings that were moderately damaged during the past earthquakes in Turkey. The results of the study indicated that the non-linear static analysis procedure is as effective as the non-linear dynamic analysis procedure for predicting the observed seismic performance of damaged buildings. The scope of the case studies and their results reported by [10] is limited to design level earthquakes corresponding to medium hazard level with a mean return period of 475 years. However, the structural contribution of the masonry infill panels was accounted in the non-linear analysis by modelling the infills as equivalent diagonal truss elements with the elastic-plastic constitutive rule that is not realistic for masonry. Moreover, the capacity spectrum method using non-linear static analysis [pushover analysis] utilized an elastic design spectrum for representing the demand curve of the earthquakes. Further, the study did not offer any quantitative conclusions on the influence of the distribution of masonry infill panels on the seismic performance of the buildings.

The Northridge [1994] earthquake was perhaps the first significant seismic event wherein the source or fault of the earthquake was directly beneath an urban area. Near-field region is the area within a radius of a several kilometers from the surface projection of the fault rupture. The ground motions

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in the near-field regions of earthquakes are termed as near-field ground motions, also referred to as the near-fault or near-source earthquake ground motions. Considering the extent and characteristics of the reported damage to civil engineering structures in the recent Northridge [1994] and Kobe [1995] earthquakes, researchers have since focused on investigating the typical characteristics of such near-source earthquakes that differentiate them from the earlier far-field earthquakes. The ground motion due to a near field earthquake is characterized by high peak acceleration with a long period velocity pulse and a large displacement. The extensive seismic damage observed in civil engineering structures during the recent near-field earthquakes such as the Northridge [1994], Kobe [1995], Chi-chi [Taiwan, 1999] and Turkey [Izmit, 1999] earthquakes has renewed the interest of the research community in the dynamic response of structures peculiar to near-field earthquake ground motions [11]. Documented seismic events in the historical past suggest that the building structures located near the fault rupture can suffer extensive damage even for moderate earthquakes [12], [13].

II. Background

A. Performance Based Seismic Design

Based on the concepts and procedures outlined in the various documents that lay the foundation of performance based design [PBD] in earthquake engineering [2]-[4], the salient common components of typical performance based methodologies may be summarized by the following six tasks:

- Task 1 Specification of a performance objective that characterizes both the seismic hazard level at the building site and the target performance level of the building structure,
- Task 2 Selection of a trial design,
- Task 3 Development of a mathematical model of the building in which all the structural and non-structural components that influence the stiffness, strength and mass of the building are realistically represented especially in the non-linear range of behaviour,
- Task 4 Analysis of the mathematical model of the trial design to determine the non-linear seismic response of the structure under the action of earthquake loads defined by the seismic hazard at the building site. The analysis may be static, quasi-static or dynamic depending on the simplicity and accuracy that is required in seismic evaluation.
- Task 5 Determination of the seismic demands on the trial design of the structure and structural elements,
- Task 6 Assessments of the seismic performance of the structure at the global and element levels to ascertain that the performance objective specified in task 1 mentioned above has been achieved. If the performance objective is not satisfied, the design is revised and tasks 3 to 5 are repeated.

The research presented in the paper addresses the Tasks 4 and 5 mentioned above.

B. Relevance of Push-Over Analysis

A fundamental objective in performance based seismic evaluation of building structures is the prediction of displacement demand imposed by the earthquake on the structure both at global and elemental levels, since the seismic damage is directly correlated to the displacement [deformation] of the structure or structural element. The displacement demand is of particular interest from the standpoint of Performance Based Design [PBD], an emerging paradigm for the next generation of standard codes of practice for earthquake resistant design [seismic design codes]. In this context, the generic analysis procedures that lend themselves to seismic evaluation within a performance based framework may be broadly classified into four categories depending on the assumption of linear elastic or non-linear structural response due to static or dynamic application of earthquake loads on the structure. Although some of the performance based seismic evaluation methods suggest the application of linear elastic procedures for estimating the seismic demands, it is debatable that the use of an over-simplified procedure in an otherwise rational and comprehensive process of performance based design [PBD] may defeat the very purpose of the PBD philosophy. Moreover, since the original rationale for departure from the traditional seismic design practice was to abandon linear elastic force based design methods and adopt inelastic displacement based methods, the present research utilizes only non-linear analysis methods that account for material non-linearity.

Pushover analysis, also known as collapse analysis, is a non-linear quasi-static monotonic lateral force-displacement analysis in which the mathematical model of the multi-degree-of-freedom structure is subjected to a distribution of incrementally increasing lateral forces until the stability limit of the structure is reached. The pushover analysis can establish the capacity curve [pushover curve] of the structure i.e. the path taken to reach the strength and ductility capacities of the structure including the sequence of cracking, yielding and failure of components. A class of equivalent static analysis procedures that employ the pushover analysis in conjunction with the inelastic response spectrum concept for predicting the seismic demands has come to be known as the capacity spectrum method [14].

III. Capacity Spectrum Method

A capacity spectrum is a transformed version of the capacity curve obtained from a pushover analysis of the building structure. A capacity curve [pushover curve] is a plot of the lateral load-deflection response of the building structure in terms of the horizontal seismic base shear force and top displacement of the building. In the capacity spectrum method [CSM], lateral forces and corresponding displacements in the pushover response are converted into spectral accelerations and spectral displacements using transformations based on fundamentals of structural dynamics [2]. The resulting form of the converted capacity curve is traditionally termed as acceleration-displacement response spectrum [ADRS] format of the capacity or pushover curve. The ADRS form of the capacity curve [pushover] is then superimposed on the inelastic response spectrum in the ADRS format, which represents the demand curve, to estimate the seismic demands.

A. Transformation of Capacity Curve into ADRS Format

The response spectrum concept is based on the dynamic response of a single degree-of-freedom [s.d.o.f.] system while R/C framed buildings are multi degree-of-freedom [m.d.o.f.] structures. Therefore, the capacity curve obtained from the pushover analysis of m.d.o.f. masonry infilled R/C framed structures needs to be modified for an equivalent s.d.o.f. system for conversion to the Acceleration-Displacement Response Spectrum [ADRS] form. The following transformations are required for recasting the capacity curve of a masonry infilled R/C frame determined from pushover analysis into the ADRS form:

$$S_{a,n} = \alpha_n \left(\frac{V_n}{W} \right) \quad (1)$$

where,

$$\alpha_n = \frac{\sum_{i=1}^{N} w_i \phi_{i,n}^{\ 2}}{\left(\sum_{i=1}^{N} w_i \phi_{i,n} \right)^2} \quad (2)$$

where $S_{a,n}$ is the spectral acceleration for mode n, V_n is the base shear for mode n, W is the seismic weight of the building, w_i is the seismic weight of the floor at level i, $\phi_{i,n}$ is the modal amplitude at the level I for mode n, and $S_{d,n}$ is the spectral displacement for mode n and $\Delta_{c,n}, \phi_{c,n}$ are the displacement and modal amplitude of control node for mode n.

$$S_{d,n} = \left(\frac{1}{\beta_n} \right) \left(\frac{\Delta_{c,n}}{\phi_{c,n}} \right) \quad (3)$$

where,

$$\beta_n = \frac{\sum_{i=1}^{N} w_i \phi_{i,n}}{\sum_{i=1}^{N} w_i \phi_{i,n}^{\ 2}} \quad (4)$$

B. Seismic Demands Based On Inelastic Response Spectrum

The inelastic response spectrum in ADRS format represents the demand side of the equation and is generated by performing the non-linear dynamic time-history analyses of an inelastic single degree-of-freedom [s.d.o.f.] oscillator with a range of natural time periods for earthquake ground motions that characterize the seismic hazard in the region. The non-linear dynamic time-history analysis of the s.d.o.f. oscillator is performed by step-by-step integration of the equations of motion using the Newmark-Beta method assuming a linear variation of acceleration within the time step. The rate independent smooth hysteretic model proposed by [15] was used to represent the inelastic spring element in the single degree-of-freedom [s.d.o.f.] mass-spring-dashpot oscillator. A damping ratio of 5 percent corresponding to natural damping of reinforced concrete was assumed for the dashpot element.

The spectral response of the hysteretic damped s.d.o.f. system is obtained for a specified ratio of the post-yielding stiffness K_y to initial elastic stiffness K_e for a range of natural time periods T. A plot of spectral accelerations versus the spectral displacements over the range of time periods in the spectrum is termed as the inelastic response spectrum in of the earthquake in ADRS format. The inelastic response spectrum in ADRS format or the demand curve of the earthquake is obtained for different values of response reduction or force reduction factor R, defined as the ratio of the elastic strength demand V_e of the earthquake to the yield strength V_y capacity of the system. A common practice in performance based seismic evaluation of building structures is to express the spectral accelerations and displacements in non-dimensional terms by normalizing the spectral accelerations with respect to acceleration due to gravity g and the spectral displacements with respect to the height of the building. The point where the demand curve corresponding to the actual value for force reduction factor R intersects the capacity curve of masonry infilled R/C frame in ADRS format is termed as the performance point of the infilled frame. The non-dimensional spectral displacement and acceleration corresponding to the performance point represent the non-dimensional structural displacement and base shear demands, respectively.

C. Methodology for Push-Over Analysis

The pushover analysis of masonry infilled R/C frames was performed using rational and realistic computational models in the present study. The pushover analysis is performed in steps for an incrementally increasing inverted triangular distribution of lateral story by increasing the distribution of lateral story forces by a constant user-specified increment at each step. The structural equilibrium equations are set up in an incremental form at each step and are thus solved to obtain the incremental displacements due to the increments in the lateral story forces for the step. The masonry infill panel is modeled in the analysis as a macro-element with a smooth strength envelope [15] that governs the relationship between the lateral force and displacement in the infill panel element. The influence of the masonry infill panels on the structural response is considered in the pushover analysis using the pseudo-force formulation by treating the lateral force in the infill panel element as a pseudo-force in the load vector of the equilibrium equations.

IV. Simulated Case Studies

Pushover analyses were performed for two planar multi-bay multi-story R/C frames shown in Figs. 1 (a) and (b) each with three different representative distributions of masonry infill panels [i] Bare frame with no masonry infills, [ii] Completely infilled frame, [iii] Infilled frame without any infill panels in the first or ground story [soft ground story], and [iv] Infilled frame with partially infilled ground story. The primary objective of the pushover analyses was to estimate the seismic demands of recorded near-field earthquake ground motions using capacity spectrum method and compare the results with those obtained from nonlinear dynamic analyses of the corresponding cases. Four near-field earthquake ground motions were considered for this purpose. i.e. Tabas [1978], Northridge [1994], Chi-chi [1999] and Erzincan [1992] earthquakes . For sake of brevity, the results for only two of the near-field earthquake ground motions considered in the research study are presented as follows.

A. Results of Case Studies

Figs. 2 and 3 display the capacity and demand curves each in ADRS format determined for two frame geometries respectively, with the above-mentioned representative distributions of masonry infill panels for only two of the near-field earthquake ground motions i.e. Tabas [1978] and Northridge [1994] earthquakes. In Figs. 2 and 3, the non-dimensional spectral displacements are plotted in terms of percentage along the x axis while the non-dimensional spectral accelerations are plotted in percentage terms along the y axis. Thus, the abscissa of the plot represents the non-dimensional structural displacements while the ordinate represents the non-dimensional structural base shear of the building structure [each in terms of percentage] on the capacity side of the equation. Figs. 2 and 3 also highlight the performance points signifying the non-dimensional structural displacement demands and base shear demands [each in percentage terms circumscribed by ellipses in the plot] of the near-field earthquakes on the frame geometries for the various considered distributions of the masonry infill panels over the frame elevation. It may be noted that the structural displacement demand at the roof level is expressed as a percentage of the total height of the building structure while the base shear demand is expressed as a percentage of the total weight of the building.

B. Interpretation of Results of Case Studies

The non-dimensional structural displacement and base shear demands of the near-field earthquakes on the two planar frames [Figs. 1 (a) and (b)] that were evaluated from the non-linear dynamic analysis are reproduced in percentage terms [enclosed in rectangles] in Figs. 2 and 3 for comparison with the corresponding seismic demands predicted by the capacity spectrum method [circumscribed by ellipses]. A brief inspection of the values indicates that the seismic demands predicted by the capacity spectrum method for the near-field earthquakes considered in the study agree reasonably well [within 10-25%] with those determined from non-linear dynamic analysis by and large for most cases. A striking case in exception is the bare frame for which the capacity spectrum method significantly underestimates the seismic demands of near-field earthquakes in comparison to the seismic demands determined by non-linear dynamic analysis. The discrepancies may be explained by the fact that the ground motion due to a near field earthquake is characterized by distinctively large long period velocity pulses due to the directivity of the fault rupture with respect to the earthquake site and a large displacement due to the ‘fling’ effect related to permanent tectonic deformation at the site. As a result, high-rise flexible framed buildings with long natural time periods will be subjected to larger seismic demands under the influence of near-field ground motions, a dynamic phenomenon that cannot be accounted for by the non-linear quasi-static pushover analysis.

V. Concluding Remarks

The capacity spectrum method using non-linear static analysis i.e. pushover analysis is a simplified and rational technique for evaluating the seismic performance of multi degree-of-freedom building structures. The push-over analysis provides a middle path solution between the non-linear dynamic time-history analysis and linear static analysis in displacement based design that is at the core of the performance based design [PBD] philosophy, an emerging paradigm for the next generation of seismic codes. A key component of the PBD methodology is the prediction of the displacement demands imposed by an earthquake on the structure both at global and elemental levels, as seismic damage is directly correlated to the displacement [deformation] of the structure or structural element. The capacity spectrum method offers a simpler and computationally efficient alternative to non-linear dynamic time-history analysis of m.d.o.f. building structures for predicting the seismic demands of earthquakes that are representative of the seismic hazard at the building site. The application of the method requires only a non-linear monotonic quasi-static lateral load analysis [pushover analysis] of the building structure to determine the capacity curve [pushover curve], transformation of the pushover curve into the ADRS form using basic concepts of structural dynamics and non-linear dynamics analysis of s.d.o.f. inelastic oscillators to generate the inelastic ADRS.

The results of the case studies presented in the paper indicate that the capacity spectrum procedure using a non-linear pushover analysis is largely adequate for predicting the seismic demands of masonry infilled R/C frames subjected to near-field earthquake ground motions. However, it should be noted that in case of masonry infilled R/C frames with low lateral stiffness [due to a lesser number and sparse distribution of infill panels] or in the specific case of a bare R/C frame subjected to near-field earthquake ground motions, the capacity spectrum method employing pushover analysis underestimates the seismic demands. The limitation may be attributed to the low frequency velocity pulses in near-field ground motions that result in the dynamic amplification of seismic response in case of long period structural frames.

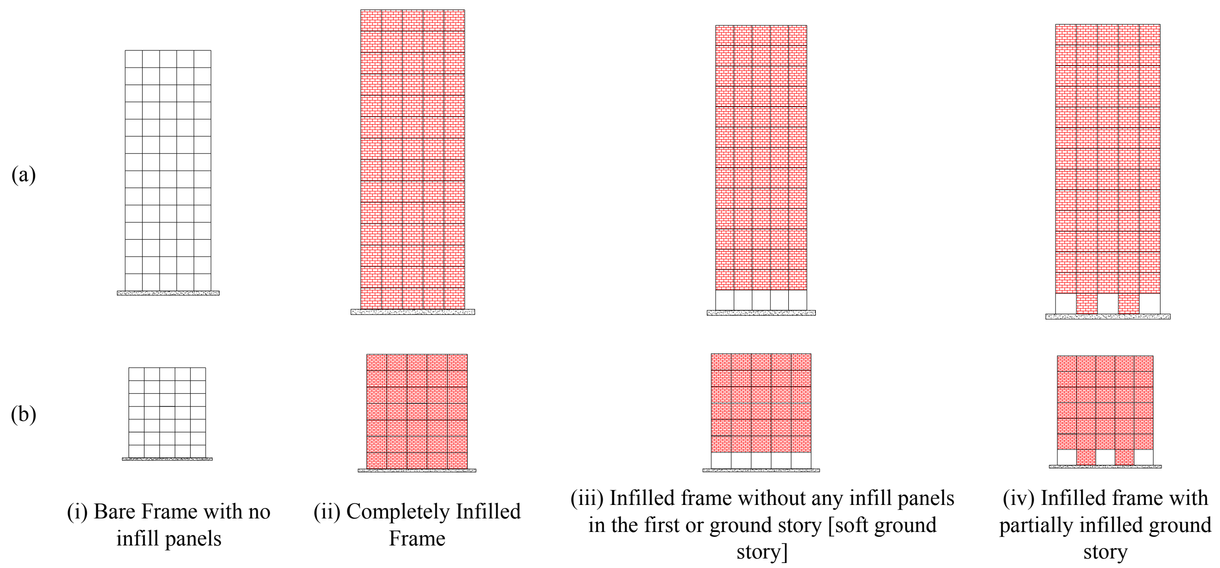
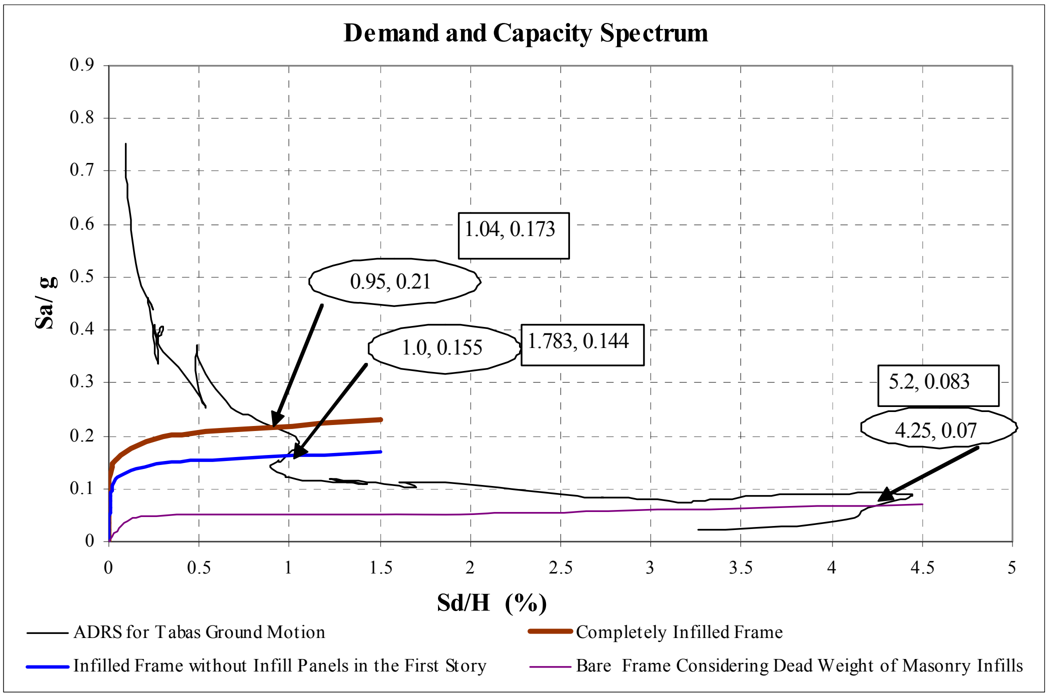
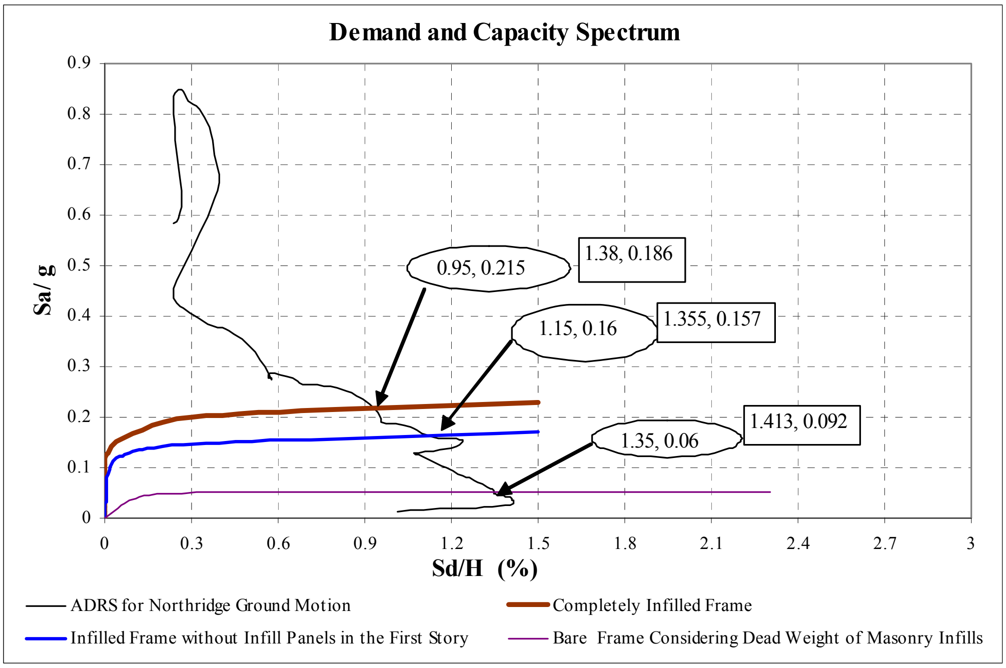


Fig. 1 Multistory multi-bay Planar Reinforced Concrete Frames with various representative distributions of Masonry Infill Panels over the Frame Elevation considered for Pushover Analysis

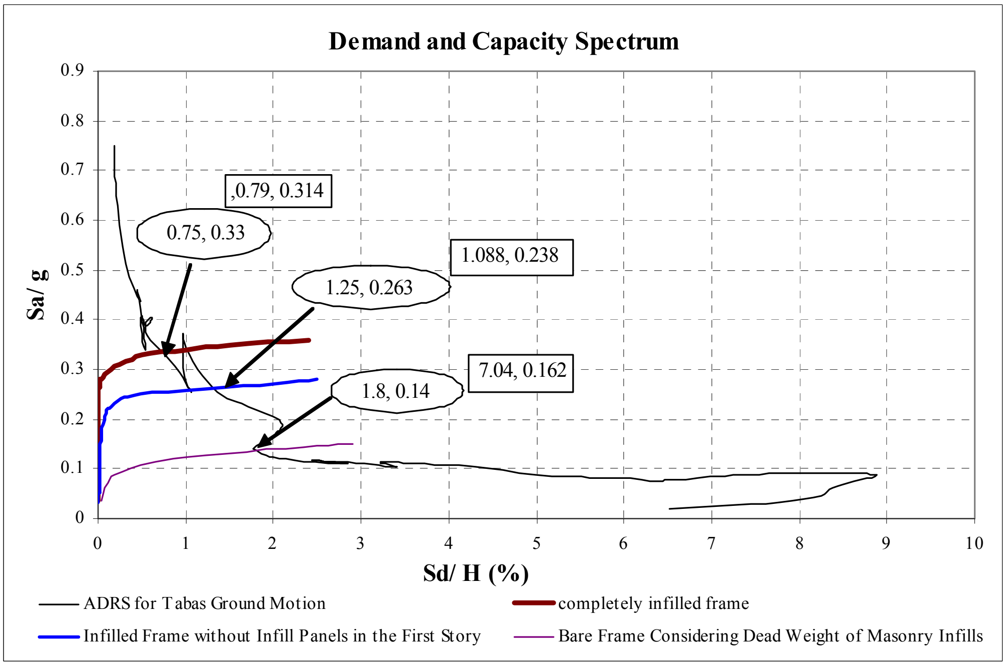


(a)

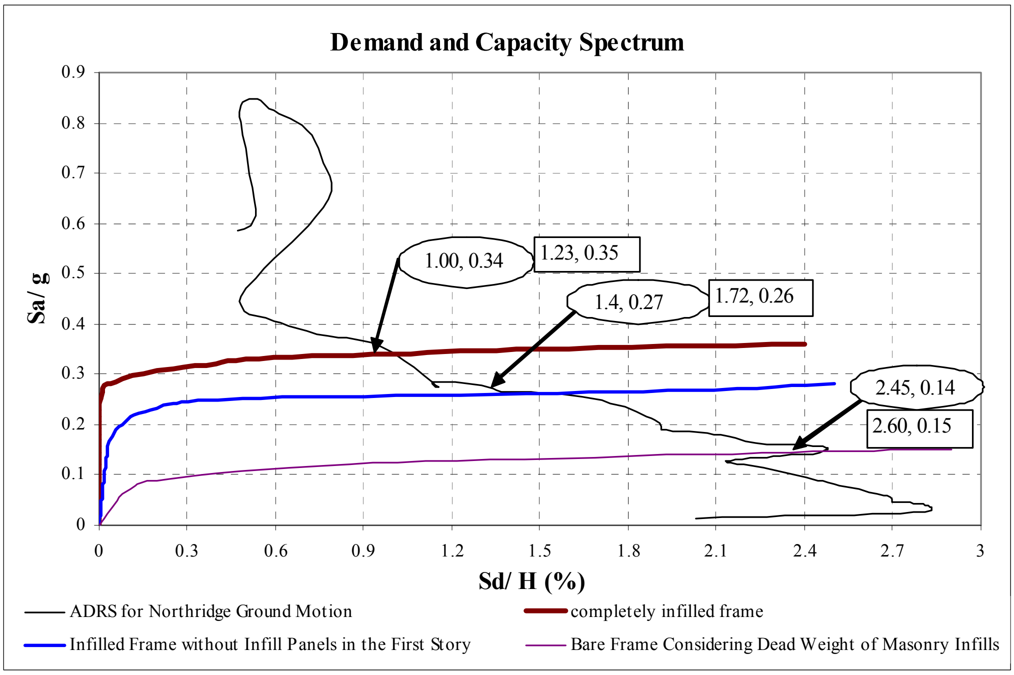


(b)

Fig. 2 Capacity and Demand Curves for (a) Tabas and (b) Northridge Earthquake both in ADRS format for Frame Geometry shown in Fig. 1 (a), S_a = Spectral Acceleration, g = Acceleration due to gravity, S_d = Spectral Displacement, H = Total Height of Building



(a)



(b)

Fig. 3 Capacity and Demand Curves for (a) Tabas and (b) Northridge Earthquake both in ADRS format for Frame Geometry shown in Fig. 1 (b), S_a = Spectral Acceleration, g = Acceleration due to gravity, S_d = Spectral Displacement, H = Total Height of Building

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