PACIFIC EARTHQUAKE ENGINEERING
RESEARCH CENTER

Development of Testing Protocol for Cripple Wall Components

A Report for the "Quantifying the Performance of Retrofit of Cripple Walls and Sill Anchorage in Single-Family Wood-Frame Buildings" Project

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PEER Report 2020/15
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ABSTRACT

This report is one of a series of reports documenting the methods and findings of a multi-year, multi-disciplinary project coordinated by the Pacific Earthquake Engineering Research Center (PEER) and funded by the California Earthquake Authority (CEA). The overall project is titled "*Quantifying the Performance of Retrofit of Cripple Walls and Sill Anchorage in Single-Family Wood-Frame Buildings*," henceforth referred to as the "PEER–CEA Project."

The overall objective of the PEER–CEA project is to provide scientifically-based information (e.g., testing, analysis, and resulting loss models) that measure and assess the effectiveness of seismic retrofit to reduce the risk of damage and associated losses (repair costs) of wood-frame houses with cripple wall and sill anchorage deficiencies as well as retrofitted conditions that address those deficiencies. Tasks that support and inform the loss-modeling effort are: (1) collecting and summarizing existing information and results of previous research on the performance of wood-frame houses; (2) identifying construction features to characterize alternative variants of wood-frame houses; (3) characterizing earthquake hazard and ground motions at representative sites in California; (4) developing cyclic loading protocols and conducting laboratory tests of cripple wall panels, wood-frame wall subassemblies, and sill anchorages to measure and document their response (strength and stiffness) under cyclic loading; and (5) the computer modeling, simulations, and the development of loss models as informed by a workshop with claims adjustors.

This report is a product of Working Group 3.2 and focuses on *Loading Protocol Development for Component Testing*. It presents the background, development process, and recommendations for a quasi-static loading protocol to be used for cyclic testing of cripple wall components of wood-frame structures. The recommended loading protocol was developed for component testing to support the development of experimentally informed analytical models for cripple wall components. These analytical models are utilized for the performance-based assessment of wood-frame structures in the context of the PEER–CEA Project.

The recommended loading protocol was developed using nonlinear dynamic analysis of representative multi-degree-of-freedom (MDOF) systems subjected to sets of single-component ground motions that varied in location and hazard level. Cumulative damage of the cripple wall components of the MDOF systems was investigated. The result is a testing protocol that captures the loading history that a cripple wall may experience in various seismic regions in California.

ACKNOWLEDGMENT AND DISCLAIMER

ACKNOWLEDGMENT

This research project benefited from the interaction of many researchers and practitioners. The author would like to thank the following project team members for their input and feedback: Yousef Bozorgnia, Henry Burton, Kelly Cobeen, Tara Hutchinson, Grace Kang, Bret Lizundia, Chia-Ming Uang, and Dave Welch.

DISCLAIMER

This research study was funded by the California Earthquake Authority (CEA). The support of the CEA is gratefully acknowledged.

The opinions, findings, conclusions, and recommendations expressed in this publication are those of the author and do not necessarily reflect the views of the CEA, the Pacific Earthquake Engineering Research Center (PEER), members of the Project Team, or the Regents of the University of California.

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1.1 INTRODUCTION

This report is one of a series of reports documenting the methods and findings of a multi-year, multi-disciplinary project coordinated by the Pacific Earthquake Engineering Research Center (PEER) and funded by the California Earthquake Authority (CEA). The overall project is titled "*Quantifying the Performance of Retrofit of Cripple Walls and Sill Anchorage in Single-Family Wood-Frame Buildings*," henceforth referred to as the "PEER–CEA Project."

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Within the PEER–CEA Project, detailed work was conducted by seven Working Groups, each addressing a particular area of study and expertise, and collaborating with the other Working Groups. The seven Working Groups are as follows:

Working Group 1: Resources Review

Working Group 2: Index Buildings

Working Group 3: Ground-Motion Selection and Loading Protocol

Working Group 4: Testing

Working Group 5: Analytical Modeling

Working Group 6: Interaction with Claims Adjustors and Catastrophe Modelers

Working Group 7: Reporting

This report is a product of the Working Group (WG) 3 denoted in bolded text above.

The report of Working Group 3.2: *Ground Motion Selection and Loading Protocol* is a product of Working Group 3 and focuses on Loading Protocol development for component testing. It presents the background, development process, and recommendations for a quasi-static loading protocol to be used for cyclic testing of cripple wall components of wood-frame structures. The recommended loading protocol was developed for component testing to support the development of experimentally informed analytical models for cripple wall components. These analytical models are utilized for the performance-based assessment of wood-frame structures in the context of the PEER–CEA Project.

1.2 OBJECTIVES

The main objective of the PEER–CEA project is to develop structural-damage fragility-modification functions that reflect the benefit of the cripple wall and sill-anchorage retrofit strategies as a function of shaking intensity. The proposed fragility functions were compared with fragility functions of HAZUS and other available sources. Figure 1.1 shows a typical fragility curve from HAZUS [FEMA 2014]. The accomplished research within the PEER–CEA project can be divided into six major tasks, starting with defining a set of wood-frame buildings that represent light-wood frames on raised foundations in California, which includes possible construction quality and retrofit measures. A testing program was developed to fill the gaps in available data for modeling and analysis of the wood-frame building set. The results of the testing program will feed into a comprehensive review and updating of the available analytical models and tools for the analysis of wood-frame buildings. Ultimately, fragility-modification functions will be developed using the updated analytical tools and set of representative wood-frame buildings.

A representative loading history is required before conducting component testing. This report summarizes the efforts in the development of such a loading protocol. We started by investigating if the currently available loading protocols in literature, namely, CUREE-Caltech [Krawinkler et al. 2002], and *FEMA-461* [FEMA 2007], are adequate for the testing program envisioned for the PEER–CEA project or is an update to those loading protocols needed.

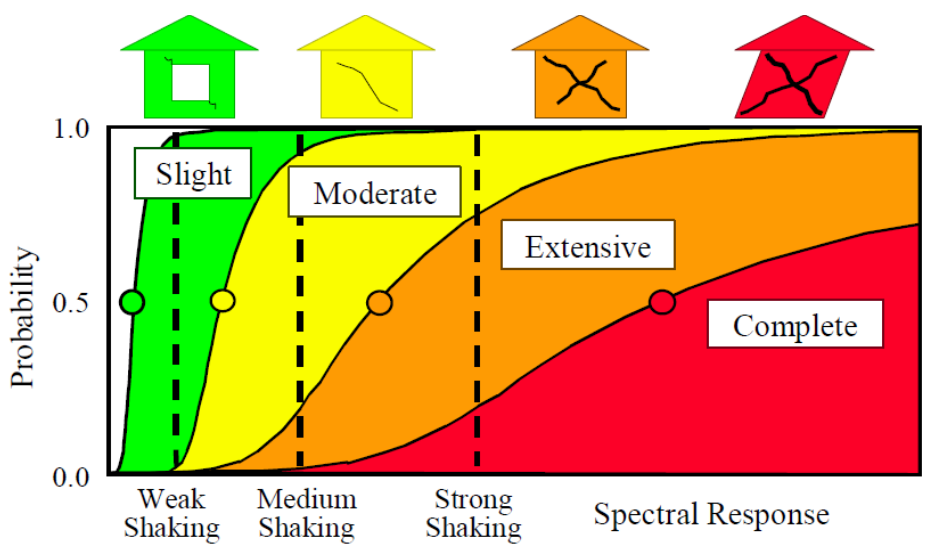

Figure 1.1 Structural-damage fragility curve from HAZUS [FEMA 2014].

1.3 CONNECTION TO OTHER EFFORTS IN THE PEER–CEA PROJECT

The development of the loading protocol for cripple wall components is tied to three other efforts within the PEER–CEA Project. First, a set of representative wood-frame buildings on raised foundations in California were compiled, and the loading protocol developed herein is tailored for this target building set [Reis 2020]. Second, multiple sets of ground motions representing various sites and hazard levels were utilized for the development of the loading protocol aimed at capturing the displacement history exhibited by cripple wall components located in various places in California during their lifetime [Mazzoni et al. 2020]. Third, the loading protocol developed was presented to the experimental research group, and feedback was requested [Schiller 2020]. Updates were made if the experimental research group required modification to the loading protocol.

1.4 BACKGROUND

With current advances in performance-based engineering of structural systems, the need for an in-depth understanding of the behavior of structural components in seismic excitation is becoming even more relevant and critical. Such an understanding will help to fill the gaps in our knowledge in the modeling of structural components, leading to a more accurate estimate of seismic demands and better quantification of the damage to structural components subjected to dynamic action. Such knowledge can reliably be acquired through laboratory testing whereby test setups replicate real-world conditions to the extent possible. The loading history (i.e., loading protocol) used for laboratory testing is one of the critical components of any testing regimen as it controls the sequence and amplitude of cumulative damage in a structural component.

Development of a single-loading protocol requires consideration of many constraints and conditions, including the type and material of the structural system/component being tested, amplitude and frequency of seismic excitation, and available resources for the experimental program. The key issue to address is how to account for cumulative damage effects through cyclic loading. Loading protocols currently being used include (1) ATC-24 [1992], Clark et al. [1997], and Krawinkler et al. [1997] for testing structural components of steel structures; (2) Porter [1987] and Krawinkler et al. [2002] for testing structural components of wood-frame buildings; and (3) FEMA [2007] for testing nonstructural components. A detailed review of these loading protocols is offered in Krawinkler [2009].

The loading protocols for structural components of wood-frame buildings developed by the CUREE-Caltech Woodframe Project [Krawinkler et al. 2002] have several advantages over the protocols listed above: (1) migration from anchoring loading history to yield deformation—a parameter that is determined based on subjective assumptions—to a deformation associated with performance objective; (2) introduction of separate loading protocols for different ground-motion hazard levels with the aim of capturing the behavior of structural components in different seismic demand regimes; and (3) introduction of "trailing cycles" that follow the preceding larger "primary cycle" at each step. This last advantage is statistically justifiable and leads to a more realistic loading history compared to the SPD Protocol [Porter 1987], in which an excessive number of cycles results in migration of dominant mode of failure from nail withdrawal to nail fatigue failure [Gatto and Uang 2002; SEAOSC 2001].

The CUREE-Caltech loading protocols were developed using the technology and information available in early 2000. In particular, these loading protocols were developed using old seismic hazard models [i.e., $Sa(T_1)$ type scaling], and old ground-motion record databases (i.e., the old PEER ground-motion database). Moreover, the CUREE-Caltech loading protocols are mostly geared towards shear walls that possess low cyclic deterioration and periods between 0.2 and 1.0 sec. These assumptions conflict with that observed in cripple wall tests by Chai et al. [2002] where the fundamental period of single-degree-of-freedom (SDOF) cripple walls was between 0.05 and 0.2 sec, with a high rate of cyclic deterioration.

Thus, it was determined that an updated loading protocol based on new technology and information would be appropriate.

1.5 SCOPE AND PLAN OF STUDY

The entire loading protocol development process is summarized here for completeness.

The target of the first stage of the two-stage process was to validate the analytical models developed by the Project Team for cripple walls and gain valuable knowledge about their dynamic behavior. The outcome of this first stage would then guide the Project Team in the next stage, where it followed an approach similar to that used to generate the CUREE-Caltech and *FEMA-461* [FEMA 2007] cyclic loading protocols. For the first stage, the Project Team suggested a few dynamic laboratory tests using a set of recorded ground motions that included records with peculiar characteristics, including near-field and soft-soil effects. The results of these tests alongside cyclic tests at UC Davis as part of the CUREE-Caltech Woodframe Project [Chai et al. 2002] would then be used to calibrate our analytical models of cripple walls at the component level as well as the system level. In particular, our validated multi-degrees-of-freedom (MDOF) models would be capable of addressing essential aspects of the dynamic response of wood-frame buildings on cripple walls, including the effect of uplift, torsion, and uneven distribution of seismic forces on stepped cripple walls.

With data available from the outcome of the ATC 110 project, the first stage of the two-stage process was deemed unnecessary. The loading protocol development team conducted the following steps (i.e., the second stage) to develop a loading protocol for cripple wall components. The team followed the method suggested by Krawinkler et al. [2002] by utilizing analytical models and ground-motion sets developed by PEER–CEA Project researchers. The new loading protocol for testing cripple walls was developed considering the following:

- The loading protocols were quasi-static (cyclic) for deformation-controlled components;
- Emphasis was placed on performance assessment on a spectrum of seismic hazard return periods (from short- to long- return periods);
- Ground-motion selection and scaling for the purpose of developing loading protocols were conducted as described in Task 3.1 [Mazzoni et al. 2020], utilizing the PEER NGA-West2 ground-motion database;
- Analytical models (i.e., MDOFs) were developed using the recommended loading protocol to explicitly model the cripple wall component with expected

characteristics. The characteristics of the MDOF models were informed by results from ATC 110 project and are representative of light wood-frame structures on raised foundations located in California; and

- Each loading protocol was anchored to a displacement representing a target performance and independent from subjective parameters such as yield deformation.

2 Loading Protocol for Deformation Control Quasi-Static Cyclic Testing

2.1 LITERATURE REVIEW

The development of loading protocols for experimental testing is not a new endeavor. During the past couple of decades, researchers have developed various loading protocols for wood-frame and nonstructural component testing. Investigations of the sensitivity of wood-frame component response to variation in the suggested loading protocol have been conducted by numerous researchers, including Krawinkler et al. [2002], *FEMA-461* [2007], Chai et al. [2002], Gatto and Uang [2002], and Krawinkler et al. [2000]. The following section summarizes the research conducted by each of the authors mentioned above, and how their work can be used to develop loading protocols for cripple wall components.

2.1.1 Krawinkler et al. [2002]

This document summarizes the authors' research in developing two quasi-static loading protocols for experimentation on components of wood-frame structures, namely, ordinary and near-fault. The suggested loading protocols are based on results of nonlinear response history analyses of representative SDOF systems whose hysteretic behavior mimics wood-frame shear-wall behavior, subject to two sets of ground motions, each of which represents a seismic hazard with 475- and 2475-year return periods. The analysis results were post-processed into representative deformation-controlled loading histories that represent cumulative damage in wood-frame components in ordinary and pulse-like ground motions.

The suggested loading histories relied on a reference deformation based on previous experience or execution of a monotonic test. The latter method, which is preferred, necessitates two experiments for a single-component test, i.e., one monotonic test to identify the reference displacement followed by a quasi-static test to assess component behavior.

2.1.2 FEMA 461 [2007]

FEMA 461 presents loading protocols for testing general structural and nonstructural elements in buildings aiming at the development of component fragility curves. Among the offered loading protocols, only the one with a deformation-controlled loading sequence is relevant for this project. This loading protocol is developed based on the response of building structures whose number of stories varied from 3 stories to 9 stories, and experienced ductility demands up to $\mu = 5$. μ is defined as the ductility demand at the most critical story, which is usually at the first story. The protocol was developed using ordinary ground motions with no near-fault effects. The analysis results were post-processed into representative deformation-controlled loading histories that represent cumulative damage. The suggested loading history starts with a reference deformation that should be safely smaller than the amplitude at which the lowest damage state is first observed (~0.0015 drift ratio). This document summarizes the authors' research in developing two quasi-static loading protocols for experimentation on components of wood-frame structures, namely, ordinary and near-fault. The suggested loading protocols were based on results of nonlinear response history analyses of representative SDOF systems whose hysteretic behavior mimicked wood-frame shear-wall behavior, subjected to two sets of ground motions, each of which represents seismic hazard with 475- and 2475-year return periods. The analysis results were post-processed into representative deformation-controlled loading histories that represent cumulative damage in wood-frame components in ordinary and pulse-like ground motions.

2.1.3 Chai et al. [2002]

This document summarizes the authors' research in evaluating the capacity of 2-ft-tall and 4-ft-tall cripple walls under existing and retrofitted designs, both in level and stepped configurations. CUREE quasi-static loading histories were used; see Section 2.1.1. It was found out that the strength (i.e., lateral load capacity) and deformation capacity of cripple walls were slightly sensitive to the utilized loading protocol. In general, the strength of cripple walls was 10% larger under the near-fault loading protocol; a higher deformation capacity with near-fault loading protocol was observed.

Loading histories used in this study were developed based on SDOF systems that mostly represented shear walls in wood-frame buildings; see Section 2.1.1. The behavior of cripple walls, however, is different (i.e., they are stiffer with highly pinching behavior and substantial cyclic deterioration) and require a re-evaluation of the suggested loading histories.

2.1.4 Gatto and Uang. [2002]

The study focused on quantifying the sensitivity of the response of 2.4 m × 2.4 m wood-frame shear walls to various loading protocols, including those referenced in Section 2.1.1. It was identified that the performance of wood-frame shear walls is highly dependent on the loading sequence; protocols with a large number of equal-size cycles were shown to be the most demanding. This research demonstrated that shear-wall components exhibit different behavior under near-fault and dynamic loading histories compared to the ordinary loading protocol.

2.1.5 Krawinkler et al. [2000]

This document shows the procedure used to develop loading histories for connection testing for Phase II of the SAC Steel Project. Two loading histories are suggested, denoted as basic and near-fault. The significance of the suggested histories is that they are not dependent on a reference deformation whose determination requires a monotonic test; see Section 2.1.1. The process for the development of the loading histories in this research is of interest.

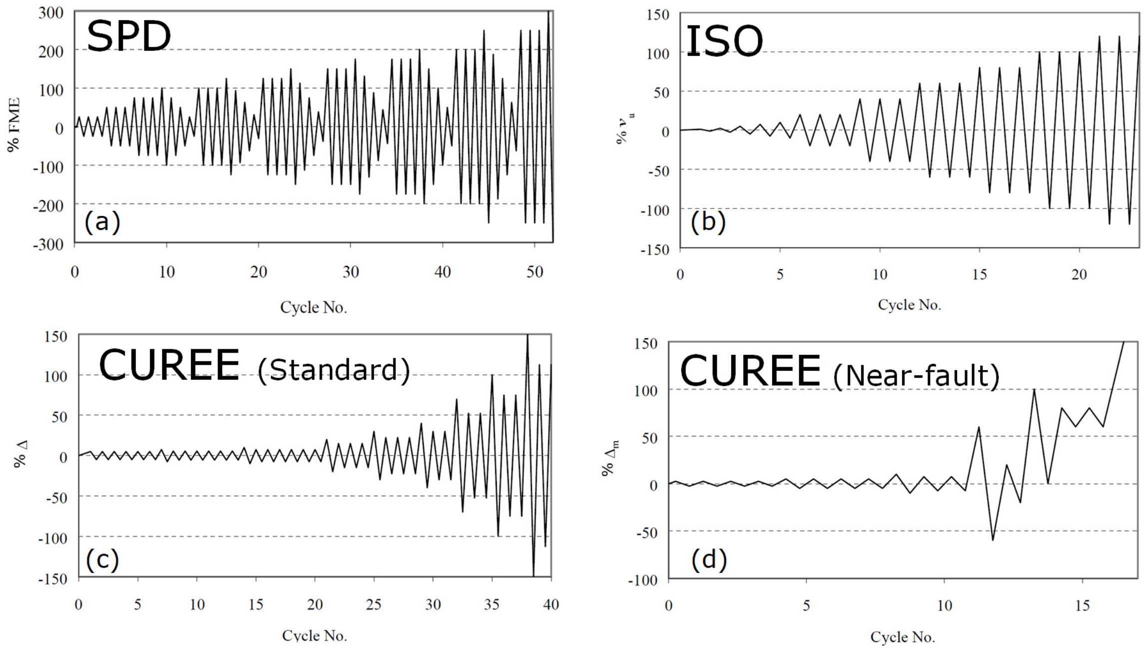

Figure 2.1 **Quasi-static loading protocols for wood-frame component testing: (a) sequential phased displacement (SPD) loading protocol after Porter [1987]; (b) International Standard after ISO *TC 165/SC N*, [2003]; (c) CUREE ordinary loading protocol after Krawinkler et al. [2002]; and (d) CUREE near-fault loading protocol after Krawinkler et al. [2002].**

2.2 RECOMMENDED LOADING PROTOCOL FOR CRIPPLE WALL COMPONENT TESTING

The suggested loading protocol presented herein is intended for cripple walls (as components of wood-frame structures) where deformation is the primary source of damage. This loading protocol is intended for quasi-static testing through which cripple wall component models can be developed and used for structural system assessment using numerical simulation in the context of performance-based earthquake engineering.

2.2.1 Presentation of the Recommended Loading Protocol for Cripple Wall Component Testing

The general form of the loading history for quasi-static loading of cripple walls is illustrated in Figures 2.2, 2.3, and 2.3. The horizontal axis of Figures 2.2 and 2.3 shows the number of cycles (denoted as i), and the vertical axis shows the relative amplitude of each cycle (denoted as a_i). The loading history suggested herein utilizes a 0.01 drift ratio as its reference deformation, i.e., $\delta_y / h = 0.01$, where h is the height of the cripple wall component. Figure 2.4 shows the drift ratio of ordered excursions for each step of the loading history; each cycle consists of two steps (i.e., one forward and one backward displacement). The loading history for cripple walls with h = 2 ft, 4 ft, and 6 ft, are illustrated in Figures 2.4, 2.5, and 2.6, respectively. With reference to Figures 2.2 and 2.3, the following sequence of cycles is to be executed:

- Seven cycles with a relative amplitude a_i of 0.05, $i \in \{1, 2, \cdots, 7\}$;
- Seven cycles with a relative amplitude a_i of 0.15, $i \in \{8, 9, \cdots, 14\}$;
- Seven cycles with a relative amplitude a_i of 0.20, $i \in \{15, 16, \cdots, 21\}$;
- Four cycles with a relative amplitude a_i of 0.40, $i \in \{22, 23, 24, 25\}$;
- Four cycles with a relative amplitude a_i of 0.60, $i \in \{26, 27, 28, 29\}$;
- Three cycles with a relative amplitude a_i of 0.80, $i \in \{30, 31, 32\}$;
- Three cycles with a relative amplitude a_i of 1.40, $i \in \{33, 34, 35\}$;
- Three cycles with a relative amplitude a_i of 2.00, $i \in \{36, 37, 38\}$;
- Two cycles with a relative amplitude a_i of 3.00, $i \in \{39, 40\}$;
- Two cycles with a relative amplitude a_i of 4.00, $i \in \{41, 42\}$;
- Two cycles with a relative amplitude a_i of 5.00, $i \in \{43, 44\}$; and
- Increasing steps of the same pattern; two cycles with an increase in relative amplitude a_i of 1.00, $a_i \in \{45, 46, \cdots\}$

Other items for the loading protocol include:

- It is not necessary to conduct cycles with less than 1/32-in. amplitude;
- Each experiment should continue until the load applied in each cycle decreases to 20% of the maximum load recorded during the entire experiment;
- It is allowed to conduct one cycle, instead of two cycles, for increments in relative amplitude a_i beyond 2.00;
- Material testing, fabrication of test specimens, experimental plan, and instrumentation design should be based on existing standards and best practices applicable to the project;
- Specimens should be investigated for possible damage, the formation of cracks, general behavior, and other standard monitoring practices at the end of each cycle; and
- Reported test results should include: (i) specimen geometry; (ii) specimen construction and mobilization details; (iii) specimen boundary condition and instrumentation detail: (iv) material testing; (v) deformation control history (input and output); (vi) instrumentation read-out for all exercised cycles; and (vii) observations made during each experiment at the end of each cycle.

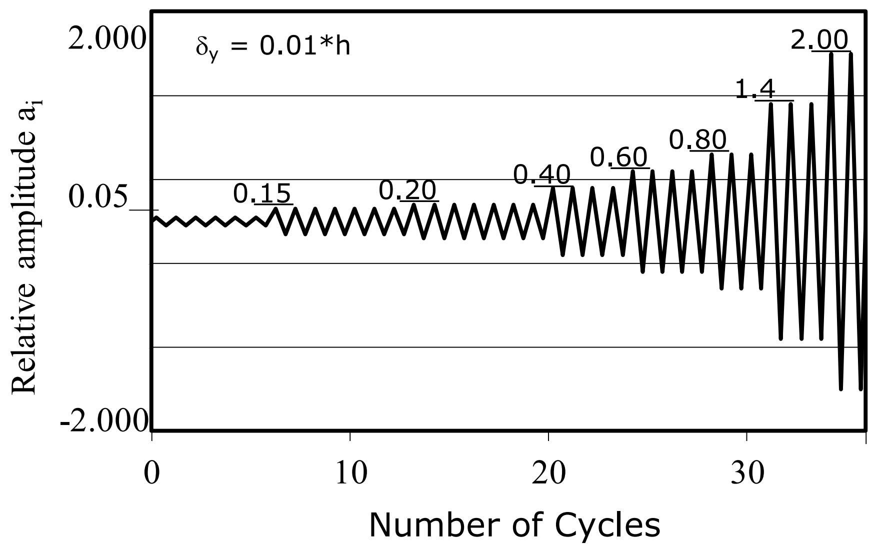

Figure 2.2 **General form of the suggested quasi-static loading protocol for cripple wall component testing.**

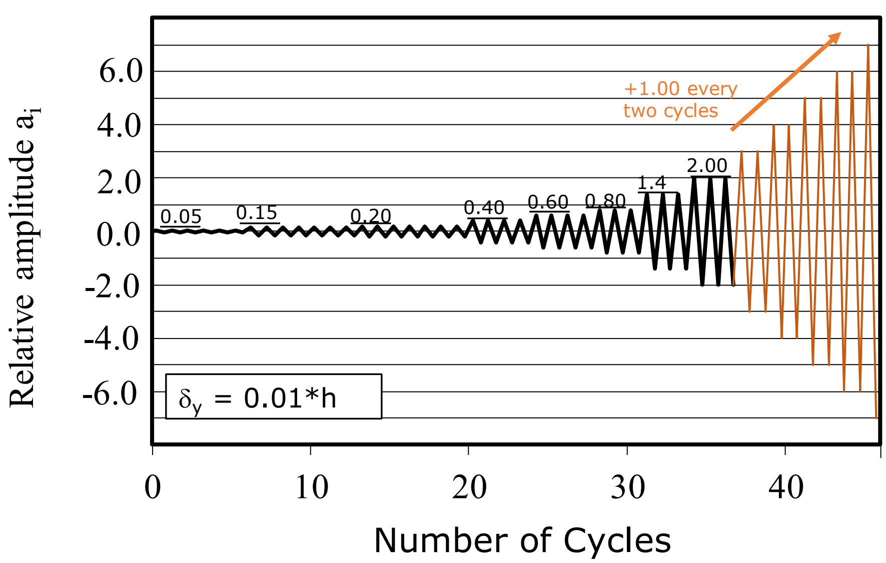

Figure 2.3 **General form of the suggested quasi-static loading protocol for cripple wall component testing with extension.**

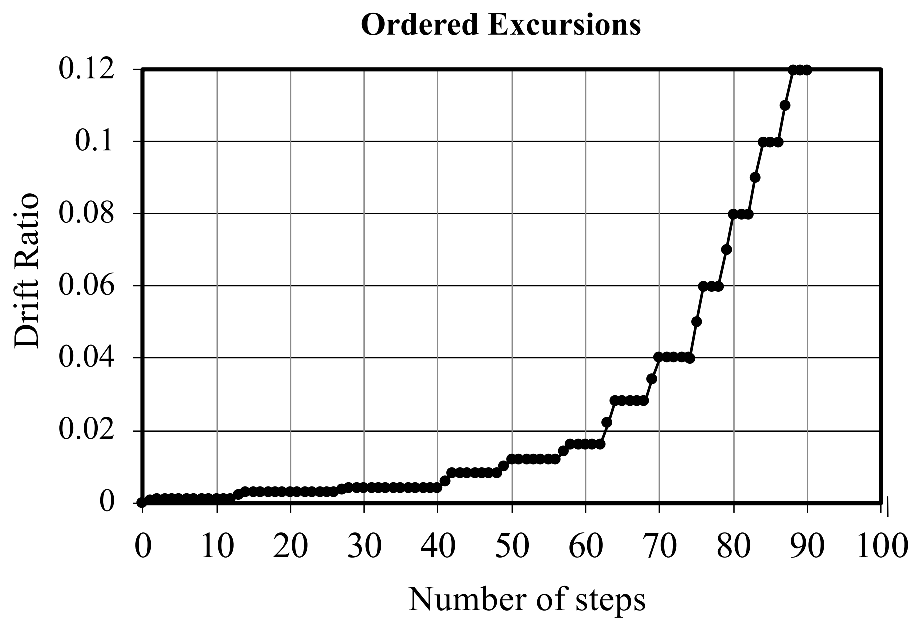

Figure 2.4 Drift ratio vs. the number of steps for the suggested quasi-static loading protocol for cripple wall component testing.

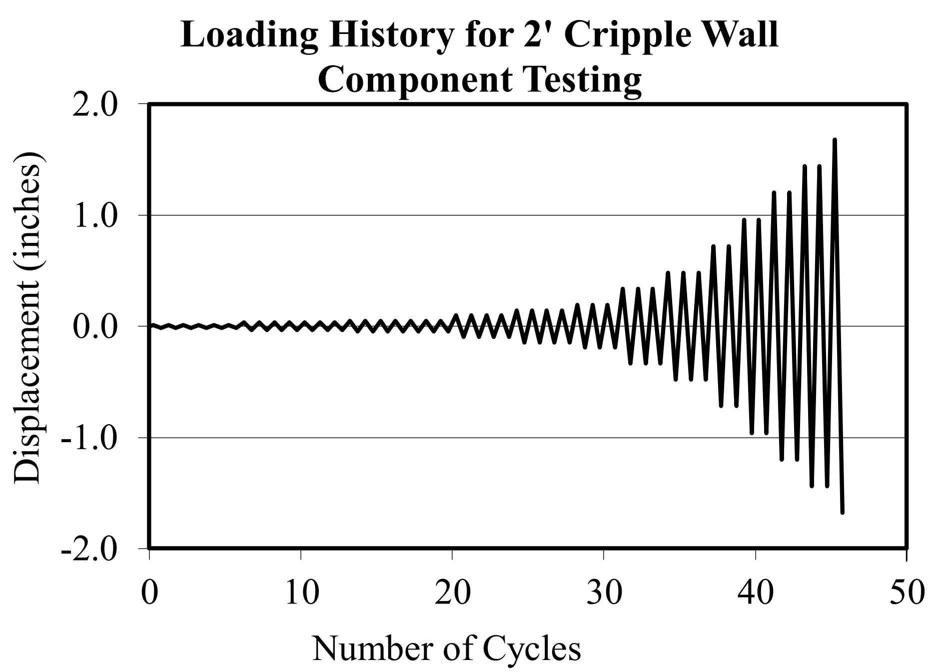

Figure 2.5 Suggested quasi-static loading protocol for 2-ft-tall cripple wall component testing.

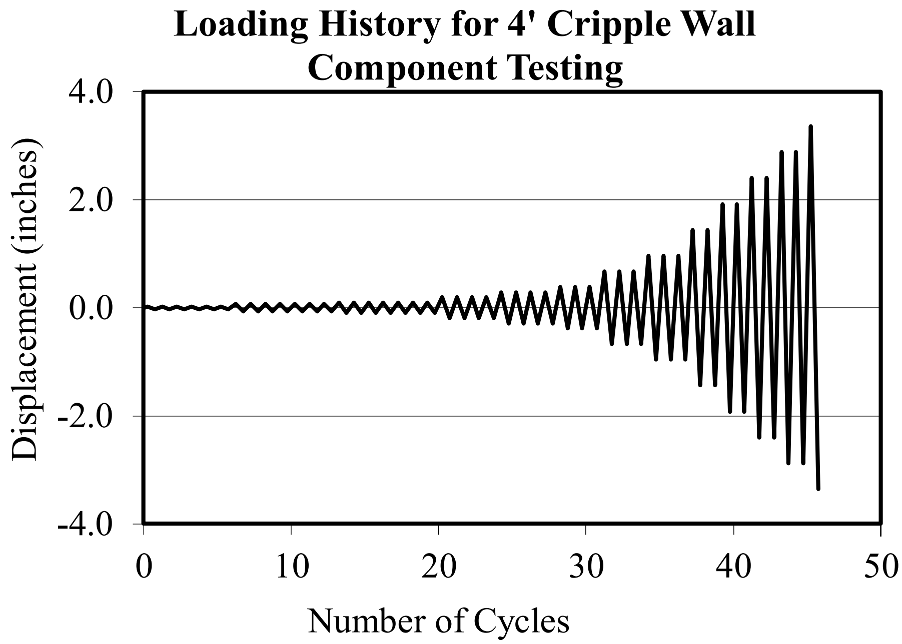

Figure 2.6 Suggested quasi-static loading protocol for 4-ft-tall cripple wall component testing.

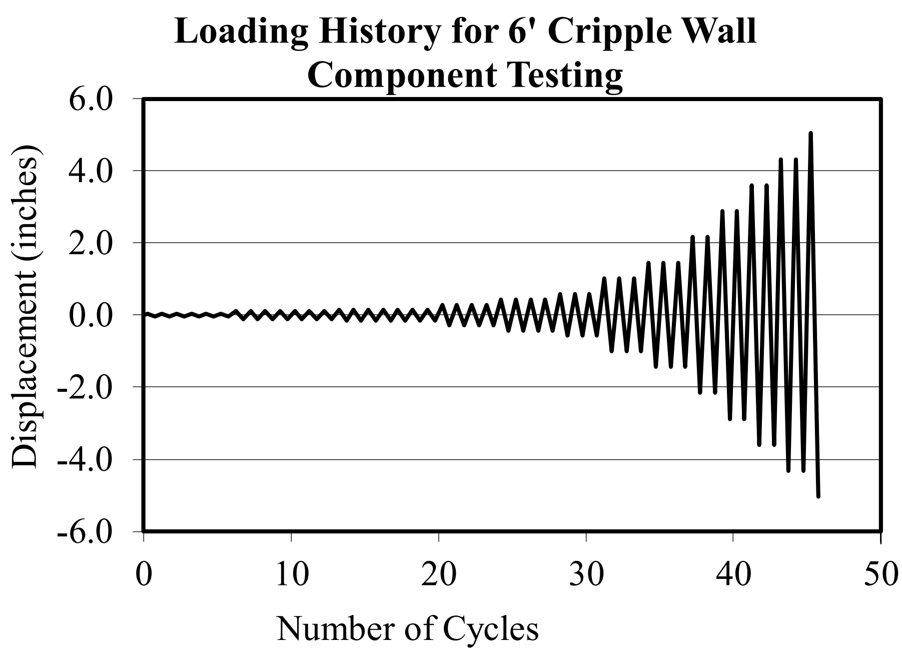

Figure 2.7 Suggested quasi-static loading protocol for 6-ft-tall cripple wall component testing.

2.2.2 Comparison of the Recommended Loading Protocol for Cripple Wall Component Testing with CUREE Quasi-Static Loading Protocol for Wood-Frame Components [Krawinkler et al. 2002]

The quasi-static loading protocol suggested herein for cripple wall testing is similar—but not identical—to the basic loading history suggested by CUREE [Krawinkler et al. 2002] for wood-frame shear-wall testing; see Figure 2.1(c). There are two main differences between the two loading histories. First, the CUREE loading history is based on a reference displacement that is informed by a monotonic test of the specimen; this reference displacement describes the deformation capacity of the test. According to Krawinkler et al. [2002], two specimens are prepared for each test: the first specimen is used to identify the reference displacement using monotonic loading and the second specimen is used for quasi-static loading. The loading history presented for quasi-static testing of cripple walls uses a drift ratio of 0.01 as its reference normalized reference displacement. This decision is informed via prior experience about the behavior of cripple walls and numerous analyses conducted as part of the ATC 110 project and this study.

The second difference between the loading history for cripple walls and the CUREE loading history is the absence of primary and trailing cycles in the former. Figure 2.8 compares the two loading histories. The CUREE loading history consists of sequences of sets of primary and trailing cycles. In each set, there is one primary cycle that is 33% larger than its trailing cycles—the amplitude of cycles increases as the number of steps increases. The cycles in the cripple wall component loading protocol do not embrace the primary-and-trailing cycle concept; the cycles in each set have a similar amplitude; see Figure 2.8 and bullet points in Section 2.2.1.

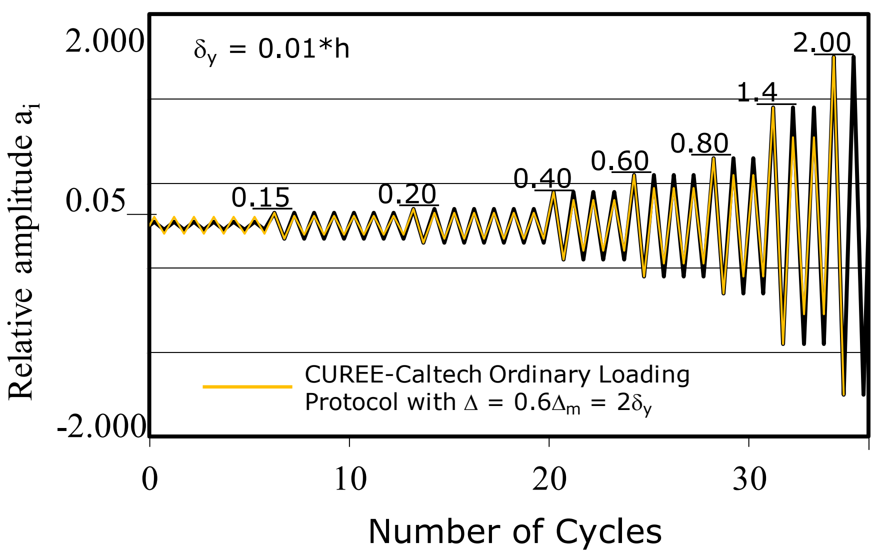

Figure 2.8 Comparison between the CUREE ordinary loading history after Krawinkler et al. [2002] and the suggested quasi-static loading protocol for cripple wall component testing.

2.3 STEPS FOR THE DEVELOPMENT OF PROJECT LOADING PROTOCOL FOR CRIPPLE WALL COMPONENTS

2.3.1 Assumptions for Developing the Project Loading Protocol for Cripple Wall Components

Embedded in the process, the development of loading protocols requires some basic assumptions. The following bullets summarize the assumptions considered in this study to develop the loading protocol suggested in Section 2.2.

- The suggested loading protocol development plan is consistent with that of Krawinkler et al. [2002] and FEMA [2007];
- Cripple wall drift ratio (i.e., top lateral displacement divided by cripple wall height = $\delta / h = \theta$) is considered as the key parameter for the proposed loading protocol, which is consistent with that of Krawinkler et al. [2000];
- Loading protocol development parameters are as follows:
    - N = Total number of damaging cycles in the loading protocol. Damaging cycles are defined as those with drift ratio range equal and larger than θ_d;
    - θ_d is defined by the leadership of the PEER–CEA Project to be equal to 0.05%. According to Chai et al. [2002]: θ_d = 0.05% to 1% is recognized as the drift ratio at which some level of damage is observed in a 4-ft-tall cripple wall (see page 81 in Chai et al. [2002]);
    - $\theta_{\max}$ = Maximum drift ratio experienced during the seismic response;
    - $\Delta\theta_1$ = The first largest drift ratio range experienced during the seismic response;
    - $\Delta\theta_i$ = i^{th} the largest drift ratio range experienced during the seismic response;
    - $\Sigma\Delta\theta_i$ = Sum of the first i^{th} largest drift ratio ranges experienced during the seismic response;
- Loading protocols will be developed for a wide range of MDOF models (see Figure 2.9) using ground-motion datasets that represent seismic hazard for the combination of geographical location (i.e., Northridge, Oakland, and San Francisco), site–soil parameter (i.e., V_{s30} = 270 m/sec and 760 m/sec), and seismic hazard level (i.e., average return periods of 72, 475, 1000, and 2475 years). Figures 2.10 to 2.14 depict target uniform hazard spectra (with solid lines) and the median spectra of the selected ground motions (with dash lines) for the mentioned sites; colors blue, green, gray, and red, represent 72, 475, 1000, and 2475 years average return period, respectively;
- The loading protocol will be developed based on the following statistics on the parameters mentioned above. These statistical measures are computed from

responses from nonlinear response history analysis for the most critical structure subject to target sets of ground motions;

  - The number of cycles in the protocol is based on the 84-percentile value of N for combined record sets;
  - The maximum deformation range of the protocol is based on the 84-percentile value of $\Delta\theta_1$ from combined record sets;
  - Cumulative deformation range is based on the 84-percentile value of $\Sigma\Delta\theta_i$ from the combined record sets; and

- As suggested and implemented by Working Group 4, the effect of pulse-like loading on cripple wall components can be replicated by a monotonic-loading test.

Following these assumptions, Table 2.1 summarizes all the cases (i.e., the combination of parameters) considered in this study to develop the cripple wall quasi-static loading protocol. The pushover curves for the analytical models indicated in Table 2.1 are illustrated in Figures 2.15 to 2.20. In these figures, the horizontal axis shows the cripple wall drift ratio, and the vertical axis shows the base-shear coefficient.

Table 2.1 List of cases considered for the development of cripple wall loading protocol [†‡].

Case no.	ID	Num. Stories	Cripple wall height (ft)	Finish	Retrofit status	Hazard adj.	Locations Soil type Hazard levels
1	1C2-M-E	1	2	Stucco	Existing	No	NR[¥] & OK[₳] 270[$] & 760[$] 74[#], 475[#], 1000[#], 2475[#]
2	1C2-M-R	1	2	Stucco	Retrofitted	No	NR[¥] & OK[₳] 270[$] & 760[$] 74[#], 475[#], 1000[#], 2475[#]
3	1C4-M-E	1	4	Stucco	Existing	No	NR[¥] & OK[₳] 270[$] & 760[$] 74[#], 475[#], 1000[#], 2475[#]
4	1C4-M-R	1	4	Stucco	Retrofitted	No	NR[¥] & OK[₳] 270[$] & 760[$] 74[#], 475[#], 1000[#], 2475[#]
5	1C6-M-E	1	6	Stucco	Existing	No	NR[¥] & OK[₳] 270[$] & 760[$] 74[#], 475[#], 1000[#], 2475[#]
6	1C6-M-R	1	6	Stucco	Retrofitted	No	NR[¥] & OK[₳] 270[$] & 760[$] 74[#], 475[#], 1000[#], 2475[#]
7	1C2-M-R*	1	2	Stucco	Retrofitted	Yes	NR[¥] & OK[₳] 270[$] & 760[$] 74[#], 475[#], 1000[#], 2475[#]
8	1C4-M-R*	1	4	Stucco	Retrofitted	Yes	NR[¥] & OK[₳] 270[$] & 760[$] 74[#], 475[#], 1000[#], 2475[#]
9	1C2-HS-E	1	2	Wood Siding	Existing	No	NR[¥] & OK[₳] 270[$] & 760[$] 74[#], 475[#], 1000[#], 2475[#]
10	1C2-HS-R	1	2	Wood Siding	Retrofitted	No	NR[¥] & OK[₳] 270[$] & 760[$] 74[#], 475[#], 1000[#], 2475[#]
11	1C2-HS-E*	1	2	Wood Siding	Existing	Yes	NR[¥] & OK[₳] 270[$] & 760[$] 74[#], 475[#], 1000[#], 2475[#]
12	1C2-HS-R*	1	2	Wood Siding	Retrofitted	Yes	NR[¥] & OK[₳] 270[$] & 760[$] 74[#], 475[#], 1000[#], 2475[#]
13	1C2-HS-E#	1	2	Wood Siding	Existing	Yes	SF[†] 270[$] 74[#], 475[#], 1000[#], 2475[#]
14	1C2-HS-R#	1	2	Wood Siding	Retrofitted	Yes	SF[†] 270[$] 74[#], 475[#], 1000[#], 2475[#]
15	1C2-LP-E#	1	2	Lath& Plaster	Existing	Yes	SF[†] 270[$] 74[#], 475[#], 1000[#], 2475[#]
16	1C2-LP-R#	1	6	Lath& Plaster	Retrofitted	Yes	SF[†] 270[$] 74[#], 475[#], 1000[#], 2475[#]

[¥]NR = Northridge, [₳]OK = Oakland, [†]SF = San Francisco

[$]270 & 760 are VS30 values in m/s for sites considered.

[#]72, 475, 1000, 2475 are average return periods.

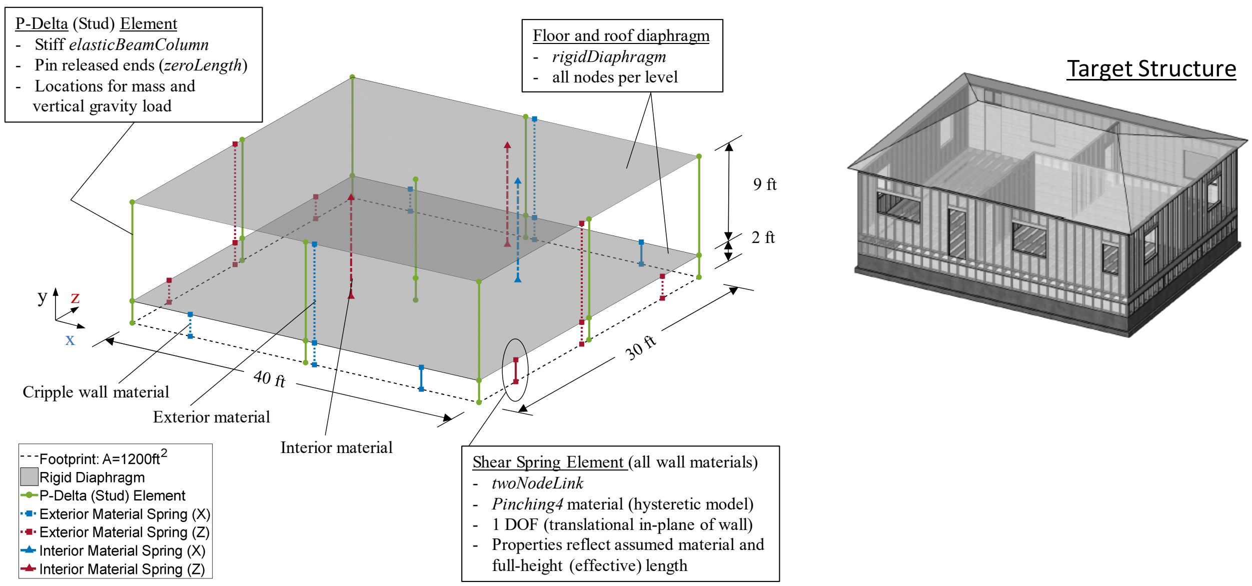

Figure 2.9 **Anatomy of the MDOF model used for the development of the recommended loading protocol.**

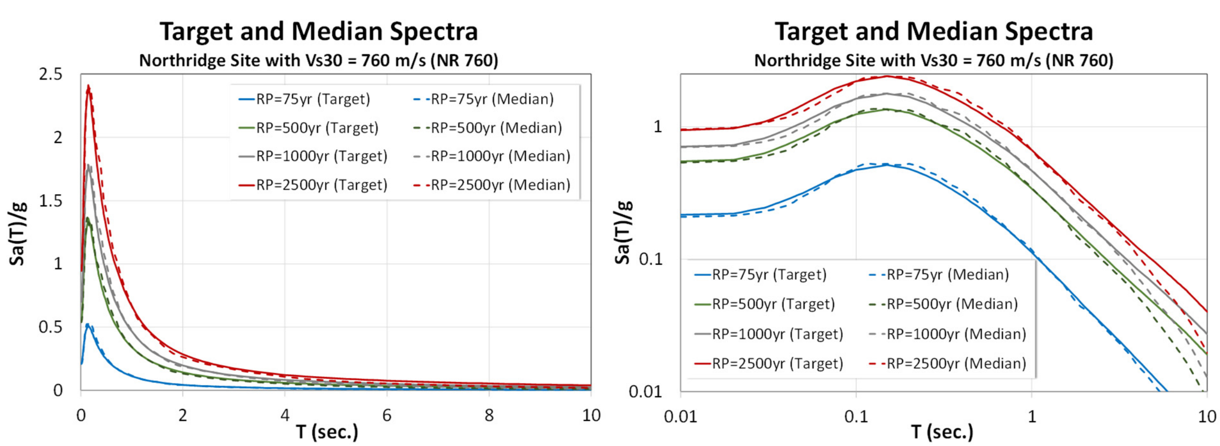

Figure 2.10 **Target uniform hazard spectra and the median spectra of the selected ground motions for Northridge site with V_{s30} = 760 m/sec.**

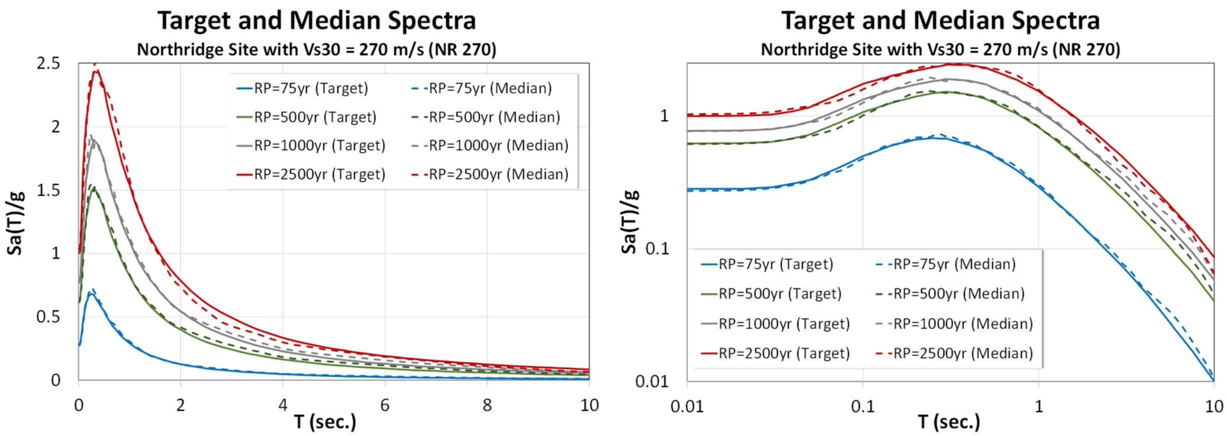

Figure 2.11 Target uniform hazard spectra and the median spectra of the selected ground motions for Northridge site with V_{s30} = 270 m/sec.

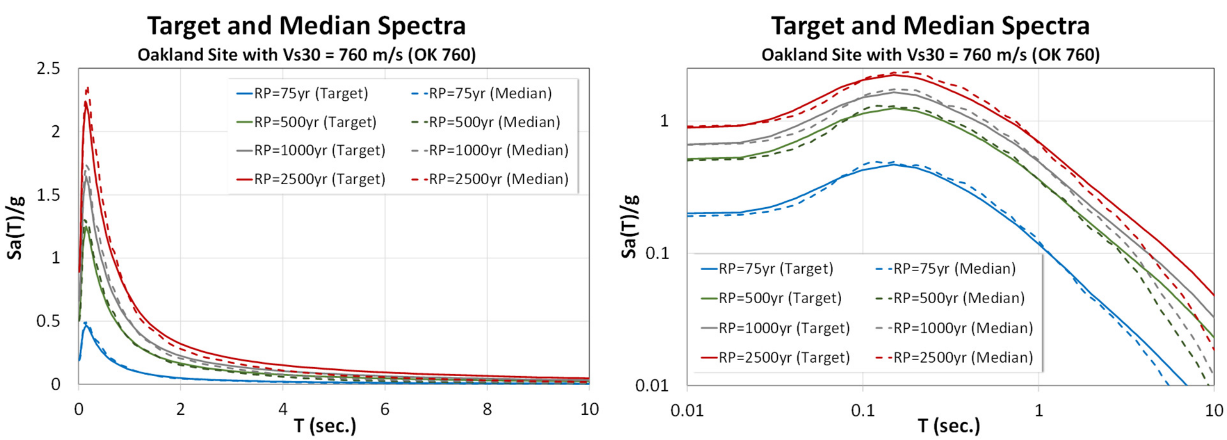

Figure 2.12 Target uniform hazard spectra and the median spectra of the selected ground motions for Oakland site with V_{s30} = 760 m/sec.

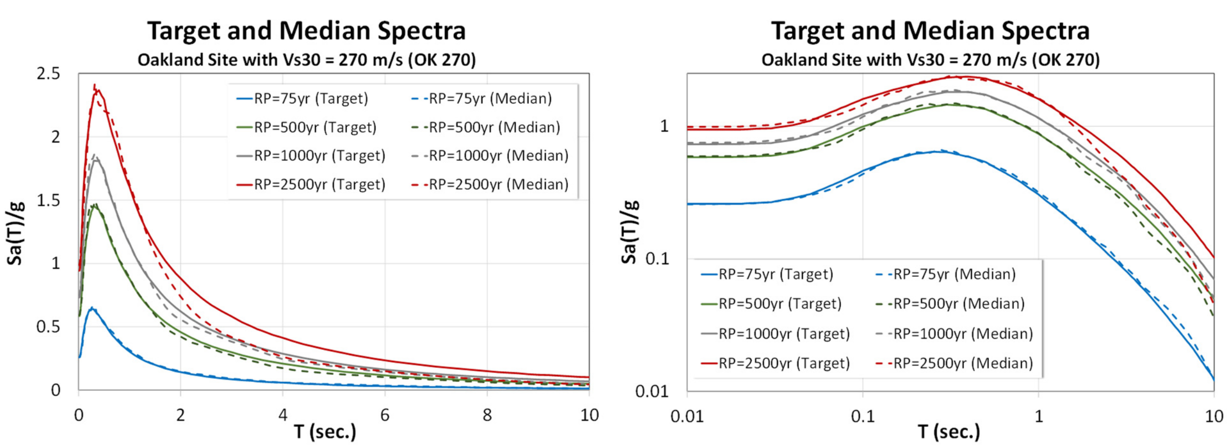

Figure 2.13 Target uniform hazard spectra and the median spectra of the selected ground motions for Oakland site with V_{s30} = 270 m/sec.

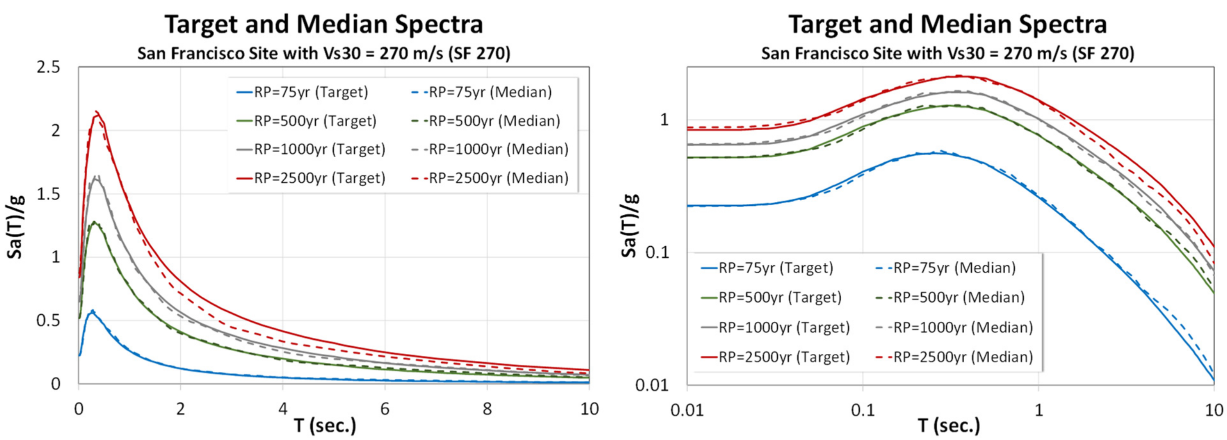

Figure 2.14 **Target uniform hazard spectra and the median spectra of the selected ground motions for the San Francisco site with V_{s30} = 270 m/sec.**

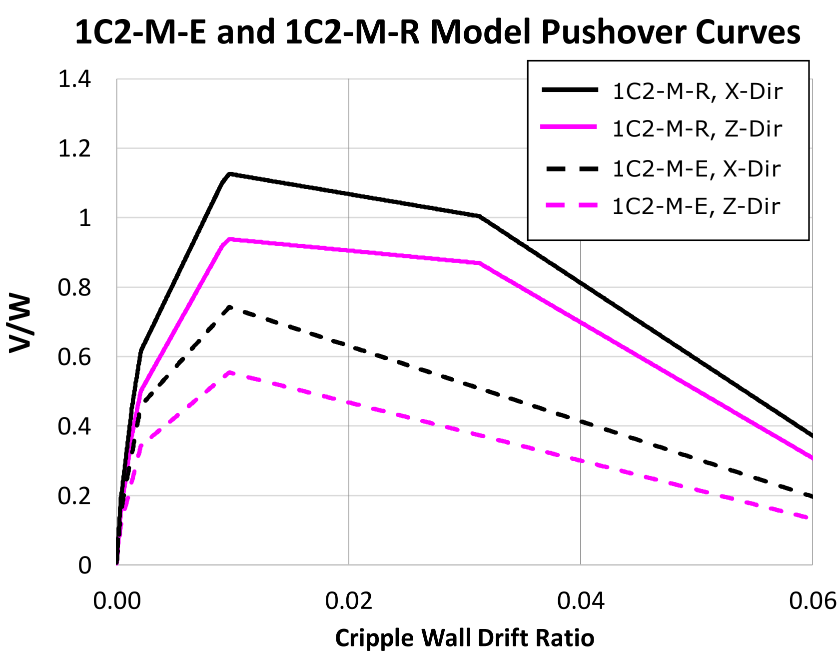

Figure 2.15 **Pushover curves for cripple wall components in 1C2-M-E and 1C2-M-R MDOF models.**

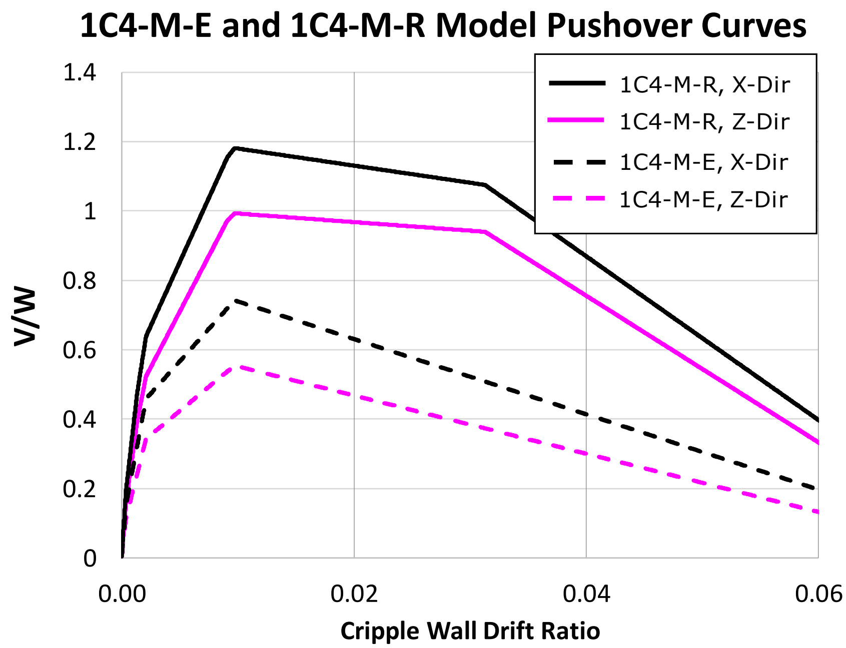

Figure 2.16 **Pushover curves for cripple wall components in 1C4-M-E and 1C4-M-R MDOF models.**

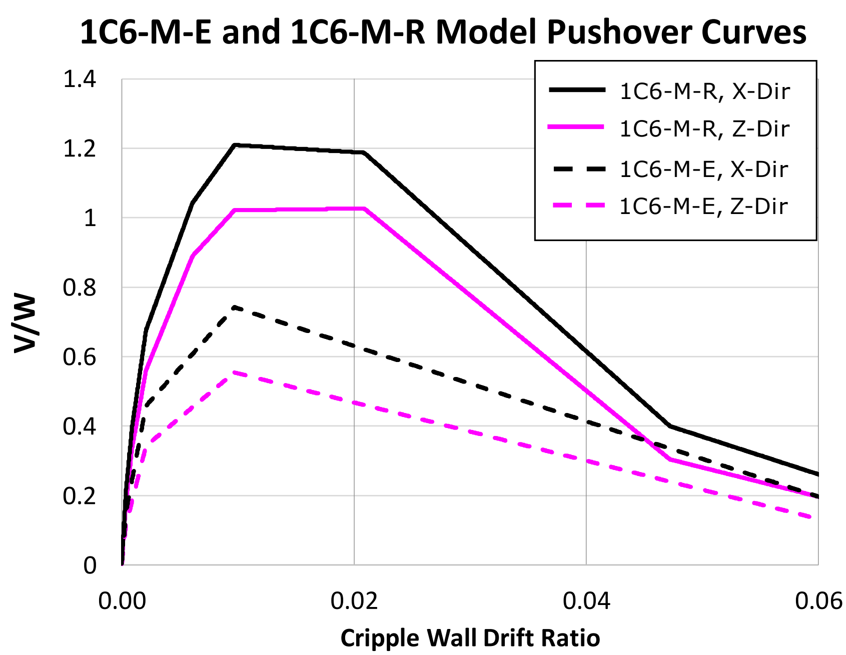

Figure 2.17 **Pushover curves for cripple wall components in 1C6-M-E and 1C6-M-R MDOF models.**

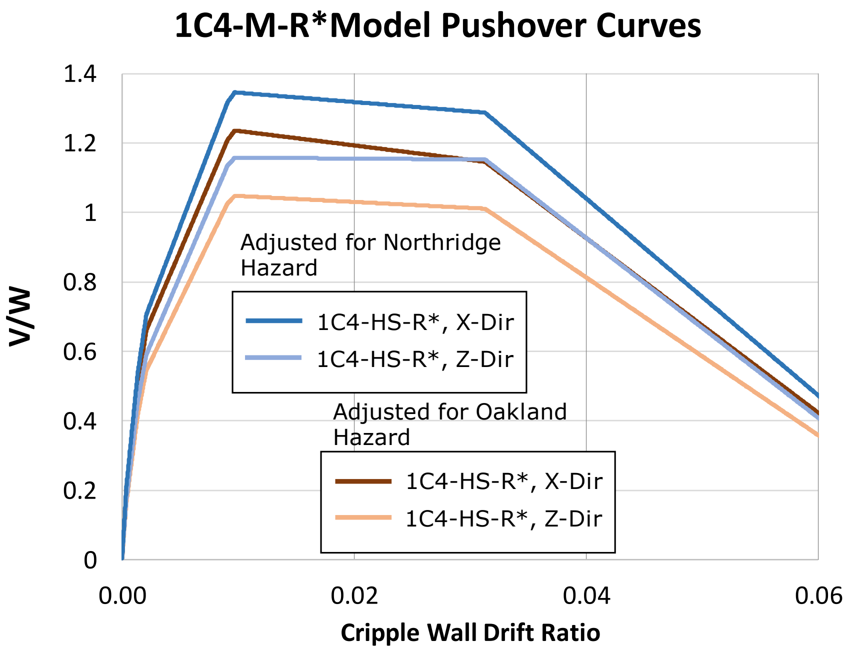

Figure 2.18 Pushover curves for cripple wall components in 1C4-M-R* MDOF models.

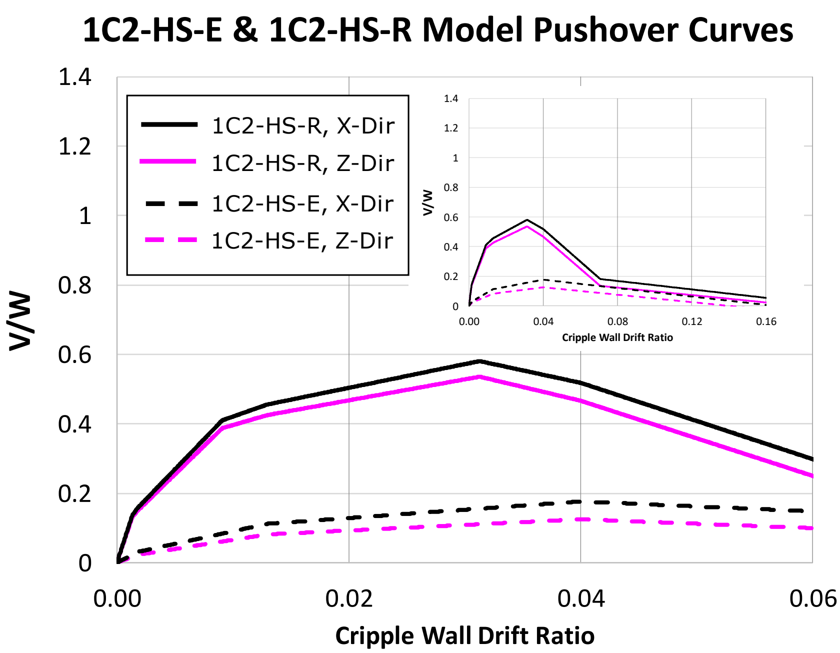

Figure 2.19 Pushover curves for cripple wall components in 1C2-HS-E and 1C2-HS-R MDOF models.

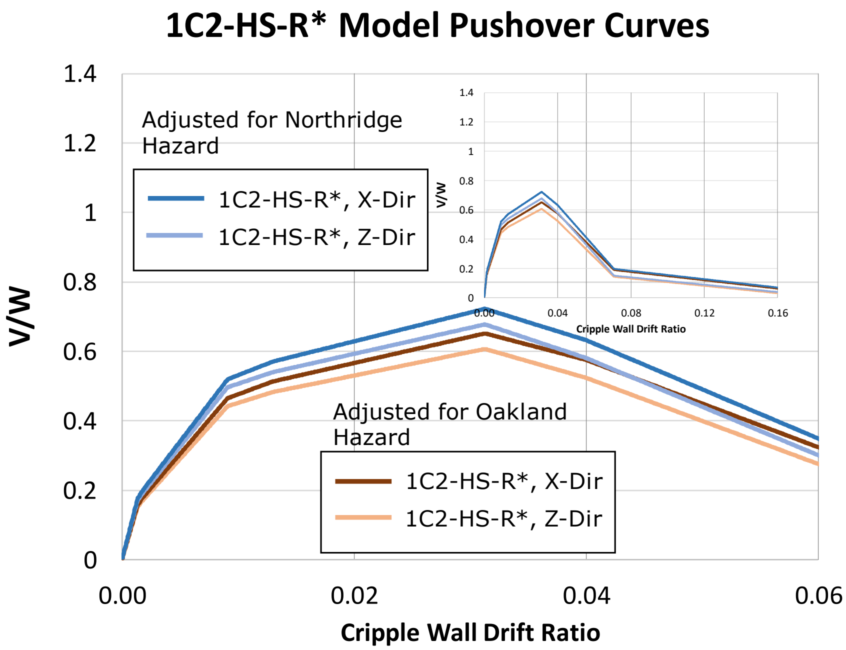

Figure 2.20 Pushover curves for cripple wall components in 1C2-HS-R* MDOF models.

2.3.2 Steps for Developing the Project Loading Protocol for Cripple Wall Components

The following steps are performed to develop the loading protocol of cripple wall components. For simplicity of explanations, the process is explained for one case up to Step #5; i.e., 1C2-M-E for the ground-motion record set representing a 1000-year average return period at Northridge with V_{s30} = 270 m/sec. From Step #6 forward, the explanation is based on the entire dataset.

1. Obtain analytical models (OpenSees) of the Index Buildings identified by Working Group 2 and the set of ground motions from Working Group 3.1.
2. Using the information in Step #1. Perform nonlinear response history analysis to obtain drift histories of cripple walls in two horizontal directions: one set of two histories for each one of the ground motions in the dataset. Identify the most critical ground motion to ensure the consistency of the process. The most critical ground motion is defined as that motion whose cripple wall response has the largest θ_{max} and $\Sigma\Delta\theta_i$.
3. Identify collapsed cases and post-process cripple wall deformation history for consistency with cases where collapse has not happened. This post-processing consists of removing the last excursion of the cripple wall (that led to collapse) and all trailing deformation.
4. Implement the RCC routine on each of the cripple wall drift histories generated in Step #2 and post-processed in Step #3 to create datasets of N, θ_{max}, $\Delta\theta_i$, and $\Sigma\Delta\theta_i$. Only pre-peak (pre-θ_{max} in response history results) data is used to develop the loading protocol to address the goals of the testing program.

5. Compute 84% statistical measures from the dataset developed in Step 4 to identify the basic information needed to generate the first draft of the loading protocol. The 84% statistical measure is obtained from the excursions in both horizontal directions obtained from RCC.
6. The first draft of the loading history is developed by assuming that cycles are symmetric, the cumulative distribution function (CDF) of the loading history in term of $\Delta\theta_i$ is below the CDF of the same parameter from analysis, and the CDF of the loading history in term of $\Sigma\Delta\theta_i$ is above the CDF of the same parameter from the analysis.
7. The first draft of the loading history is modified as needed, and Steps 4 to 6 are repeated to converge into a single symmetric loading history. In particular, the 84% statistical measure of pre-peak excursions is slid across the loading history, to align with the suggested loading history, as shown in Figure 2.21.

The suggested approach for developing the loading protocol for cripple walls leads to an outcome in which the impact of ground motions with higher probability is incorporated in ramping up of the loading history from small excursions to larger ones. Figures 2.22 to 2.25 illustrate the alignment of 84% pre-peak excursions for the 1C2-HS-R* system. The excursions from the suggested loading history are illustrated by the color yellow. The 84% pre-peak excursions for 1C2-HS-R* for 72-, 475-, 1000-, and 2475-year average return period are shown in blue, green, gray, and red, respectively. The figures show where the data associated with each average return period are generally located on the excursions of the suggested loading protocol. As seen in Figure 2.22, the early part of the leading protocol represents the impact of the 72-year average return period ground motions on the 1C2-HS-R* cripple walls. In Figures 2.23 to 2.25, the larger excursions are marked to show that the suggested loading protocol can address the difference between the deformation history of the cripple walls as ground motions become more intense.

Figures 2.26 to 2.34 compare the excursions of the suggested loading protocol for cripple wall components with the 84% RCC datasets.

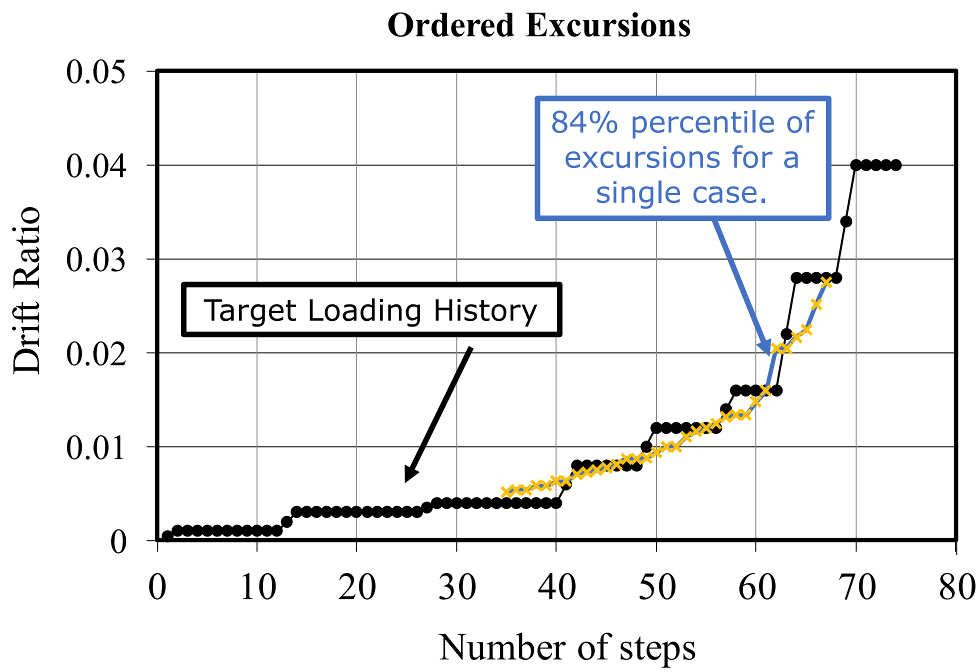

Figure 2.21 Matching of the 84% excursions statistics with the target loading history.

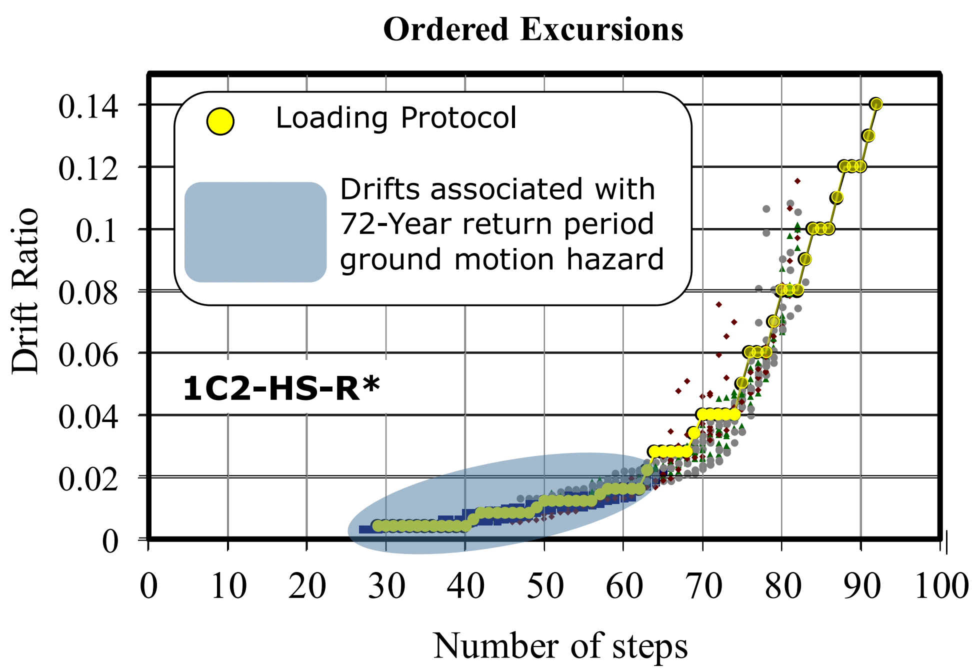

Figure 2.22 Significance of ordered excursion data points associated with 72-year average return period ground-motion hazard and the suggested loading protocol for 1C2-HS-R8 MDOF system.

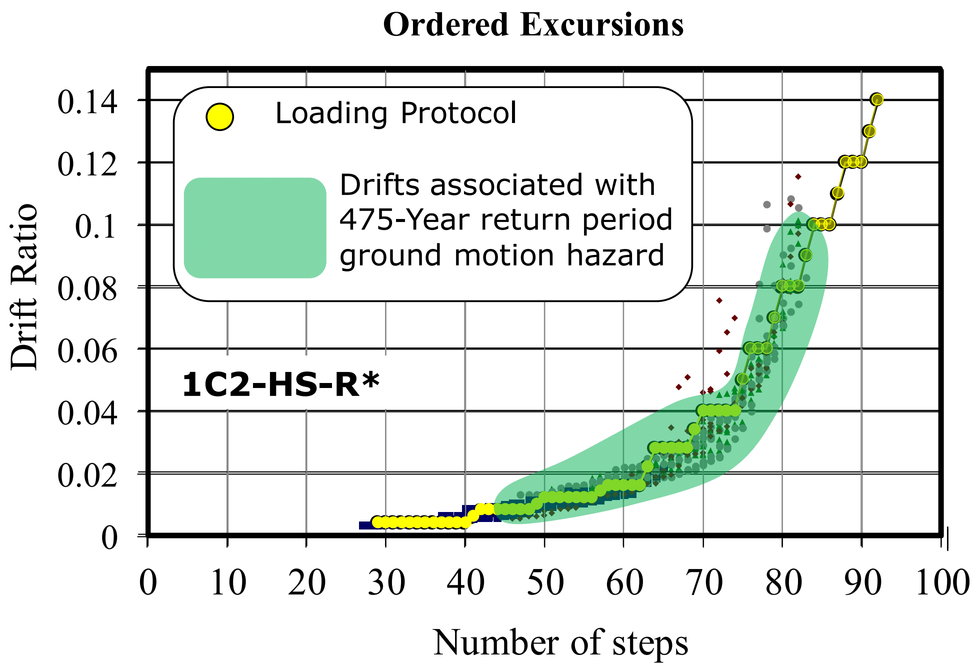

Figure 2.23 **Significance of ordered excursion data points associated with 475-year average return period ground-motion hazard and the suggested loading protocol for 1C2-HS-R8 MDOF system.**

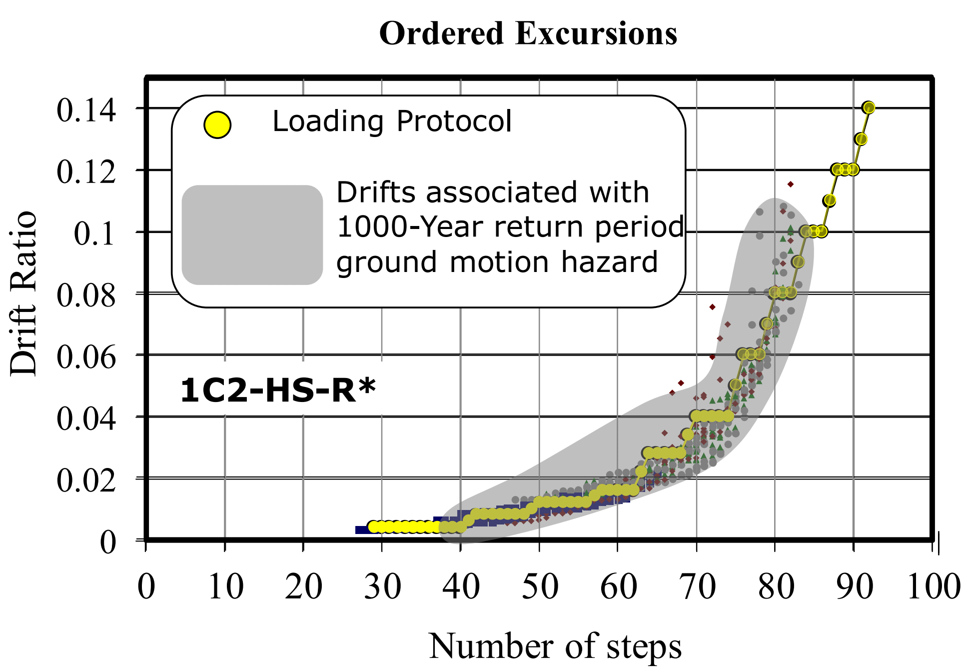

Figure 2.24 **Significance of ordered excursion data points associated with a 1000-year average return period ground-motion hazard and the suggested loading protocol for 1C2-HS-R8 MDOF system.**

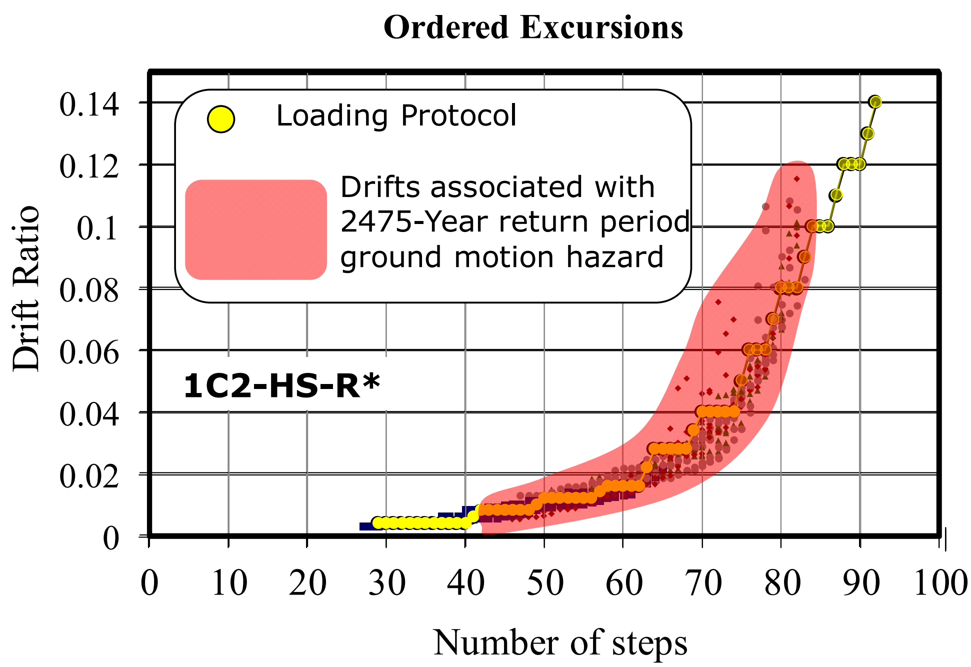

Figure 2.25 **Significance of ordered excursion data points associated with 2475-year average return period ground-motion hazard and the suggested loading protocol for 1C2-HS-R8 MDOF system.**

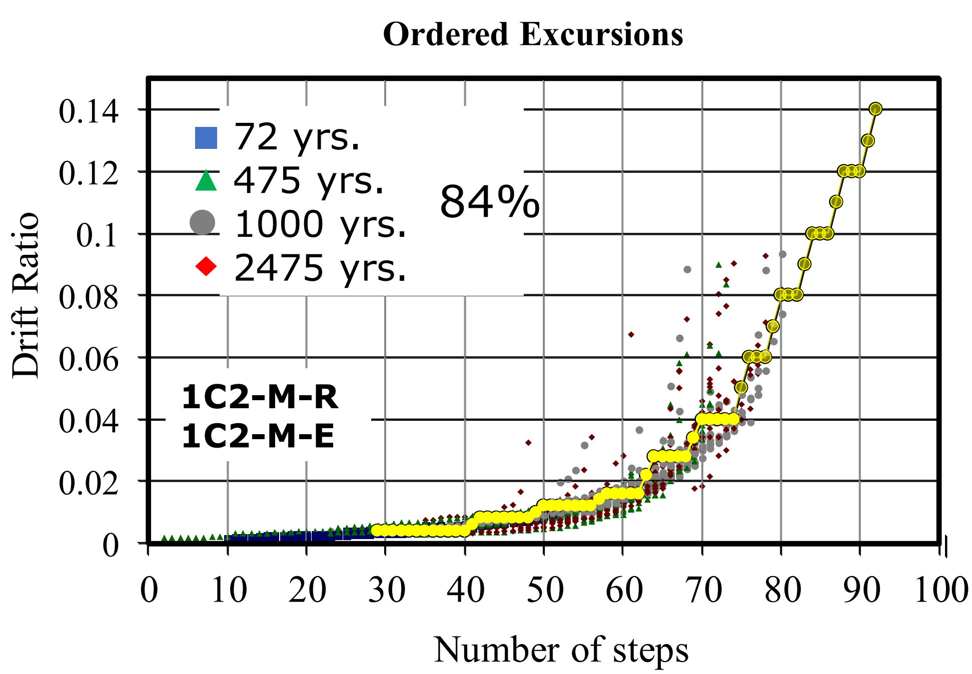

Figure 2.26 **Ordered excursion data points associated with various average return period ground motion-hazard and the suggested loading protocol for 1C2-M-R and 1C2-M-E MDOF systems.**

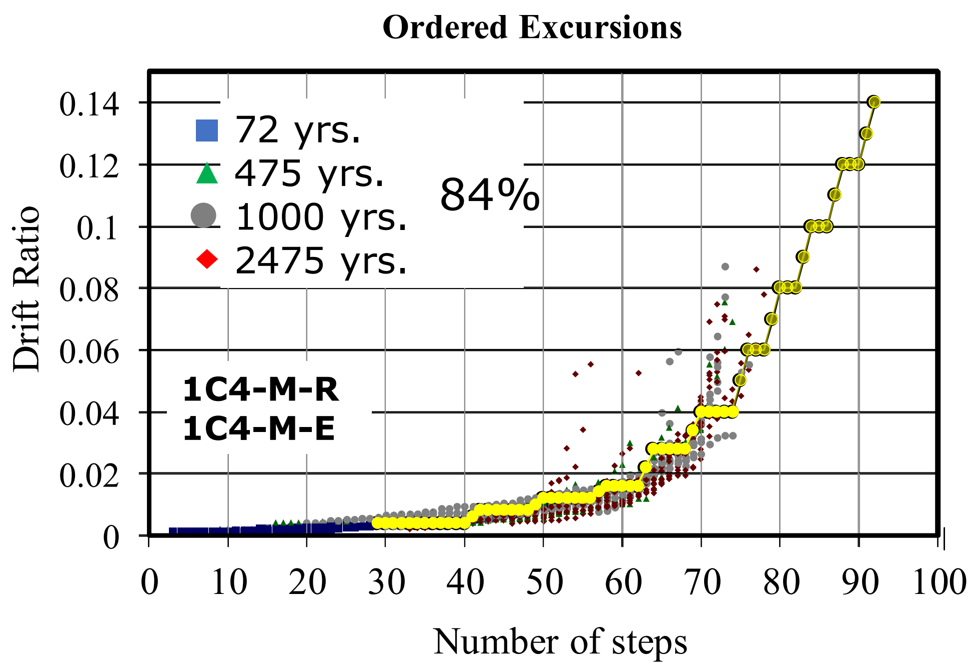

Figure 2.27 Ordered excursion data points associated with various average return period ground-motion hazard and the suggested loading protocol for 1C4-M-R and 1C4-M-E MDOF systems.

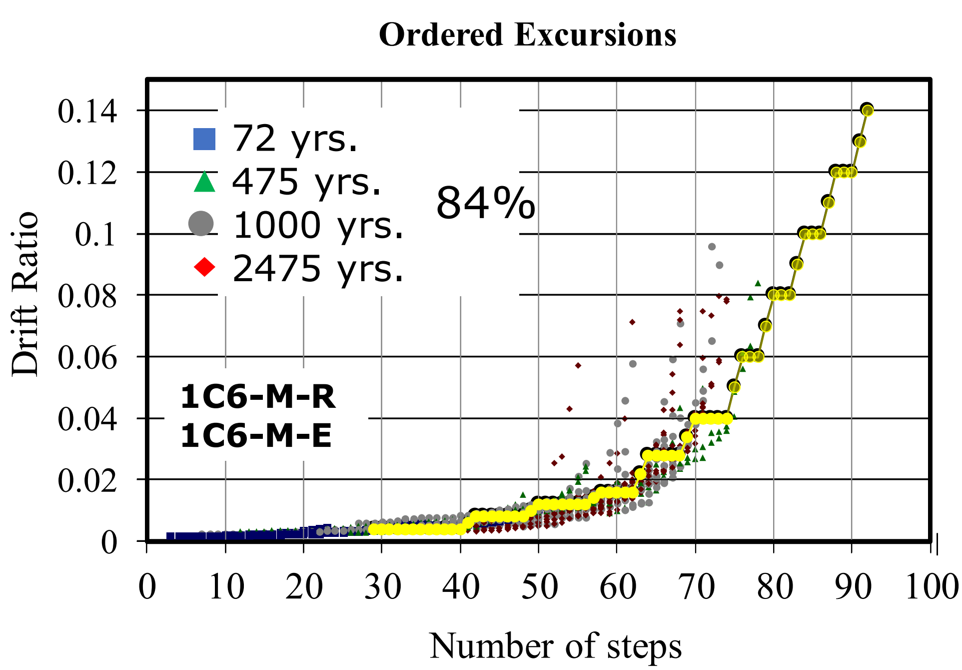

Figure 2.28 Ordered excursion data points associated with various average return period ground-motion hazard and the suggested loading protocol for 1C6-M-R and 1C6-M-E MDOF systems.

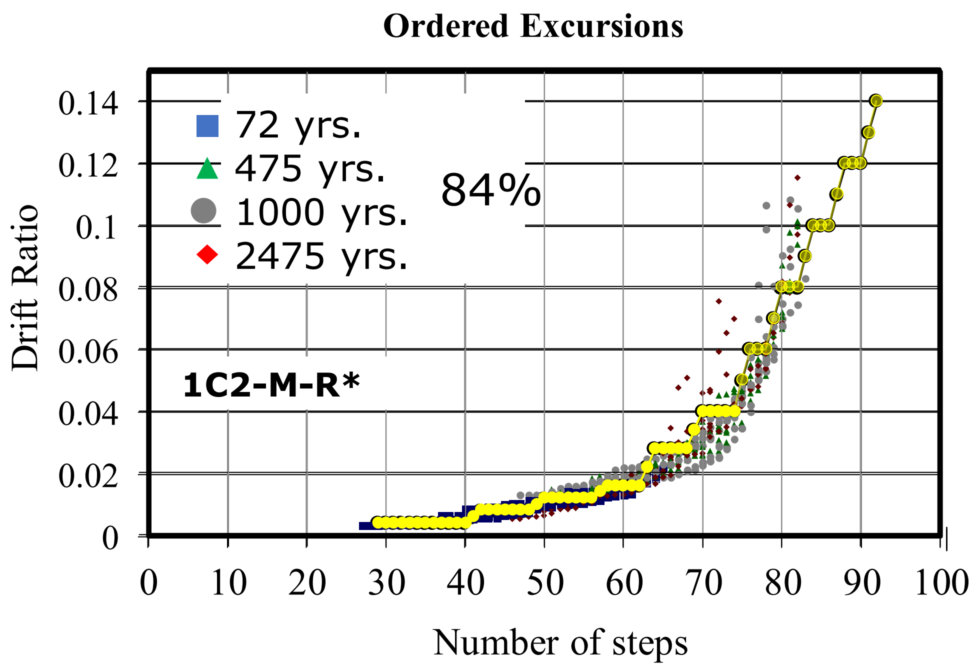

Figure 2.29 **Ordered excursion data points associated with various average return period ground-motion hazard and the suggested loading protocol for 1C2-M-R* MDOF systems.**

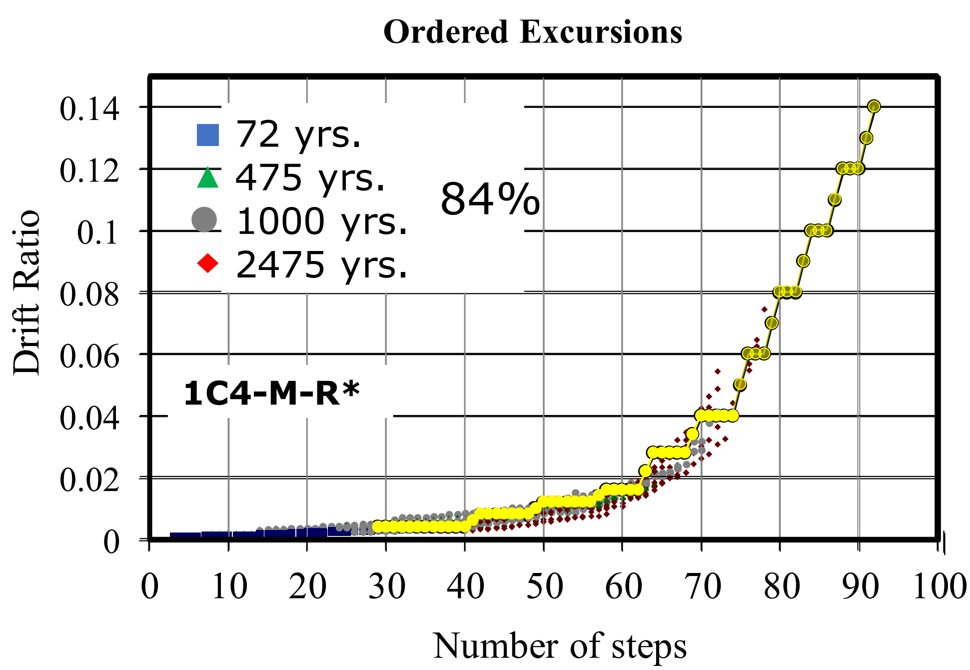

Figure 2.30 **Ordered excursion data points associated with various average return period ground-motion hazard and the suggested loading protocol for 1C4-M-R* MDOF systems.**

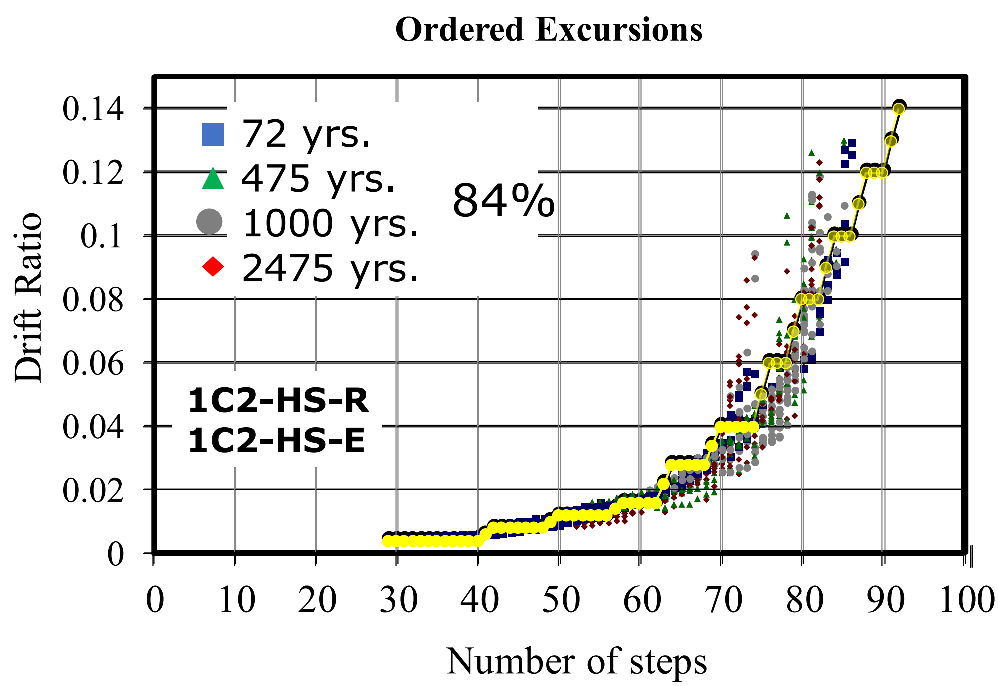

Figure 2.31 Ordered excursion data points associated with various average return period ground-motion hazard and the suggested loading protocol for 1C2-HS-R and 1C2-HS-E MDOF systems.

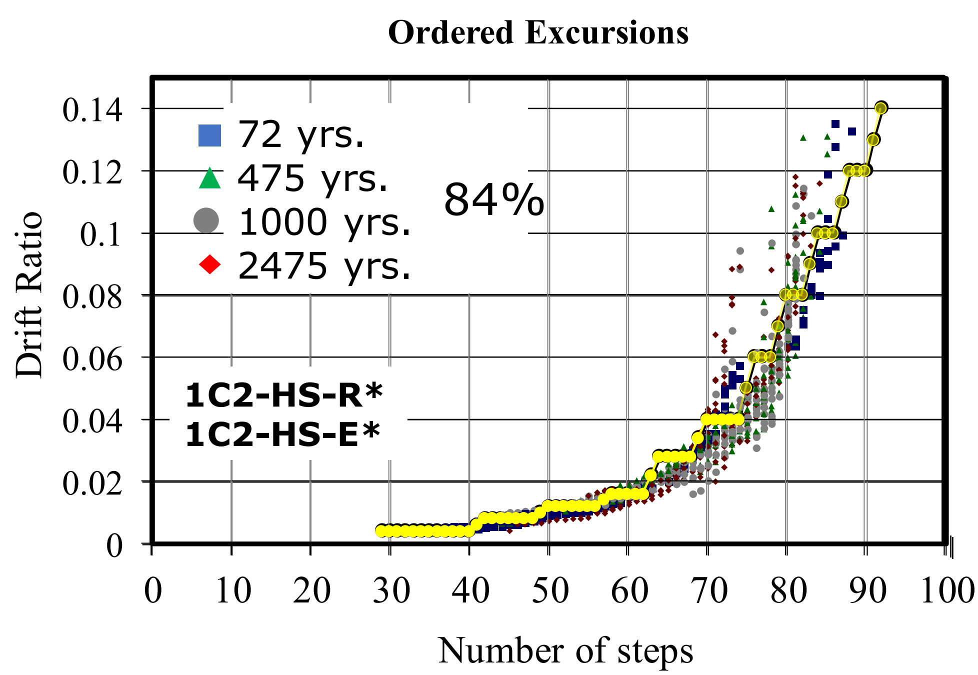

Figure 2.32 Ordered excursion data points associated with various average return period ground-motion hazard and the suggested loading protocol for 1C2-HS-R* and 1C2-HS-E* MDOF systems.

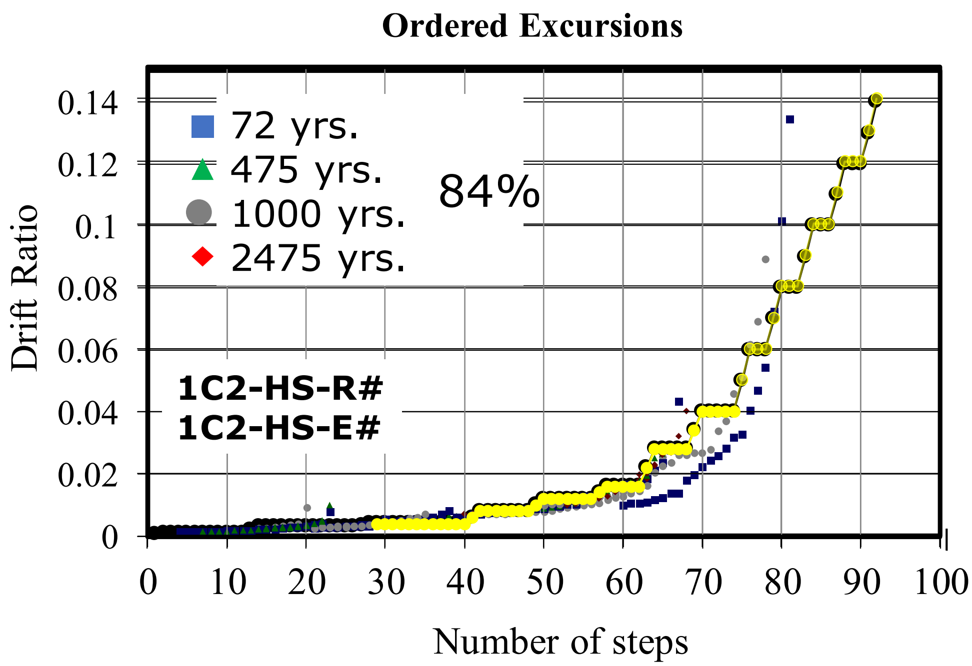

Figure 2.33 **Ordered excursion data points associated with various average return period ground-motion hazard and the suggested loading protocol for 1C2-HS-R# and 1C2-HS-E# MDOF systems.**

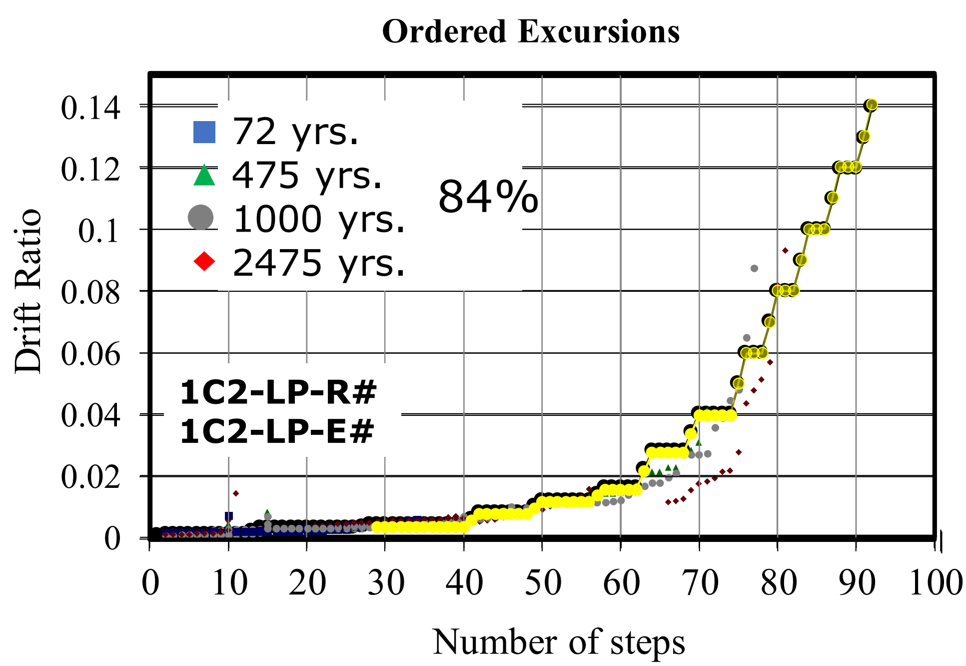

Figure 2.34 **Ordered excursion data points associated with various average return period ground-motion hazard and the suggested loading protocol for 1C2-LP-R# and 1C2-LP-E# MDOF systems.**

3 Conclusions

3.1 CURRENT STUDY

This report presents the essential knowledge and data for the development of a quasi-static loading protocol for cyclic testing of cripple wall components of wood-frame structures. The recommended loading protocol was developed for component testing to aid in the development of experimentally informed analytical models for cripple wall components. These analytical models are used for performance-based assessment of wood-frame structures in the context of the PEER–CEA Project [Welch and Deierlein 2020].

The recommended loading protocol was developed using nonlinear dynamic analysis of representative MDOF systems subjected to sets of single-component ground motions that varied in location and hazard level. Cumulative damage of the cripple wall components of the MDOF systems was investigated using RFCC routines. The result is a testing protocol that captures the loading history a cripple wall may experience in various seismic regions in California.

3.2 FUTURE STUDY

The proposed loading protocol for the quasi-static loading of cripple wall components is limited by the assumptions and considerations outlined earlier. Additional loading histories can be developed to incorporate the issues listed in the following depending on the availability of data and testing equipment/setup.

- Using dynamic loading protocols [Retamales et al. 2011], as opposed to quasi-static, to demonstrate loading-rate effects in the behavior of cripple wall components;
- Investigate the development of non-symmetric loading cycles [Krawinkler et al. 2002];
- Investigate the applicability and possible updates to the suggested loading protocol for stepped cripple walls, and other related variation in cripple wall configuration and boundary conditions (see [Schiller et al. 2020]);
- Investigate the effect of ground-motion directionality and ground-motion sequences for the development of new loading protocols to ensure that analytical models of cripple wall behavior capture their behavior accurately; and

- Should a performance expectation standard arise from this effort and other cripple wall studies, developing prequalifying test loading protocols would be warranted.

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ISSN 2770-8314
https://doi.org/10.55461/OLPV6741