The blind side: using 'canned' loading protocols in seismic testing

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ABSTRACT

The seismic behavior of a building component (e.g., shear wall) is a fundamental attribute engineers need to assess the earthquake performance of a building. It is no surprise that component behavior is often dependent on the loading history. Repeatedly cycling a specimen with increasing displacement amplitudes tends to produce different response than simply applying a monotonically increasing displacement. This is quite intuitive to most engineers. However, laboratory tests are often carried out with "canned" (termed here as "standard") fully-reversed cyclic loading protocols that do not reflect actual earthquake loadings. Why? Because of historical precedence of using certain standard protocols, and general recognition that standard protocols are considered worst case loadings. With the emergence of performance-based engineering, it is essential to use realistic estimates of component performance. We summarize standard protocols commonly used in practice and point out problems of using them as the main (and sometimes only) source of seismic performance determination. We then compare the incremental dynamic analysis (IDA) results of building models using component backbone curves based on "standard" lab tests to a model using more realistic backbone curves. It is found that the second model is much more rugged and has better agreement with the expected performance of new building designs. Given the challenge of accurately and economically simulating the degradation behavior of structural components, it is encouraged that researchers need to include testing with more realistic loading protocols so that the results are best suited for performance-based engineering.

Keywords: loading protocols, experimental testing, cyclic performance, performance-based seismic engineering

INTRODUCTION

The inelastic behavior of a building component is a fundamental attribute that engineers often need to assess building seismic performance. It is no surprise that the behavior is dependent on the loading history. This concept is not new. In 2000, Krawinkler et al., who were responsible for several popular loading protocols, noted that "the choice of testing program and associated loading history depends on the purpose of the experiment, type of test specimen, and type of anticipated failure mode..." [1]. With the growing popularity of performance-based engineering, it is essential to have good estimates of component behavior during actual earthquakes. However, the vast majority of testing programs still lack a thorough treatment of loading protocols, and often use those that have been used in the past. This is understandable due to the expense associated with laboratory tests thus limiting the numbers of specimens that can be tested within a given budget. However, the lack of attention to loading protocols has created a "blind side" in the understanding of component behavior.

In this paper, we summarize "canned" (termed here as "standard") protocols commonly used in experimental studies. Next, we note the shortcomings of these standard protocols including the fact that they can lead to low estimates of component ductility, which in turn, can lead to conservative acceptance criteria. To illustrate this point, we compare the incremental dynamic analysis results of a model using backbone curves based on hypothetical standard laboratory tests to a model using more realistic backbone curves. We show that the performance of the second model is more consistent with the expected performance of new building designs. Given the challenges of estimating building seismic performance, we encourage researchers to include testing with more realistic loading protocols so that the results are best suited for performance-based engineering.

LOADING PROTOCOLS

Krawinkler [2] summarizes loading protocols frequently used in practice. Most common are "standard" protocols having fully-reversed cyclic loading with progressively increasing displacement amplitudes (Figure 1). However, loading patterns during actual earthquakes can be very different from standard protocols. Figure 2 shows loading protocols derived from numerous earthquake response simulations of four-story buildings. Figure 2a shows a collapse-consistent protocol representing a near-collapse condition. In essence, it has numerous undulations centered on one major excursion in the positive direction. Figure

2b shows a MCE-level protocol based on the median results at maximum considered earthquake (MCE) shaking intensities. The MCE-level protocol has smaller peak drift than the collapse-consistent protocol as expected since the latter is an incipient collapse condition. Both protocols are similar in as much as they have relatively few major excursions having a one-direction bias. A DE-level protocol corresponding to a design earthquake (DE) is similar to the MCE-level protocol except with several more major excursions at smaller peak drift.

It follows that results from component laboratory tests using standard protocols will differ from those using actual earthquake loading patterns. Recognizing the potential problems with standard loading protocols, the ASCE 41 standard [7], *Seismic Evaluation and Retrofit of Existing Buildings* was revised and the latest version ASCE 41-17 (section 7.6) now emphasizes the importance of protocols in the formulation of backbone curves. The rationale for the change can be found in reference [6].

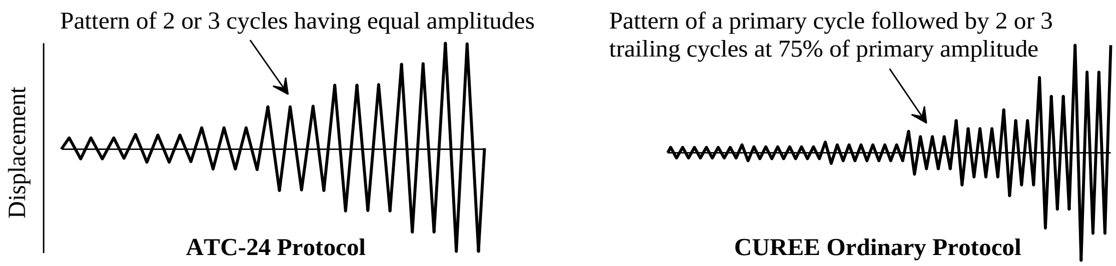

Figure 1. Representative standard loading protocols: ATC-24 [3] and CUREE ordinary [4].

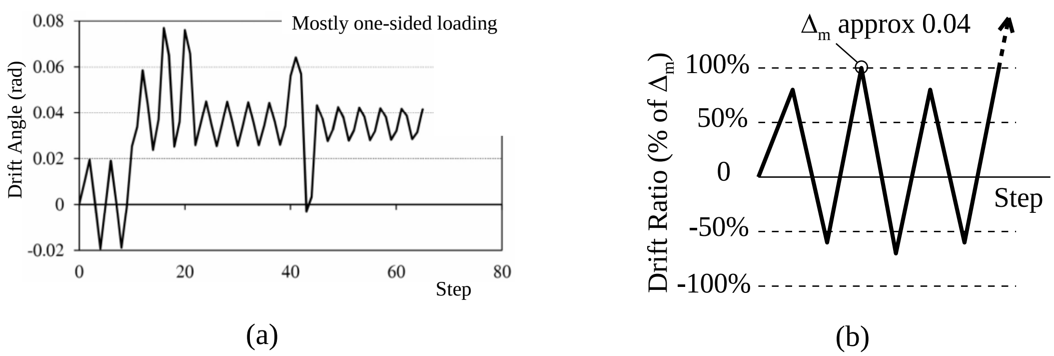

Figure 2. Loading protocols based on simulated building response. (a) Collapse-consistent protocol (adapted from Figure 8a in [5]), and (b) maximum considered earthquake (MCE) protocol based on median building response (adapted from Figure 18a in [6]).

EFFECT OF PROTOCOLS ON LABORATORY TEST RESULTS

The choice in loading protocol has two effects that are discussed below: (1) it sets the values for modeling parameters, and (2) it sets the values for acceptance criteria. Both issues can cause problems on their own. If the model is not capable of adequately capturing the varying behavior due to different loading histories, an unrealistic prediction of performance can result. This can include an under-prediction of demands in adjacent members that may have been designed using capacity-protected methodologies. Likewise, if the acceptance criteria values are set lower than would be indicated by actual earthquake-consistent loading histories, a false indication of unacceptable performance can result.

Three cases from the literature are discussed to illustrate the significant effect loading protocols can have on test results. The first is from a series of plywood shear wall tests shown in Figure 3. In this case, there is little difference between the envelope of cyclic response and a monotonic test out to about 3 % drift. However at about 4 % drift, the cyclic envelope strength was less than one-half that of the monotonic envelope strength.

In performance-based engineering (e.g., ASCE 41), a backbone curve is formulated as an envelope of component hysteresis loops derived via laboratory testing and is a key factor for displacement-controlled component modeling and acceptance criteria. A backbone curve for the plywood shear wall would be vastly different depending on which envelope is taken as representing the behavior. However, a collapse-consistent protocol representing near-collapse seismic behavior is closer to the monotonic test (Figure 2a). Hence, use of the backbone from the cyclic test underestimates shear wall seismic ductility, and can lead to rejection of a building that is otherwise acceptable should the modeling and acceptance criteria be based on laboratory tests using realistic earthquake loading patterns.

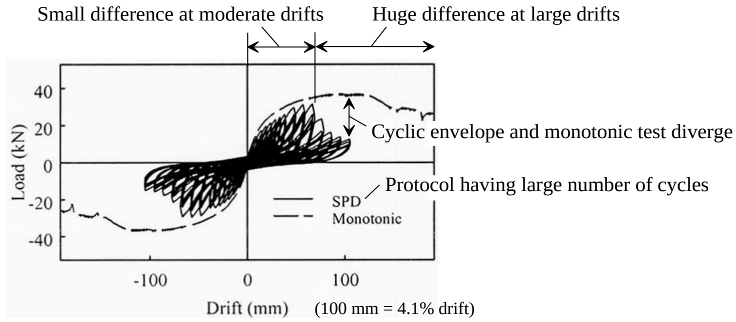

Figure 3. Results from experimental tests of identical plywood shear walls using two different loading protocols (adapted from Figure 6 in [8].

The second case is from a series of tests on reinforced concrete bridge piers shown in Figure 4. The backbone curves (envelopes) are essentially the same out to 2.5 % drift, but they differ significantly for larger drifts depending on the protocol. Standard-type fully-reversed cyclic loadings having numerous cycles produce backbones with the smallest drift capacities.

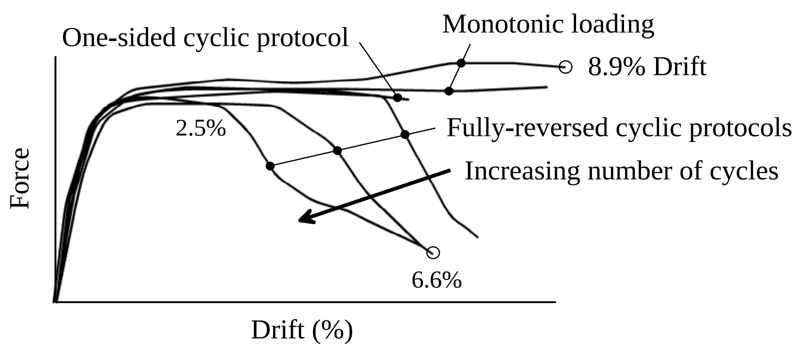

Figure 4. Envelopes of cyclic test results (backbones) from six identical reinforced concrete bridge piers subjected to various loading protocols. Figure adapted from Figure 2-20 in FEMA P-440A report (ATC-62 project), The Effects of Strength and Stiffness Degradation on Seismic Response [9].

The third case is from a series of wide-flange steel column tests (Figure 5). Drifts at which various types of damage occurred were determined from 38 tests using standard loading protocols, and nine tests using collapse-consistent protocols representing a near-collapse condition. For drifts beyond 1.3 % (onset of flange local buckling, LB), the drift defining damage states from a collapse-consistent protocol are *two-times* larger than those from using a standard protocol.

Performance-based engineering component acceptance criteria are typically set at particular damage states. For immediate occupancy (IO), the maximum allowable drift might be set at LB, and there is little difference in test results using the different protocols (1.3 % drift). However, for collapse prevention (CP), a drift limit might be set at the onset of excessive damage (ED), and the result based on a collapse-consistent protocol (9.6 %) is over twice that from a standard protocol (4.3 %).

Building columns could be rejected using CP acceptance criteria based on tests using the standard protocol, whereas they might be permissible using criteria based on the more realistic collapse-consistent protocol. This is one reason why studies applying ASCE 41 methodologies to steel buildings designed to the latest ASCE 7 requirements reveal that ASCE 41 often rejects “new” buildings meeting current building code as being unsafe [11,12]. Since many prior laboratory tests used standard protocols, it is likely that many of the ASCE 41 default acceptance criteria are conservative and default component backbone curves are conservative absent modeling techniques that sufficiently capture the effects of different loading histories (thus are able to simulate both monotonic and cyclic response).

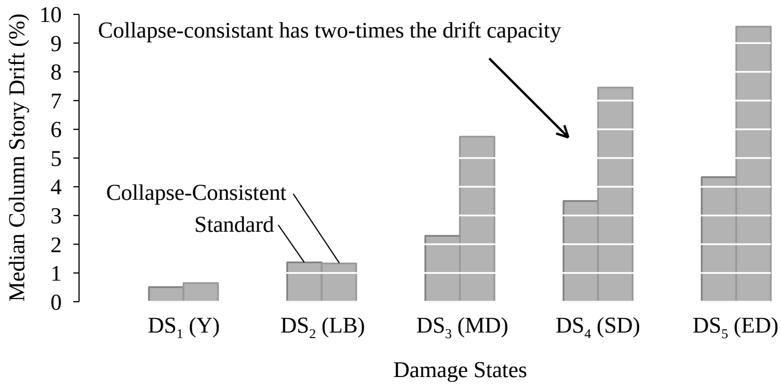

Figure 5. Drifts defining column damage states from laboratory tests using different loading protocols (standard and collapse-consistent). Data taken from Tables 3 and 8 of [10]. Y = onset of yielding, LB = onset of local buckling, MD = onset of moderate damage, SD = onset of severe damage, and ED = onset of excessive damage.

Key points follow.

- Typical standard protocols do not mimic actual earthquake demands. Laboratory tests using such protocols tend to result in component response envelopes (backbones) that have progressively decreasing deformation capacities according to increasing numbers of fully-reversed loading cycles. They also can produce component damage modes that do not occur under more realistic earthquake loading patterns [13] which may promote spurious component models.
- For relatively small drifts (say 2 % to 3 %), the envelopes of response (backbone curves) are mostly independent of the loading protocol.
- For relatively large drifts (say > 3 %), backbone curves are heavily influenced by the loading protocol.

BACKBONE CURVES AND COLLAPSE PERFORMANCE

Presented below is a case study of a simplified model of three-story steel building to illustrate the influence of the component backbone curve shape on the collapse performance (Figure 6). The building was proportioned according to ASCE 7-16 [14] for a site having high seismicity representative of the western U.S. (Table 1). The model does not have cyclic degradation.

Two models are formulated having the same properties except for the backbone curves representing the lateral force-drift relationship in each story. The first is a "Realistic" model having backbones with gradual strength degradation (Figure 6) intended to represent results from lab tests reflecting earthquake loading patterns (Figure 2). The second is a hypothetical "Standard" model based on backbones that degrade at a higher rate than that of the Realistic model intended to mimic the trend in Figure 5. That is, damage state drifts from use of standard protocol are much smaller than those from use of the collapse-consistent protocol.

Incremental dynamic analyses (IDA) are carried out using two suites of records representing 2,475-year return period earthquakes for sites in the cities of Los Angeles and Seattle (Figure 7). The Los Angeles suite represents coastal California earthquakes having mostly near-fault records, whereas the Seattle suite has many records from subduction earthquakes having larger site-to-source distances [15].

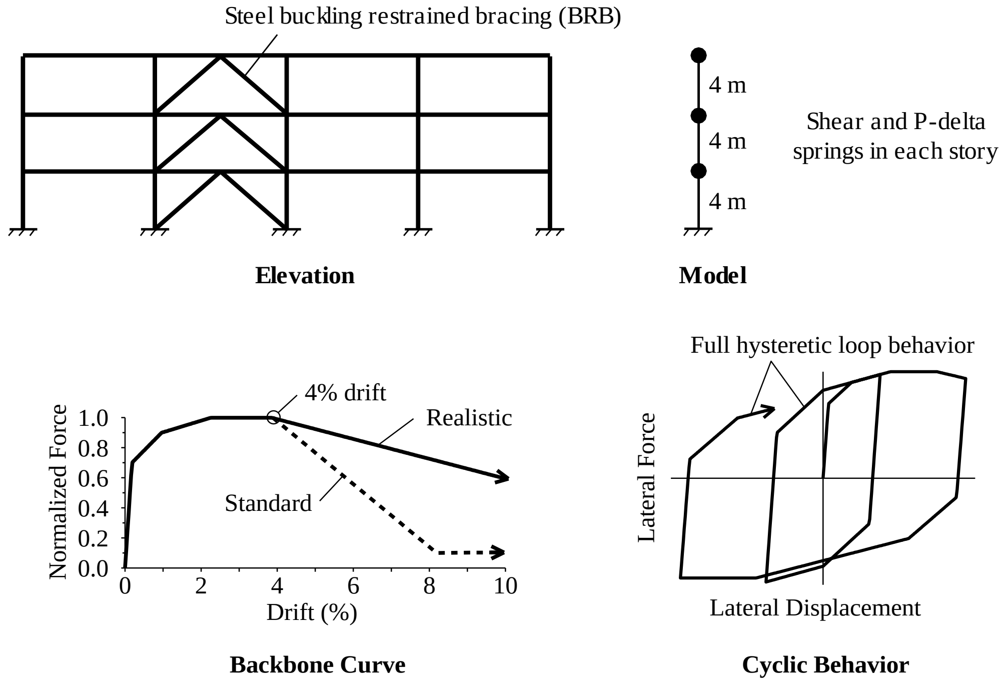

Figure 6. Case study building.

Table 1. Case study building.

Property	Value
Fundamental period[a] (T)	0.47 s
Ultimate base shear[b] (V_U)	$0.38W$
Story strength distribution (top-to-bottom)	$0.19W : 0.31W : 0.38W$

[a]Period: $T = C_1 h^x$, where h = building height, $x = 0.75$, $C_1 = 0.02$.

[b]Ultimate base shear: $V_U = \dfrac{S_{DS} \times \Omega}{R} W$

Where, $S_{DS} = 1.2$, $R = 8$, $\Omega = 2.5$, and W = 27,000 kN = 6,000 kips.

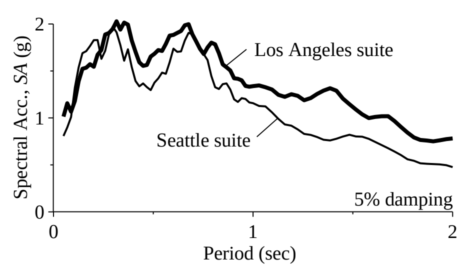

Figure 7. Median response spectra from earthquake suites. Each suite has 20 records.

The IDA approach used here is like that used by FEMA P-695 for the quantification of building seismic performance factors [16]. A suite of ground motion records is taken as representative of a characteristic earthquake in which the intensity (e.g., PGA) of individual records exhibit dispersion about the median value of the suite. A best estimate is taken as the median intensity of the suite when scaled such that one-half of the records in the suite (10 of 20) cause the building to collapse (large unbounded lateral displacements).

Figure 8 shows sample time history results from the two models when subjected to the same earthquake record from the Seattle suite. The Standard model has a 32 % larger peak drift than the Realistic model. Hence, component backbone curves derived from lab tests using standard protocols can lead to over-estimation of peak displacement response.

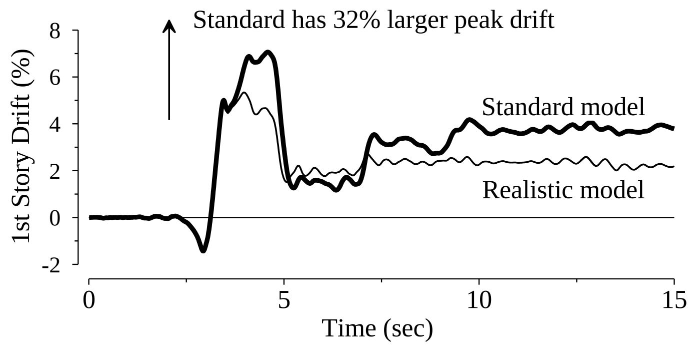

Figure 8. Sample first story drift time histories from Standard and Realistic models.

Figure 9 shows the hysteretic response of the first story from the same Seattle record. The rapid strength loss at large drift in the Standard model causes it to have greater peak drift than the Realistic model.

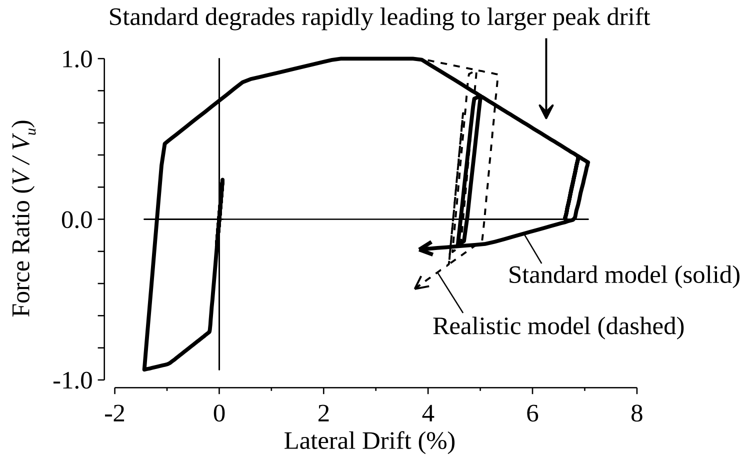

Figure 9. Sample first story hysteretic response from Standard and Realistic models

Figure 10 compares the median spectral accelerations (at a period of 1 s) for the two models and two earthquake suites. The Realistic model collapses for one-half of the records (10 of 20) when the Seattle suite is scaled by 1.85 corresponding to a median spectral acceleration of 2.14 g. The Standard model collapses for one-half of the records when the Seattle suite is scaled by 1.38, corresponding to a median spectral acceleration of 1.60 g. Hence, the Realistic model can survive a shaking intensity 34 % greater than that for the Standard model (1.34 = 2.14 ⁄ 1.60). The trend is similar for the Los Angeles suite with the Realistic model being able to survive shaking 21 % more intense than that for the Standard model. Hence, building models consisting of backbones based on laboratory test data from standard protocols can produce significantly conservative assessments of collapse vulnerability.

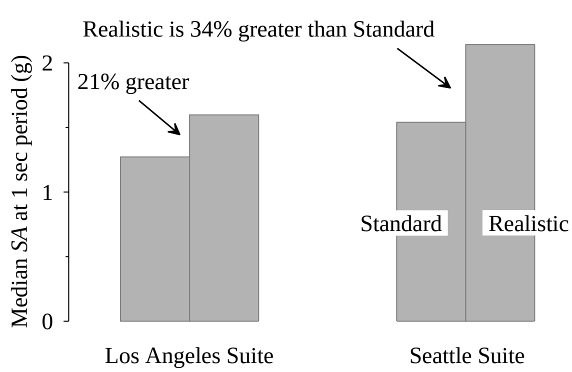

Figure 10. Standard and Realistic building model IDA results for median spectral acceleration at 1 s period causing collapse.

CONCLUSION

Standard laboratory test loading protocols typically consist of fully-reversed cyclic loading with progressively increasing displacement amplitudes. This type of protocol continues to be used in many component test programs. However, loading patterns during actual earthquakes can be very different from standard protocols.

With the emergence of performance-based engineering, it is essential to have good estimates of component behaviors during actual earthquakes. There are two key shortcomings when using laboratory test data derived via use of standard protocols.

- Component ductility can be underestimated, which in turn, can lead to conservative acceptance criteria.
- Component backbone curves used in building models for seismic evaluation can lead to over-prediction of peak inelastic displacements.

The combination of above has a compounding effect that can result in rejection of a building that would otherwise be considered acceptable should component behaviors be determined from tests using realistic earthquake loading patterns. We encourage researchers to include tests with more realistic loading protocols so that the results are better suited for performance-based engineering.

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