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LOADING PROTOCOLS AND BACKBONE CURVES: U.S. AND JAPAN PERSPECTIVES

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Abstract

With the gaining popularity of performance-based engineering, it is essential to have reliable estimates of component (e.g., steel beam or column) performance under actual earthquake loading demands. Physical laboratory tests are traditionally used to determine component inelastic behaviors. A loading protocol refers to the sequence of quasi-static displacements applied to a test specimen to simulate the demands imposed by an earthquake. The vast majority of *standard* tests use loading protocols consisting of fully-reversed cyclic loading with progressively increasing amplitudes. Standard tests are in many cases, unlike the demands posed by earthquakes, and using realistic earthquake loading patterns can lead to different conclusions on component performance. Unfortunately, there are relatively few tests using realistic earthquake loading patterns. Likewise, there are relatively few tests using monotonic loading that may best represent the demands at incipient collapse caused by large near-field type shaking.

In the United States, a component *backbone* curve representing the inelastic force-deformation behavior is typically taken as the envelope of laboratory test hysteresis data. A shortcoming is that the backbone curve is dependent on the loading protocol used in the tests, and customary standard tests can lead to overly pessimistic estimates of component behavior. This can cause rejection of buildings that would otherwise be considered acceptable should component behaviors be based on tests using realistic earthquake loading patterns. It is therefore recommended that future tests consider realistic earthquake loading protocols so that the results are best suited for performance-based engineering.

Alternatively, a Japanese *skeleton* curve concept using decomposition of standard test data may be a way to leverage the current wealth of available standard test data thereby providing a better description of component seismic performance than simply taking an envelope of standard test data. The skeleton curve consists of horizontally stacked hysteretic loops that resemble a monotonic curve. To demonstrate this concept, a simple *adaptive* component model incorporating skeleton curves is presented. The model accounts for both in-cycle and cyclic strength degradation. It is shown to mimic observed monotonic and cyclic behaviors depending on the displacement loading history. The model is simple and can be easily incorporated into structural analysis computer programs used for building evaluation. Ongoing work includes more validation of the adaptive model as well as possible extension to other materials such as reinforced concrete and wood components.

Keywords: loading protocols; performance-based engineering; backbone curves; experimental tests, steel components

1. Introduction

Performance-based engineering, in which a structure is proportioned to meet certain predictable performance requirements, necessitates good estimates of component (e.g., steel beam) inelastic behavior during earthquakes. In the United States, a so-called *backbone* curve is the customary way of describing component behaviors over a range of deformations. It is formulated as an envelope of hysteresis loops from component experimental tests and is a critical factor in component modeling and acceptance criteria [1].

To determine backbone curves, the vast majority of steel component tests use *standard* displacement loading patterns (protocols) that do not necessarily simulate realistic earthquake demands. Results from standard tests can lead to overly conservative component backbone curves (i.e., indicating premature failure), especially for components meeting current ductility requirements in steel construction standards. This can cause rejection of buildings that would otherwise be considered acceptable should component behaviors be based on tests using loading patterns that simulate actual earthquake demands [2, 3].

This paper underscores the influence loading protocols have on backbone curves and demonstrates how a Japanese *skeleton* curve concept can be used in a simple *adaptive* model for steel components. Strength degradation caused by local buckling is separated into in-cycle and cyclic parts. The model incorporates the skeleton curve to mimic observed monotonic and cyclic behaviors depending on the displacement loading history. It better describes inelastic behaviors as opposed to a conventional approach using an envelope of the standard test hysteretic loops. The model can be easily implemented into structural analysis computer programs for the seismic evaluation of structures.

2. Loading Protocols

Figure 1 contrasts a standard protocol to that of a simulated earthquake response from a building undergoing inelastic actions. It consists of a series of fully-reversed displacement cycles having progressively increasing amplitudes. In contrast, the earthquake response has relatively few cycles with a one-direction bias.

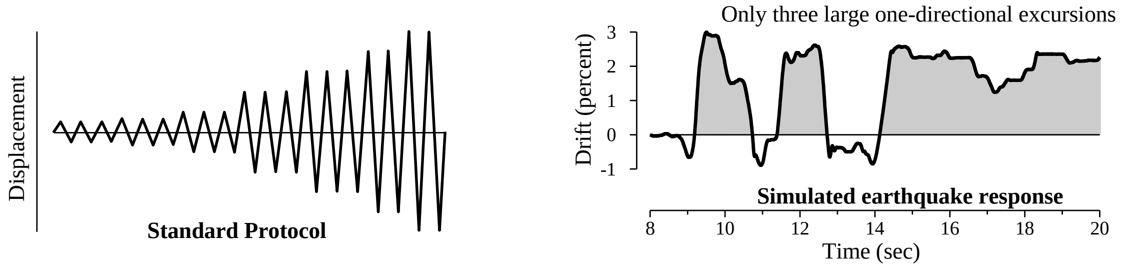


Fig. 1 – Typical standard protocol [4] compared to simulated building inter-story drift earthquake response.

With the advancement and increasing use of nonlinear structural analysis, a better understanding of actual seismic response has led researchers to propose different protocols better reflecting building inelastic seismic response (Figure 2). Such protocols are termed here as *realistic*. Realistic protocols differ from standard protocols, and their use can lead to different conclusions about component performance. Unfortunately, relatively few tests have been conducted using realistic protocols as compared to the plethora of tests using standard protocols. Likewise, relatively few tests have been conducted using monotonic loading that provide insights about component performance at near-collapse displacements [5].

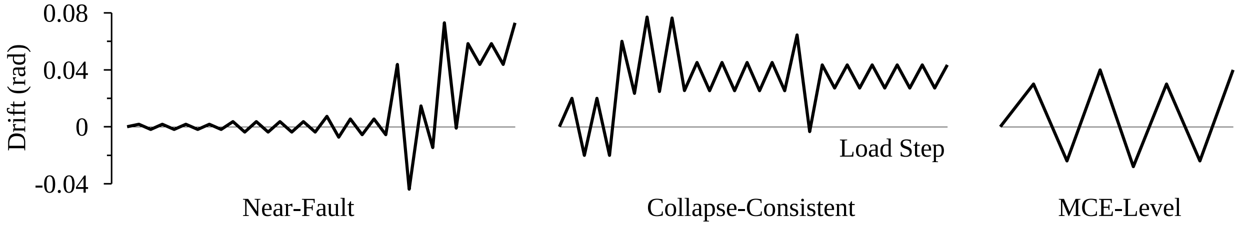


Fig. 2 – Realistic protocols simulating building inelastic drift response during earthquakes: Near-Fault [6], Collapse-Consistent [7], and MCE-Level [8].

3. United States Backbone Curves

Figure 3 shows backbone (envelope) curves from component tests of steel reduced beam section (RBS) connections using standard and realistic loading protocols [9]. The displacement reversal points control where there is an abrupt decline in force giving the impression that the component has a 5 % ultimate drift capacity in the standard test, whereas it has 8 % ultimate drift capacity in the realistic test (1.6-times larger). In reality, the component can have greater capacity than that from either test since the ultimate drifts are an artifact of the protocol reversal points, and not an intrinsic property. This is of particular importance for ductile components such as those designed and constructed in accordance with current steel construction standards such as AISC 341-16 [10]. Nevertheless, realistic tests are most likely better representations of earthquake performance since the loadings mimic actual earthquake demands. Additional shortcomings of standard tests are discussed in reference [8]. Given the abundance of tests conducted using standard loading protocols, it may be advantageous to decompose existing standard test results to gain insights about component performance during earthquakes, as proposed in the next section.

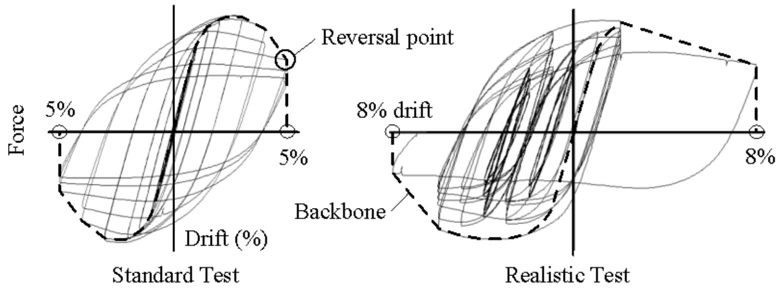


Fig. 3 – Backbone curves from RBS connection tests using standard and realistic loading protocols.

4. Japanese Skeleton Curves

Yamada et al. [11, 12] studied the hysteretic behavior of steel beam-columns having rectangular hollow shaped (RHS) sections. It was found that the cyclic degradation of the moment-rotation relationship caused by local buckling can be represented by a so-called *skeleton* curve. A novel way to decompose the results from a standard test to create a skeleton curve was developed. The process takes the individual hysteretic loops from a standard test and expands them to resemble a monotonic curve. The skeleton curve was then incorporated into an analytical model that reasonably captured RHS inelastic moment-rotation behaviors under random earthquake loadings.

Used here is a modified version of the Yamada skeleton approach as presented by Kimura et al. [13, 14, 15] for steel sections having H-shapes. Figure 4 illustrates the decomposition of the positive-side hysteretic loops to construct a skeleton. The skeleton strength deterioration is based on segments of the hysteretic loops that have declining strength. The segments are shifted horizontally so they connect at the respective unloading rotation in the previous loading cycle. Another skeleton curve can be constructed in a similar manner using the negative-side data.

For the case in Figure 4, the skeleton suggests ductile behavior out to about 0.2 rad that is well beyond the limits of the standard test (0.04 rad). The skeleton curve can serve as an improved (less conservative) backbone curve compared to the conventional approach of taking an envelope of the standard test hysteretic loops. The skeleton curve lacks an abrupt decline in strength like that in conventional backbones (Figure 3) signaling the ultimate rotation. Thus for component acceptance criteria, it may be appropriate to set the ultimate rotation as when the skeleton moment drops below some value (e.g., below 50 % of peak value). However, for computer modeling in building analysis/evaluation, it seems more correct for the component to follow the skeleton even at relatively large rotations.

It should be noted that if a monotonic curve is available, then it can be referenced directly without construction of a skeleton curve. However, there is relatively scant monotonic test data so using decomposition of the plentiful standard test data is an attractive alternative.

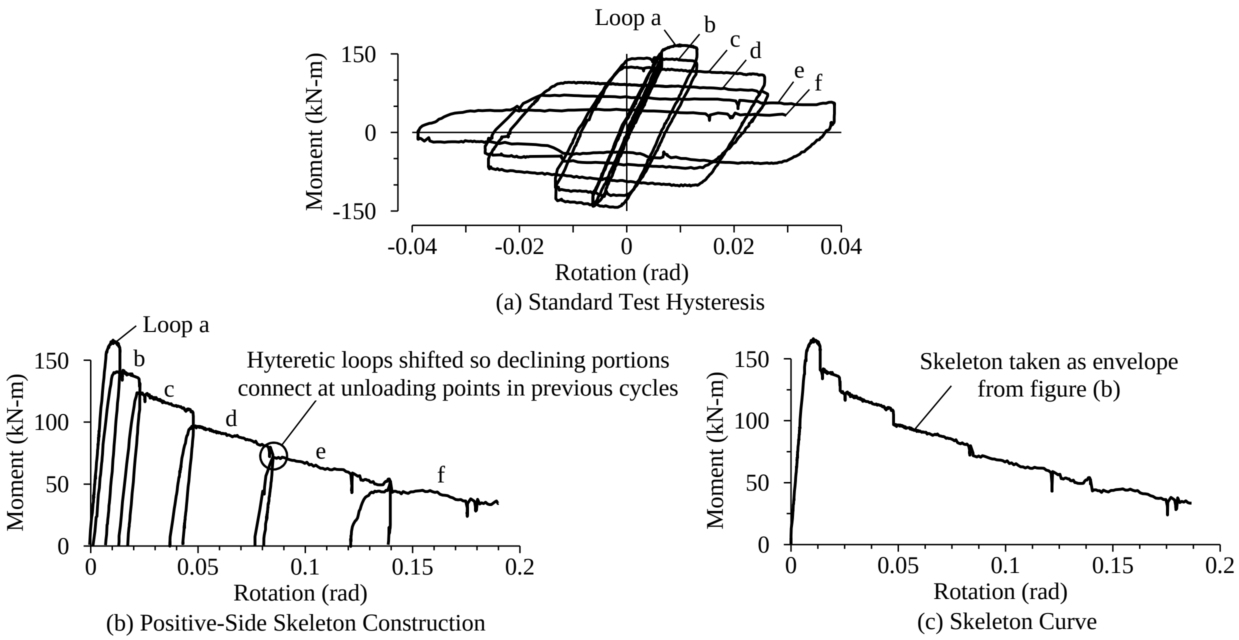


Fig. 4 – Skeleton curve derived using positive-side hysteretic loops from standard test.

5. Case Study Using Skeleton Curves

To further explain the concept of skeleton curves and how they can be used in an adaptive model, a set of experimental test data by Kimura et al. [13] for steel H-shaped sections is studied. The test arrangement and hysteretic responses from two tests are shown in Figures 5 and 6, respectively. Case A had no axial force, and Case B had an applied constant compressive axial force of 30 % of the yield force. Conventional backbone (envelope) curves are denoted by red dashed lines in Figure 6.

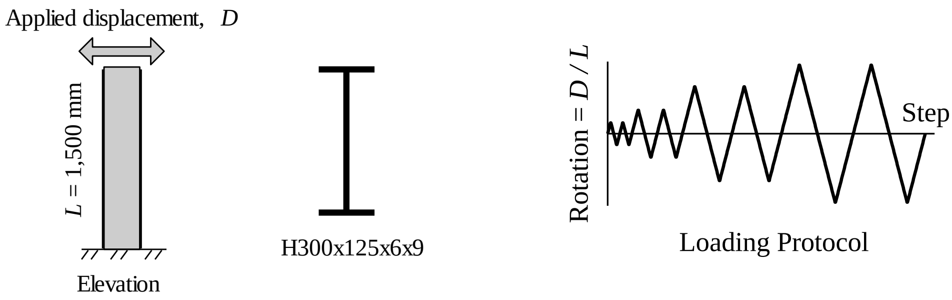


Fig. 5 – Experimental arrangement of standard test.

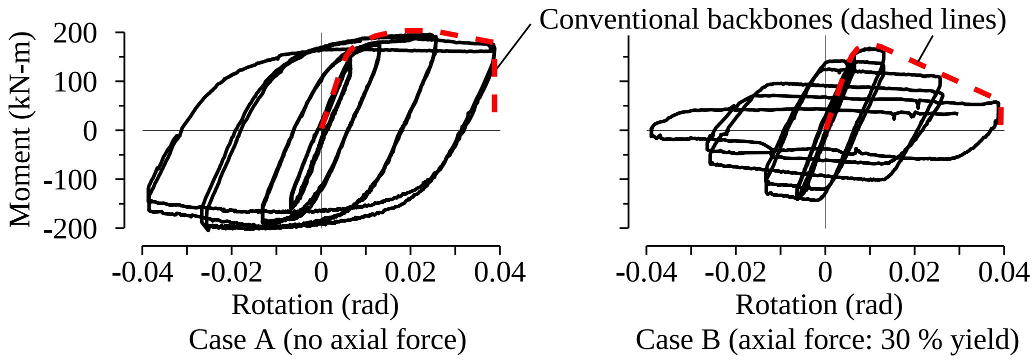


Fig. 6 – Hysteretic response from standard tests.

Figure 7 shows the skeleton curves using the hysteretic loop decomposition technique explained in section 4. The skeleton curves are in reasonable agreement with the monotonic curves for both cases. Case B exhibits earlier strength degradation that is more rapid than that for Case A due to the compressive axial force in Case B promoting local buckling. Conventional backbone curves (red dashed lines), taken as envelopes of the hysteretic loops in Figure 6 indicates ultimate rotation of 0.04 rad defining failure simply due to the fact this was the maximum rotation used in the tests. Both Case A and B would have ultimate rotations well beyond 0.06 rad based on the skeleton curves (Figure 7). Hence, using the skeleton as the backbone curve could have an ultimate rotation for use in acceptance criteria at least 50% greater than the conventional backbones.

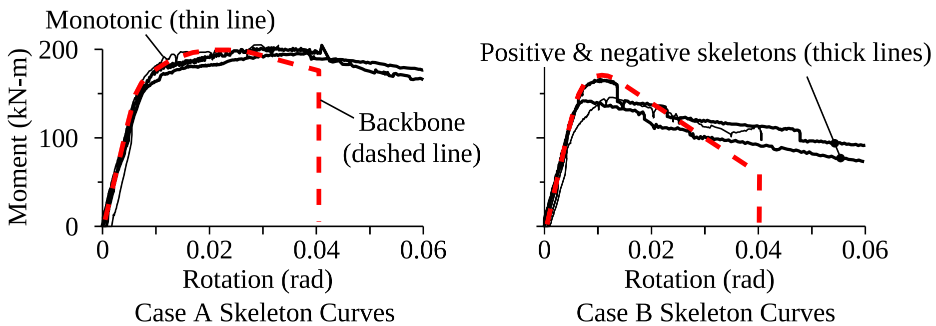


Fig. 7 – Skeleton curves derived from decomposition of standard test hysteretic loops.

Figure 8 shows piecewise linear representations of the skeleton curves from Figure 7. These will be used in a simple adaptive model described in the next section.

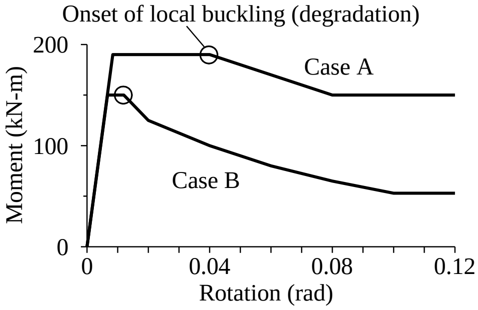


Fig. 8 – Piecewise linear skeleton curves from standard tests.

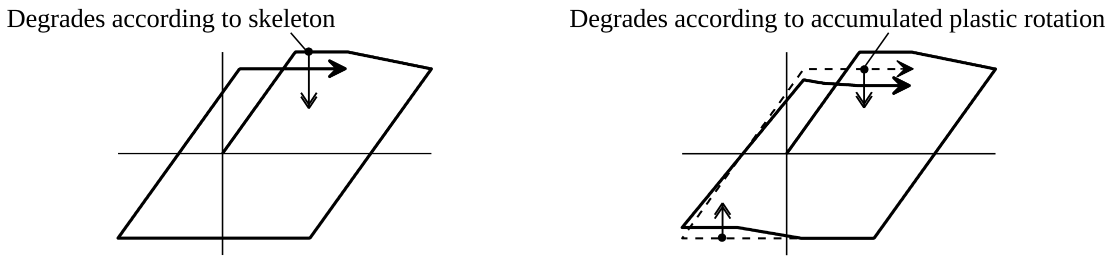
6. Adaptive Model

A simplified version of the Yamada et al. approach for the moment-rotation behavior is presented here. It is based entirely on observations of standard test hysteretic behaviors through use of skeleton curves to account for strength degradation. It should be noted that if a monotonic curve is available, then it can be referenced directly without construction of a skeleton curve. The model is termed *adaptive* because it can reflect monotonic as well as hysteretic strength degradation depending on the deformation loading history.

Strength degradation can be considered as having two parts [16]: in-cycle and cyclic. In-cycle is characterized by loss of strength occurring within a single cycle (e.g., during a monotonic push). Cyclic is delineated by loss of strength occurring in subsequent cycles (e.g., after cycles having the same peak-to-peak displacements).

6.1 In-Cycle Degradation

The skeleton curve serves as the boundary limit for the peak moment. In-cycle degradation is controlled by the skeleton curve as indicated in Figure 9a. The behavior is elasto-plastic and as the rotation increases, the ultimate moment progressively decreases according to the skeleton curve boundary.



(a) In-Cycle Degradation (b) Cyclic Degradation

Fig. 9 – Adaptive mode strength degradation controlled by skeleton curve.

6.2 Cyclic Degradation

Cyclic degradation is modeled by a shrinking of the backbone curve according to cyclic actions (Figure 9b). The backbone curve is progressively scaled smaller as a function of the cumulative positive (*APR+*) and negative plastic rotations (*APR-*). The *smaller* of *APR+* or the absolute value of *APR-* is taken as a measure of the cyclic action. A scale factor is computed as the ratio of moments from the skeleton curve (Figure 10). The scaling occurs continuously as the plastic rotations accumulate during the loading history.

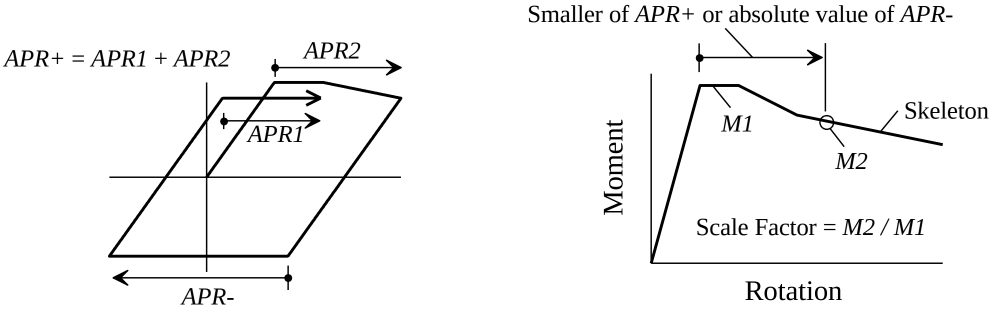


Fig. 10 – Adaptive model cyclic strength degradation feature.

6.3 Comparison to Test Results

The adaptive model was implemented into a computer program and numerical simulations performed. The program has rotation as input and computes the moment according to the adaptive model algorithm described above. A future step is to implement the model into a structural analysis program for building seismic analysis.

Figure 11 compares the results from the adaptive models to monotonic test results. The models produce close fits to the tests. This is expected since there is no cyclic action and therefore no cyclic degradation occurs in the model.

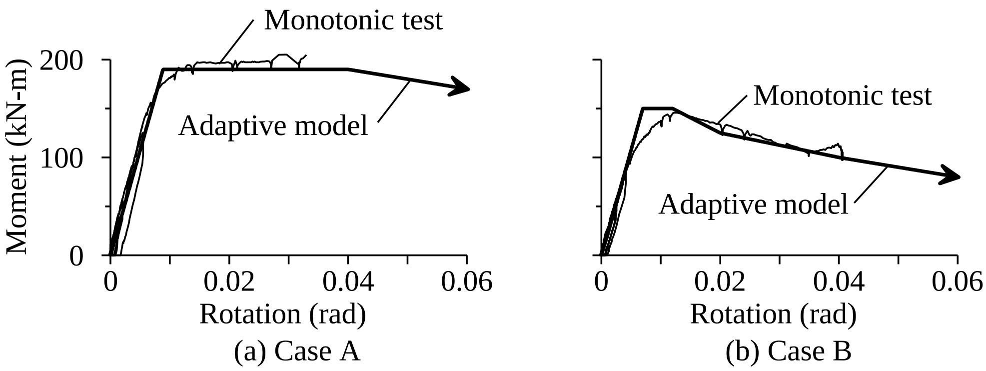


Fig. 11 – Comparison of monotonic results.

The Case A adaptive model hysteresis is compared to the standard test in Figure 12. The model exhibits reasonable agreement with the test, albeit the strength degradation is modest.

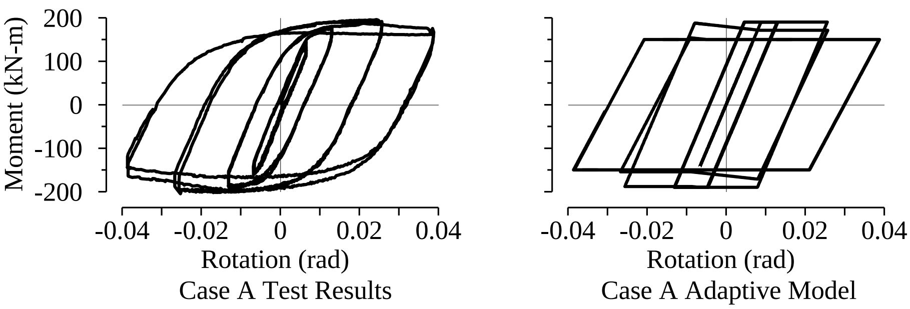


Fig. 12 – Comparison of Case A hysteretic response (no axial force).

Figure 13 shows the Case A moment versus cumulative absolute rotation. This can be thought of as a pseudo-time history of moment response. The model reasonably captures the degradation of peak moments in the test and has an excellent fit out to about 0.3 rad cumulative rotation.

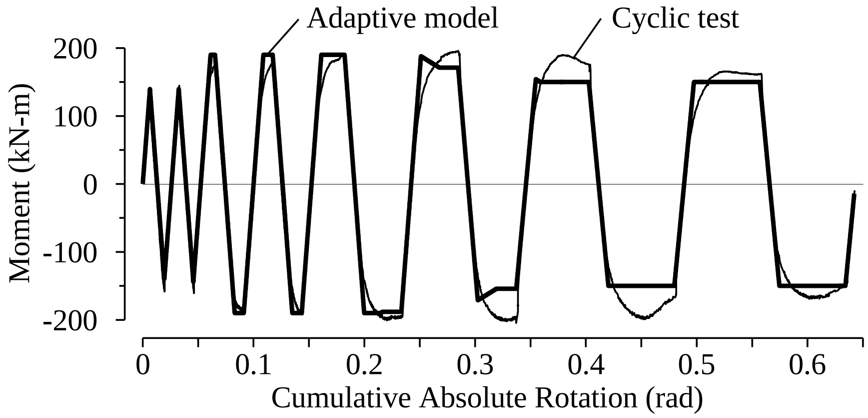


Fig. 13 – Case A (no axial force) moment versus cumulative rotation (pseudo-time history).

The Case B adaptive model hysteresis is compared to the standard test in Figure 14. There is a large amount of strength degradation due to the relatively large axial compression. The model reasonably simulates the test.

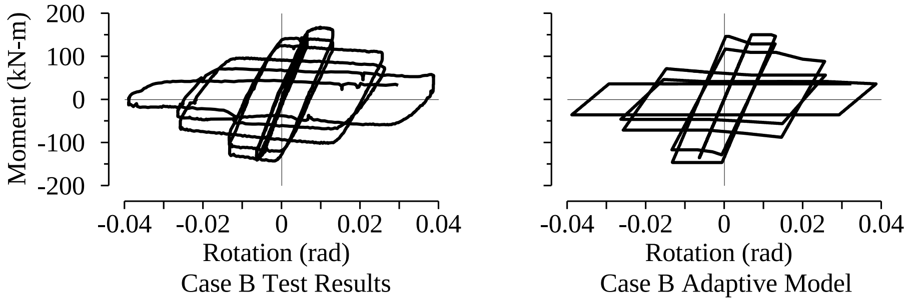


Fig. 14 – Comparison of Case B hysteretic response (axial force: 30 % yield).

Figure 15 shows the Case B moment versus cumulative absolute rotation (pseudo-time history of moment response). The model reasonably tracks the moment degradation in the test.

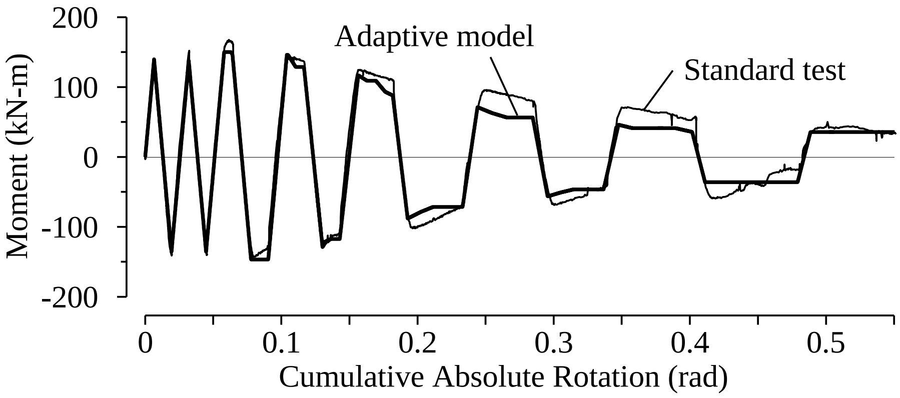


Fig. 15 – Case B (axial force: 30 % yield) moment versus cumulative rotation (pseudo-time history).

The above demonstrates how a simple adaptive model can reasonably mimic component moment response under monotonic as well standard loading patterns. The model incorporates a skeleton curve derived from decomposition of standard test data. Alternatively, should monotonic test curve be available, it can be used in place of the skeleton curve.

7. Realistic Seismic Loading Patterns

The response of the adaptive model from realistic seismic loading patterns (Figure 2) is presented in this section. The near-fault and collapse consistent protocols represent building response at an incipient collapse state. The deformations have a one-direction bias with peak drifts in the 7 to 8 % range. The MCE-Level protocol represents a modern code-conforming building response to a maximum considered earthquake. It also has a one-direction bias but with a smaller peak drift of 4 %.

7.1 Hysteretic Response

Figures 16, 17 and 18 show the adaptive model hysteretic behaviors. Both in-cycle and cyclic degradation are apparent. Case A, having no axial compressive force, has only a modest amount of strength degradation even out to 0.08 rad. This suggests that strength degradation (local buckling) plays only a minor role in the component seismic performance when there is little axial force (e.g., girders in steel moment frame structures). Case B, having significant axial compression, the situation is quite different with significant strength degradation. Hence, columns in steel moment frames are likely to be more susceptible deterioration from the effects of local buckling.

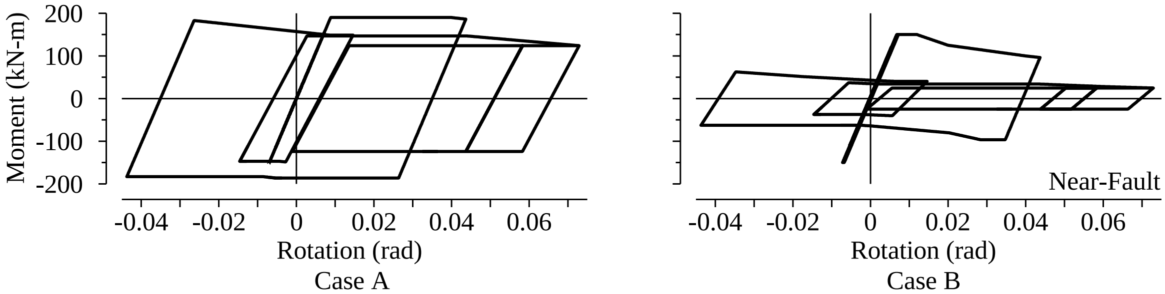


Fig. 16 – Adaptive model hysteresis from *near-fault* loading protocol.

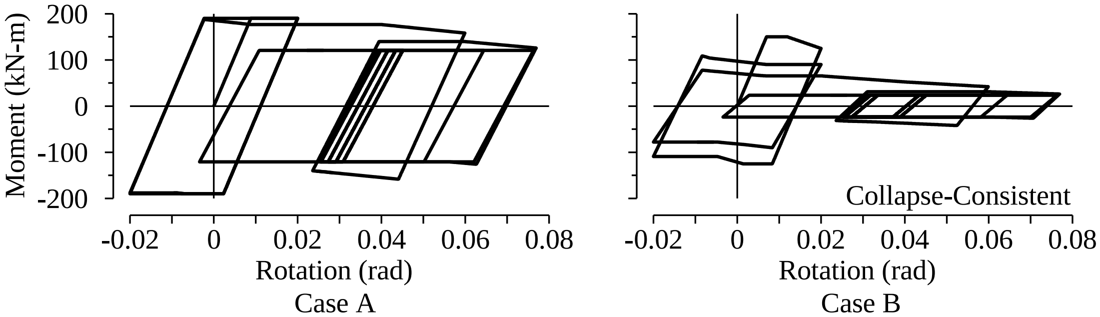


Fig. 17 – Adaptive model hysteresis from *collapse-consistent* loading protocol.

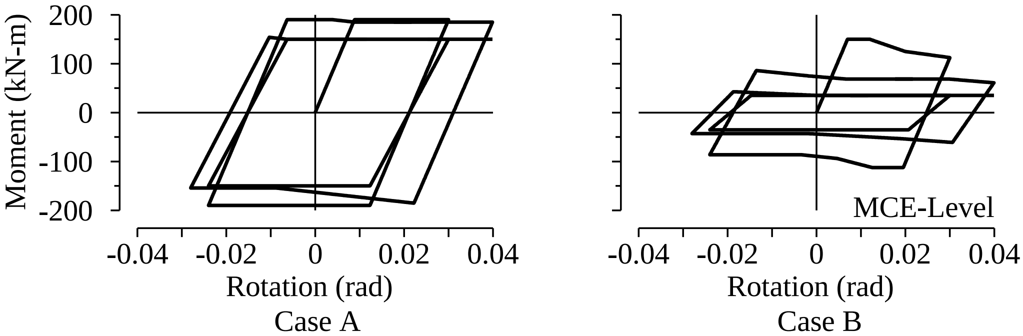


Fig. 18 – Adaptive model hysteresis from *MCE-level* loading protocol.

7.2 In-Cycle vs. Cyclic Degradation

The relative influence of in-cycle and cyclic strength degradation is illustrated in Figures 19 and 20. The adaptive model having both in-cycle and cyclic degradation is compared to the situation having only in-cycle degradation. Case A has a total 34 % strength reduction of which about one-half (17%) is from cyclic degradation. Case B has a huge total strength reduction of 83 % of which about two-thirds (64 %) is from cyclic degradation. For this example, the adaptive model in-cycle and cycle strength reduction features both had significant contributions.

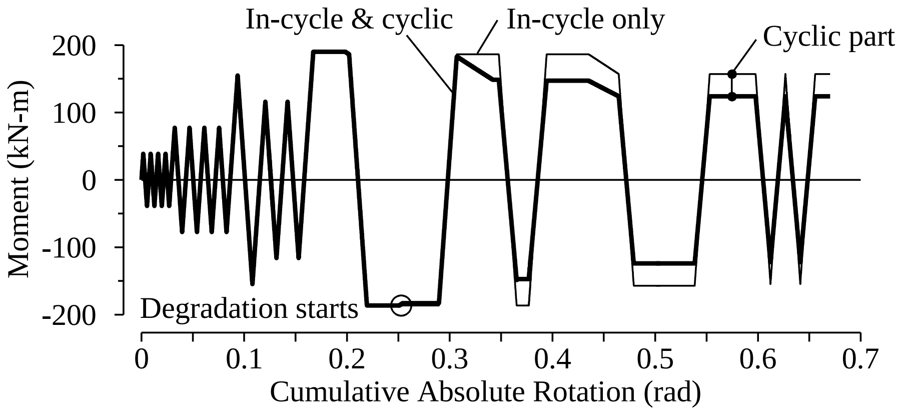


Fig. 19 – Case A (no axial force) moment versus cumulative rotation (pseudo-time history) from *near-fault* loading protocol.

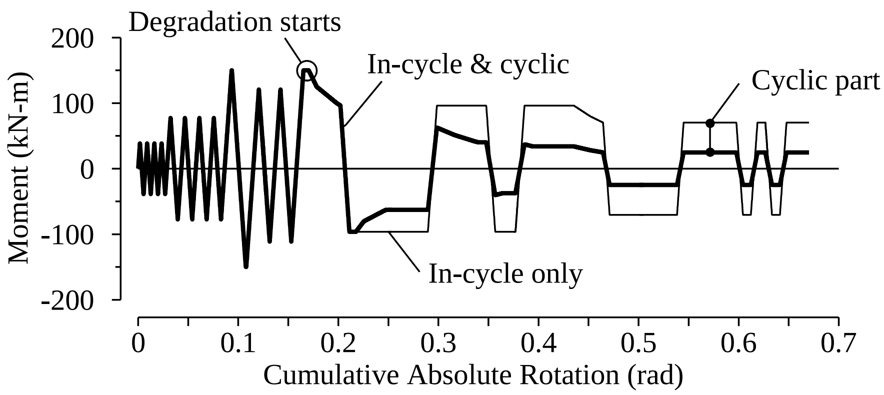


Fig. 20 – Case B (axial force: 30 % yield) moment versus cumulative rotation (pseudo-time history) from *near-fault* loading protocol.

8. Conclusion

Performance-based engineering requires good estimates of component behaviors during actual earthquakes. Customary U.S. practice describes component seismic performance by a backbone curve taken as an envelope of hysteresis loops from experimental tests. Standard tests use loading protocols consisting of fully-reversed cyclic loading unlike the loading patterns posed by earthquakes. Standard tests can lead to overly pessimistic estimates of component behavior.

There are two underlying shortcomings when using standard test data: (1) ductility can be underestimated, which in turn, can lead to very restrictive acceptance criteria, and (2) derived backbone curves used in analysis models for seismic evaluation can lead to over-estimation of peak inelastic displacements, unless those models explicitly account for degradation. These have a compounding effect causing rejection of buildings that would otherwise be considered acceptable should component behaviors be based on tests using realistic earthquake loading patterns. Hence, it is encouraged that future lab tests include realistic earthquake loading protocols so that the results are better suited for performance-based engineering.

There are large numbers of standard tests as opposed to relatively few realistic and monotonic tests. The Japanese skeleton curve concept provides a way to obtain additional useful information from standard test data. Skeleton curves resemble monotonic curves. They can provide less conservative estimates of ultimate rotations (and therefore acceptance criteria) compared to the conventional backbone approach of taking an envelope of the standard test hysteretic loops. In addition, skeleton curves can be used a simple adaptive component model as presented here. The model accounts for both in-cycle and cyclic strength degradation, and is shown to mimic observed monotonic and cyclic behaviors depending on the displacement loading history. The model is simple and can be easily incorporated into structural analysis computer programs used for building evaluation.

Ongoing work includes: more validation of the adaptive model; possible extension to other materials such as reinforced concrete and wood components; and implementation of the adaptive model into structural analysis computer programs to assess the importance of degradation in building global seismic response.

9. Acknowledgement

The authors appreciate Prof. Yamanishi of Hiroshima Institute of Technology, and Dr. Suzuki and Prof. Kimura of Tohoku University in Japan for kindly sharing the experimental test data used in this study. This project is dedicated to the continued cooperation of the Japan and United States earthquake engineering communities. Sharing of our knowledge is the best way toward the advancement of earthquake engineering thereby mitigating hazards posed by earthquakes.

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