DEVELOPMENT OF A QUASI-STATIC LOADING PROTOCOL FOR DISPLACEMENT-SENSITIVE NONSTRUCTURAL BUILDING COMPONENTS

B. Shafei[1] and F. Zareian[2]

[1] *Graduate Student Researcher, Dept. of Civil and Environmental Engineering, University of California, Irvine (UCI), USA, Email: behrouz.shafei@uci.edu*
[2] *Assistant Professor, Dept. of Civil and Environmental Engineering, University of California, Irvine (UCI), USA, Email: zareian@uci.edu*

ABSTRACT:
Findings from both analytical and experimental research projects as well as observations of damage occurred by previous earthquakes indicate that the loading history has a significant influence on the induced damage in nonstructural components of buildings in seismic events. For the purpose of either designing new buildings or performance evaluation of existing ones, it is necessary to use appropriate loading protocols in experimental tests for developing accurate component damage fragility functions. The crucial concern here is to suggest loading protocols which could be representative of the actual demand imposed by a seismic event. Current quasi-static cyclic loading protocols have been mainly developed in part by statistical evaluation of seismic response data and in part by judgment. Hence, the need for statistically well-defined standardized protocols that outline the test procedure is clear. The main goal of the present research is to develop quasi-static loading protocols for displacement-sensitive nonstructural components. Developed quasi-static loading protocols help to predict the probable behavior of displacement-sensitive nonstructural components during an earthquake more accurately by considering the loading history characteristics of the seismic event, and as a result, optimize the cyclic testing results for both design procedures and loss estimation purposes.

KEYWORDS:
Quasi-static loading protocol, nonstructural component, statistical methods, cyclic testing, and seismic response

1. INTRODUCTION

Experimentation in earthquake engineering may have a variety of objectives and may utilize different testing techniques, ranging from field to laboratory experimentation, dynamic to quasi-static experimentation, and two- to three-dimensional experimentation (ATC-29 1992). The work presented in this paper is concerned with development of quasi-static loading protocol for experimentation of displacement-sensitive nonstructural components. “Quasi-static” implies that load or deformation cycles are imposed on a test specimen in a slow, controlled, and predetermined manner, and dynamic effects as well as rate of deformation effects are not considered (FEMA-461 2007). Cyclic tests are useful to provide basic information on nonstructural component behavior, including data on strength and stiffness characteristics, deformation capacities, cyclic hardening or softening effects, and deterioration behavior at large deformations.

Much experimental work on nonstructural components directed towards achieving a better understanding of their response to seismic excitations has been done in recent years. Most commonly, these experiments are performed with slow cyclic load application on nonstructural components. In these experiments, selection of loading histories has always been a critical issue. Hence, this has raised many questions in interpretation of experimental results, and has made a consistent assessment of seismic performance of nonstructural components a difficult task (Krawinkler et al. 2000).

The present work proposes quasi-static loading protocols for displacement-sensitive nonstructural components mounted on regular buildings. For this purpose, the deformation demands for displacement-sensitive nonstructural components supported on inelastic regular moment-resisting frame structures are statistically analyzed. The response of a variety of stiff and flexible frame structures with 4, 8, 12, and 16 stories subjected to a set of 40 ground motions are evaluated. The nonstructural components under consideration are those that can be represented by single-degree-of-freedom systems with masses that are small compared to the total mass of the supporting structure. This study evaluates and quantifies the dependence of the nonstructural component displacement time-history on parameters like the location of the nonstructural component in the structure, the period and damping ratio of the component, and also properties of the supporting structure such as its natural period and number of stories. The results are in accordance with the current quasi-static loading protocols suggested by FEMA-461, and show that these loading protocols can be improved specially by considering the dynamic characteristics of nonstructural components.

2. ANALYSIS METHODOLOGY

The methodology used in this study consists of performing dynamic simulations in which structural models (three-bay, two-dimensional frames) are exposed to ground motions whose frequency content does not exhibit near-fault, forward-directivity characteristics. These ground motions were recorded in stiff soils, i.e. NEHRP site class D, have a moment magnitude that varies from 6.5 to 6.9, and closest distances to the fault rupture area in the range of 13 to 30 km (Medina et al. 2006). Each record was scaled differently for each frame (Richards and Uang 2003). Scale factors were calculated to make the spectral acceleration of each record, with 5 percent damping, equal to the design spectral acceleration multiplied by 1.5 (equal to the Maximum Considered Earthquake) at the period of each frame. The 5 percent damping design spectra was obtained from IBC 2006, site class D, and is shown in Figure 1. For a given structural model and ground motion, the acceleration response at all floor levels was obtained, and used as input for the SDOF systems. The damping ratios, ξ, of interest for the nonstructural components are 2%, 5%, and 10%. Time-history analyses were performed using a modified version of DRAIN-2DX that incorporates structural components that undergo monotonic and cyclic deterioration (Ibarra and Krawinkler 2005).

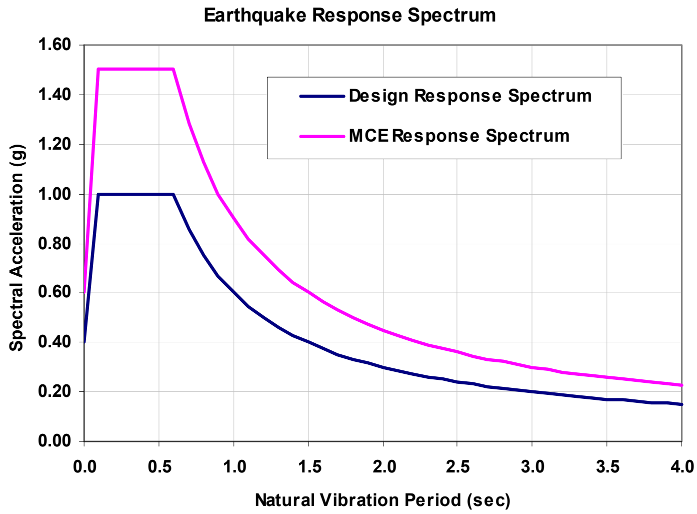

Figure 1: Response spectrum of design and maximum considered earthquake (MCE), IBC 2006 for site class D

3. BUILDING MODELS

The building models with 4, 8, 12, and 16 stories utilized in this study correspond to moment-resisting frame structures with the same mass at all floor levels. The family of frames consists of 3-bay frames with each bay span equal to 36ft. and story height of 12ft. Figure 2 shows a schematic representation of the moment resisting frames under consideration. Defining N as the number of stories, three variations for the first mode period, T, are considered for the generic frames: T = 0.10N (stiff frame), 0.15N, and 0.2N (flexible frame) with 5% Rayleigh damping assigned to the first and third mode of elastic range. All frames are designed for $R_\mu = 1.5$, and also the variation of story stiffness along the height of each frame is such that a straight line deflected shape is obtained when the frame is subjected to the NEHRP lateral load pattern. It is assumed that stiffness and strength of structural elements are proportional; therefore, variation of beam and column strength along the height of each frame is identical to variation of stiffness of the same elements along the height (Zareian and Krawinkler 2007).

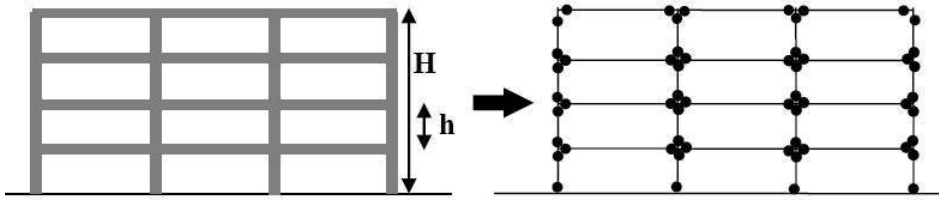

Figure 2: Schematic representation of moment-resisting frames under consideration (Zareian and Krawinkler 2007)

4. STRUCTURAL ANALYSIS AND CRITICAL STORY

Each of the models is analyzed using each of the 40 scaled ground motion records. Acceleration is calculated at each step of time-history analysis, and then, acceleration time-histories are generated for the floors in all 12 frames under all 40 ground motions. Figure 3 shows typical acceleration time-histories from different floors of the 4-story frame with the natural period of 0.60sec excited by the ground motion No.27 (randomly selected).

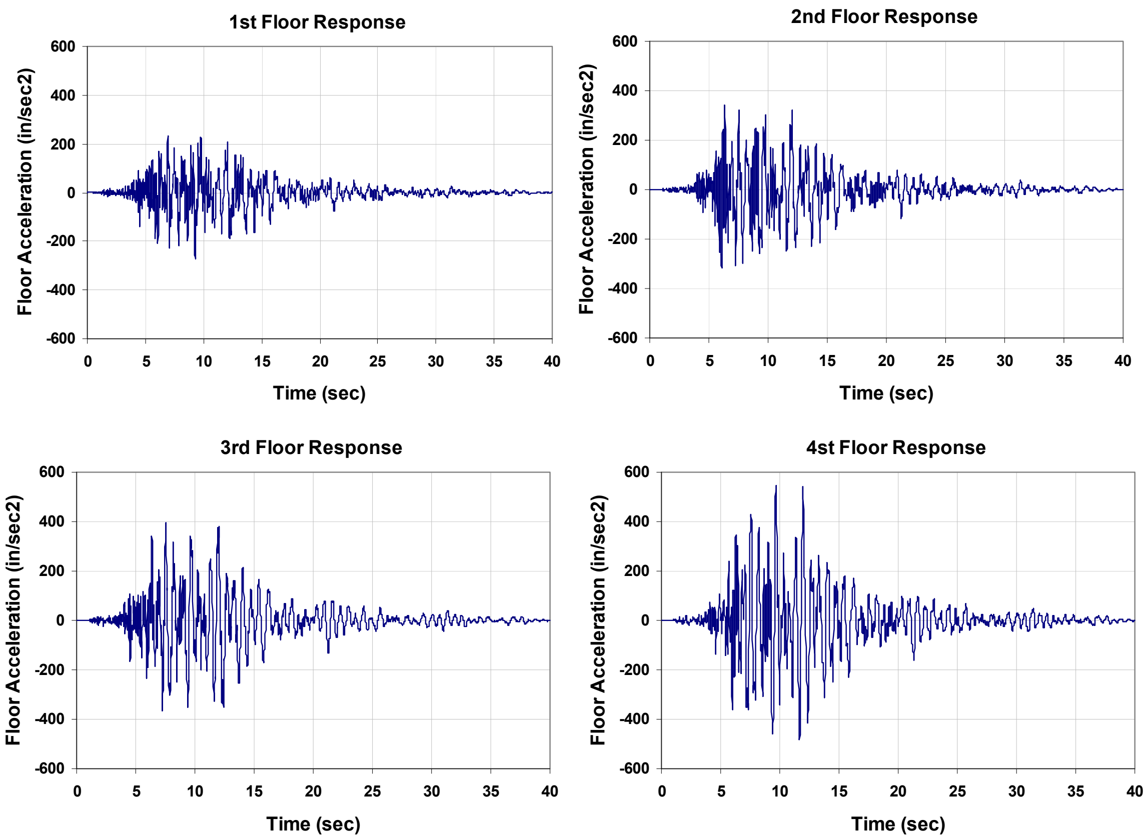

Figure 3: Acceleration time-histories for different floors of the 4-story frame with the period of 0.60sec excited by the ground motion No.27 (randomly selected)

In the development of the quasi-static loading protocol for nonstructural components, a "critical story" is identified from each structure, and loading protocol development will be based on data from the critical story. According to Krawinkler et al. (2000), critical story is a story which has the largest demand values. Comparing results from different floors of studied frames shows that the largest acceleration values in a specific frame can be seen at the top floor (as can be seen in Figure 3). Hence, for all studied frames, the top floor is assumed as the critical floor. The acceleration time-histories of critical floors are used as input for analysis of nonstructural components modeled as single-degree-of-freedom systems. It should be mentioned that although SDOF analyses are limited to those placed on critical floors, the final loading protocol can be used in other stories by some modifications.

5. ANALYSIS OF NONSTRUCTURAL COMPONENTS

In order to obtain the maximum demand on nonstructural components, it is assumed that nonstructural components are placed on the critical floors. 40 floor acceleration time-histories calculated for critical stories of 12 studied frames at the previous step were applied to elastic SDOF systems representing nonstructural components. Nonstructural components under consideration have three different periods, 0.02, 0.10, and 1.00sec (representing a range of rigid to flexible components), and also three different damping ratios, ξ, 2%, 5%, and 10%. Totally 9 different SDOF systems were analyzed, each using 480 acceleration time-histories obtained from critical stories. Displacement response of each of 9 SDOF systems were calculated at each time step using a FORTRAN code written based on the Newmark linear acceleration method (Chopra 2007). Figure 4 shows displacement time-histories of three SDOF systems with the periods of 0.02, 0.10, and 1.00sec and 5% damping ratio, all located on the critical story of the 4-story frame with the period of 0.6sec excited by the ground motion No.27 (randomly selected).

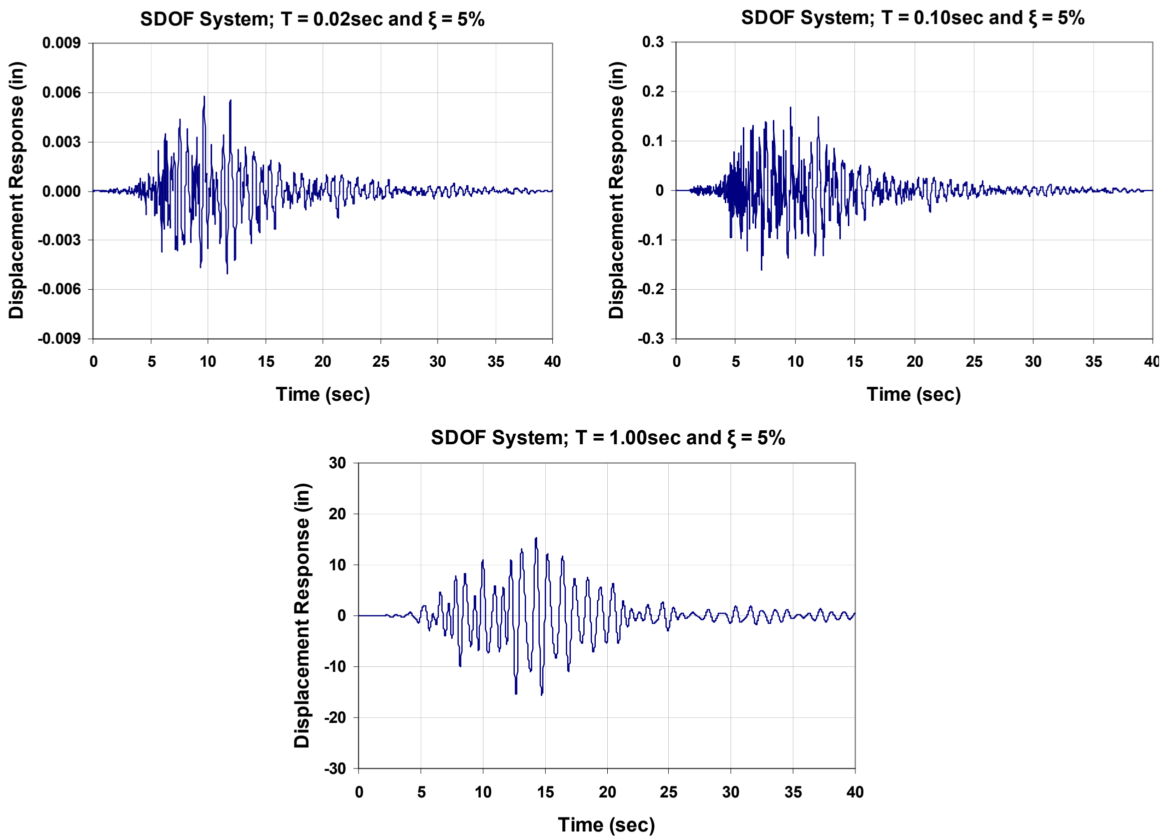

Figure 4: Displacement time-histories of three SDOF systems with the periods of 0.02, 0.10, and 1.00sec and damping ratio of 5%

6. RAINFLOW CYCLE COUNTING

Considering that real nonstructural components never experience constant amplitude displacements during an earthquake, some type of cycle counting scheme must be employed to reduce a complex irregular displacement time-history into a series of constant amplitude events. The rainflow counting method is one of the most efficient methods for this purpose, and defines cycles as closed hysteresis loops (Downing and Socie 1982). In the current research, because of the fact that the displacement time-histories obtained for different SDOF systems needed to be converted into series of cycles before using for loading protocol development, the rainflow cycle counting algorithm suggested by ASTM E 1049 was employed.

According to the ASTM algorithm, all of the peaks and valleys are identified first in the time history. Cycle counting starts at the beginning of time-history. Once a cycle is counted and recorded, the peak and valley associated with the cycle are not considered for further cycle counting purposes. A cycle is counted when the second range in a peak-valley-peak or valley-peak-valley combination is greater than the first range. The cycle counted is defined by the first peak-valley or valley-peak combination. The range of the cycle is the difference in displacement between the peak and valley. The mean value associated with the cycle is the average of the displacement values at the peak and valley associated with the cycles. Counting continues from left to right and starts again at the beginning when the end is reached. Counting continues until the entire history is exhausted. By means of a FORTRAN program, this algorithm was applied to all displacement time-histories of different nonstructural components, and then obtained results were arranged in an ascending order. Figure 5 shows arranged rainflow cycle counted displacement time-histories of the SDOF system shown in Figure 4.

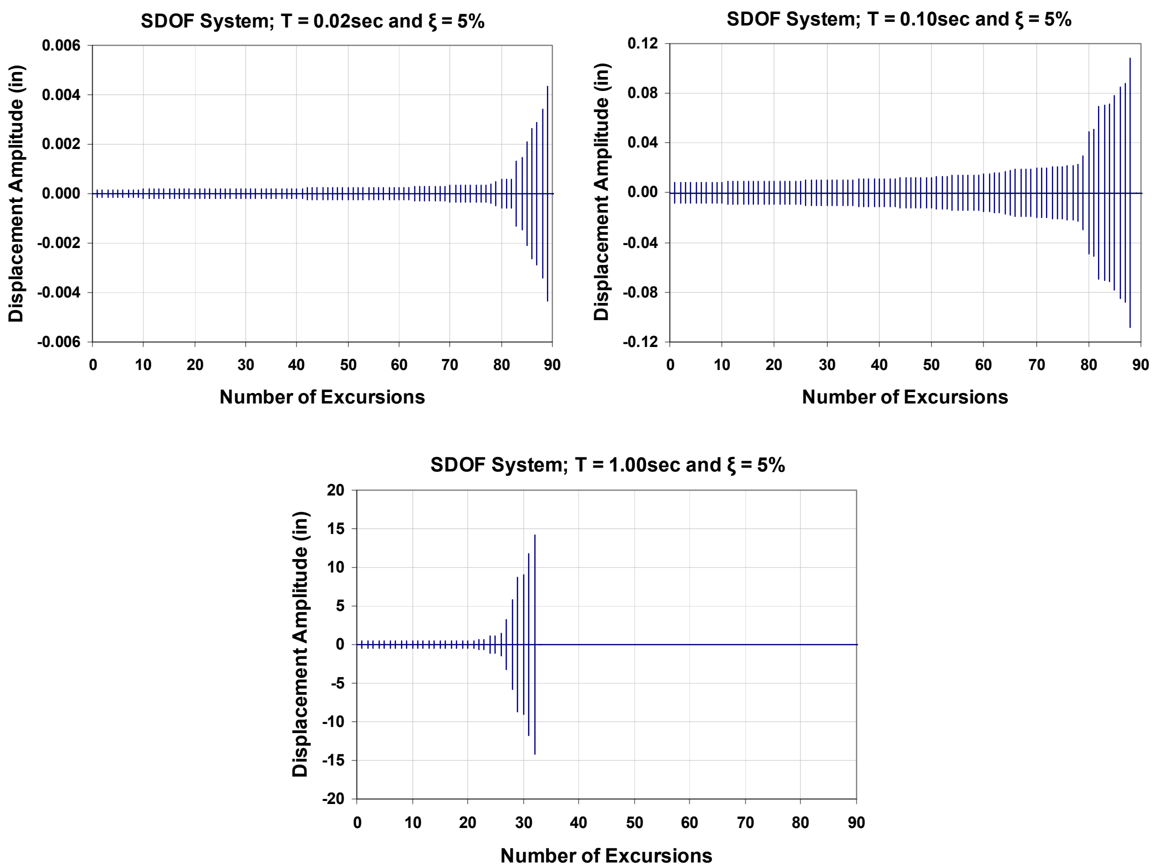

Figure 5: Arranged rainflow cycle counted displacement time-histories of three SDOF systems with the periods of 0.02, 0.10, and 1.00sec and damping ratio of 5%

7. STATISTICAL ANALYSIS AND DATA REDUCTION

Considering that for each SDOF system there are 480 displacement time-histories obtained from analyses of 12 different frames by 40 ground motions, it is required to use a statistical approach for data reduction. Hence, the median values of arranged rainflow cycle counted displacement time-histories are calculated for bins of 40 ground motions. By this approach, just one median rainflow cycle counted time-history can be introduced as the representative of all 40 displacement responses obtained from 40 floor accelerations for each of 9 different nonstructural components mounted on different 12 frames.

In the next step, median values obtained for each SDOF system placed on 12 different supporting frames can be combined together. For this purpose, the new median of these 12 median values are calculated. As a result, the obtained rainflow cycle counted displacement time-histories are independent of the supporting structure characteristics, and just depend on periods and damping ratios of SDOF systems. Figure 6 shows median of arranged rainflow cycle counted displacement time-histories of all 9 SDOF systems with the periods of 0.02, 0.1, and 1.0sec, and damping ratios of 2%, 5%, and 10%. It should be added that the displacement response values less than 5% of the maximum value have been filtered for the purpose of clarity. By reviewing the arranged rainflow cycle counted displacement time-histories for 9 different SDOF systems, it can be seen that for an SDOF with a specific period, the displacement responses do not change significantly by damping ratios especially for systems with smaller periods. As a result, it is possible here to propose the loading protocol just based on the period of the nonstructural component.

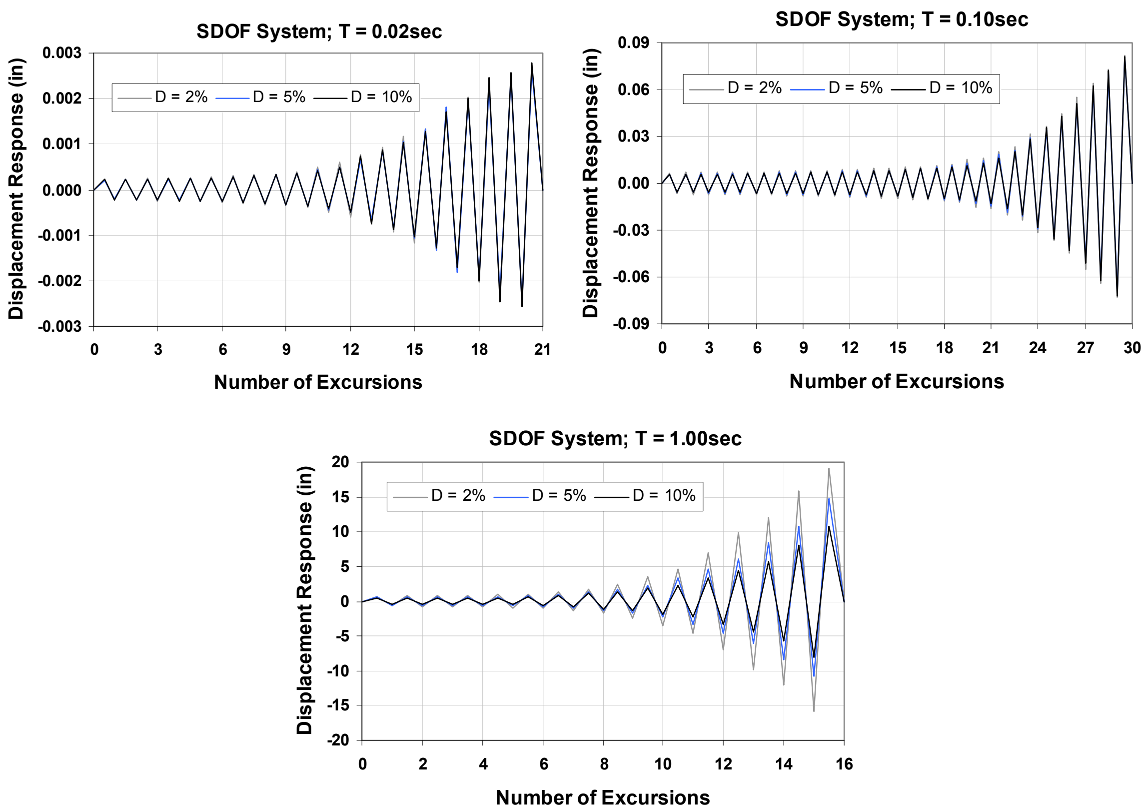

Figure 6: Median of arranged rainflow cycle counted displacement time-histories of all SDOF systems with the periods of 0.02, 0.10, and 1.00sec, and damping ratios of 2%, 5%, and 10%

8. PROPOSED QUASI-STATIC TESTING PROTOCOLS

The proposed testing protocols for nonstructural components are developed based on the demand values described in the previous sections. These protocols are for nonstructural components with different periods, and consist of repeated cycles of step-wise increasing displacement amplitudes. In these loading protocols, the targeted maximum displacement amplitude of the loading history is an estimated value of the imposed displacement at which the most severe damage level is expected to initiate. On the other hand, the targeted smallest displacement amplitude of the loading history must be safely smaller than the amplitude at which the lowest damage state is first observed. At the lowest damage state, it is recommended to execute few cycles before launching the main cycles (FEMA-461 2007). In this study, the targeted smallest displacement amplitude has been assumed equal to 10% of the maximum deformation amplitude. It should be also noted that cycles with the amplitudes less than 10% of the maximum value can cause negligible damage compared to larger cycles, and therefore have been omitted. Figure 7 shows proposed loading protocols normalized by their largest values. Normalization of the loading protocol helps the user to adjust the loading pattern according to the desirable maximum displacement amplitude.

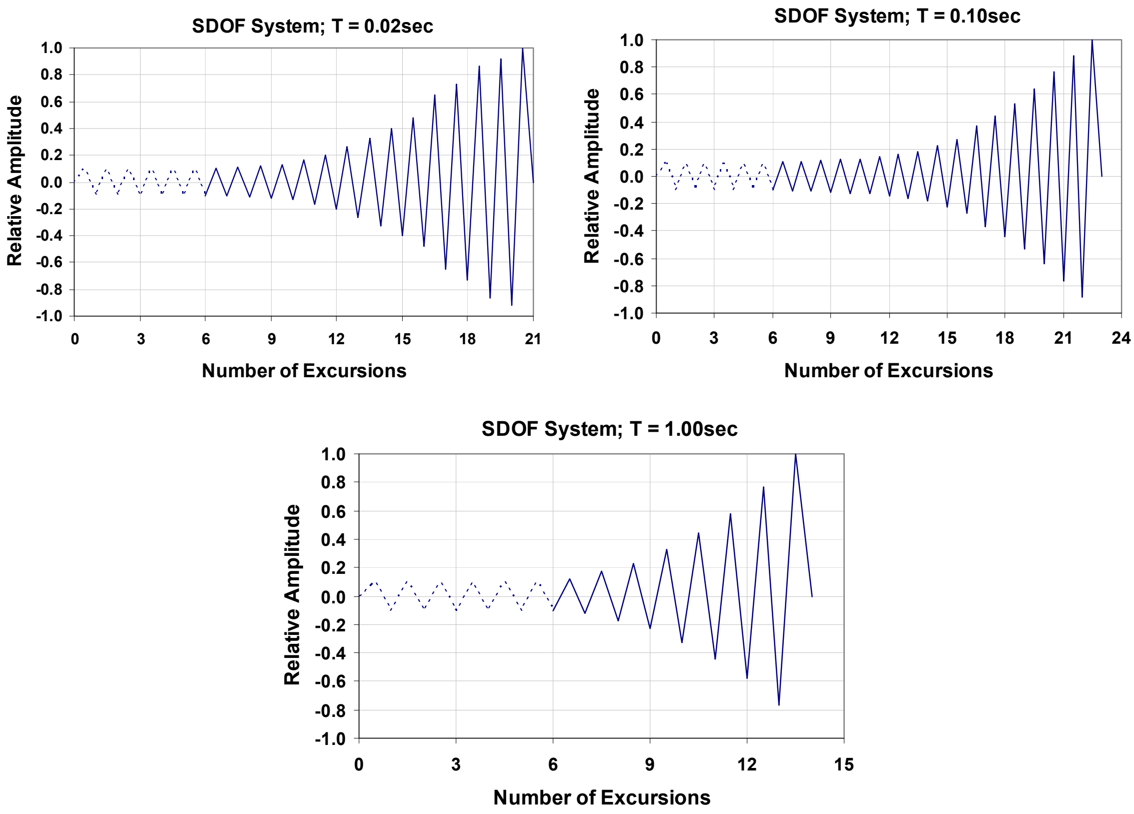

Figure 7: Proposed loading protocols normalized by their largest values

Comparison of the proposed and FEMA-461 loading protocols shows that the developed quasi-static loading protocols are in accordance with those suggested by FEMA-461. According to FEMA-461, the number of cycles is calculated based on the ratio of targeted maximum to targeted minimum displacement amplitudes. In this approach, the amplitude a_{i+1} of the step $i+1$ is then assumed to be equal to the amplitude of the preceding step, a_i, multiplied by a fixed number, 1.40. Calculations of this ratio for loading protocols developed in the current paper also approve this multiplication value especially for flexible nonstructural components.

Results obtained from the dynamic analysis of nonstructural components mounted on studied moment-resisting frames show that the loading protocols developed for nonstructural components are dependent on dynamic characteristics, including damping ratios and especially natural periods, of nonstructural components. Assuming the minimum targeted displacements equal to 10% of the maximum targeted displacements, multiplication values for the ratio of consecutive amplitudes in developed loading protocols are equal to 1.10, 1.15, and 1.35 for nonstructural components with the periods of 0.02, 0.1, and 1.0sec respectively. These values are almost close to the value suggested by FEMA-461, and also show the role of dynamic characteristics of nonstructural components in modifying the loading protocol demands.

9. CONCLUSIONS

The work presented in this paper proposed the quasi-static loading protocols for displacement-sensitive nonstructural components mounted on regular buildings. These protocols were developed by calculation of deformation demands on displacement-sensitive nonstructural components supported on inelastic regular moment-resisting frame structures. For this purpose, the seismic responses of a variety of stiff and flexible frame structures with a range of different stories subjected to a set of ground motions were evaluated. The acceleration time-histories in critical floors of studied frames were used as input for analysis of nonstructural components modeled as single-degree-of-freedom systems. Results obtained from dynamic analyses of SDOF systems were then rainflow cycle counted and finally proposed loading protocols were developed by employing statistical approaches. The loading protocols developed in this study are in accordance with the current quasi-static loading protocols suggested by FEMA-461, and shows that these loading protocols can be improved specially by considering the dynamic characteristics of nonstructural components.

ACKNOWLEDGEMENTS

This work was supported by the National Science Foundation award CMMI-0654409. Their support is gratefully acknowledged. Any opinions, findings and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect those of the National Science Foundation.

REFERENCES

American Society for Testing and Materials (2003) Standard Practices for Cycle Counting in Fatigue Analysis. Standard ASTM E 1049-85 (Reapproved 1997), West Conshohocken, PA.

Applied Technology Council (1992) Guidelines for Cyclic Seismic Testing of Components of Steel Structures. Report ATC-29, Redwood City, CA.

Chopra, A.K. (2007) Dynamics of Structures. 3rd Edition, Prentice-Hall, Inc.

Downing, S.D., Socie, D.F. (1982) Simple Rainflow Counting Algorithm. International Journal of Fatigue, 4(1) 31-40.

Federal Emergency Management Agency (2007) Interim Testing Protocols for Determining the Seismic Performance Characteristics of Structural and Nonstructural Components. FEMA Report 461, Washington.

Ibarra, L., Krawinkler, H. (2005) Global Collapse of Frame Structures under Seismic Excitations. PEER Report 2005/06, University of California, Berkeley, CA.

Krawinkler, H., Gupta, A., Medina, R., Luco, N. (2000) Loading Histories for Seismic Performance Testing of SMRF Components and Assemblies. SAC Steel Project, Report SAC/BD-00/10, Stanford, CA.

Medina, R., Sankaranarayanan, R., Kingston, K.M. (2006) Floor Response Spectra for Light Components Mounted on Regular Moment-Resisting Frame Structures. Journal of Engineering Structures, 28(14) 1927-1940.

Richards, P., Uang, C.M. (2003) Development of Testing Protocol for Short Links in Eccentrically Braced Frames. Report SSRP-2003/08, University of California, San Diego, CA.

Zareian, F., Krawinkler, H. (2007) Sensitivity of Collapse Potential of Buildings to Variations in Structural Systems and Structural Parameters. In: Proceedings of the 2007 Structures Congress, Long Beach, CA.