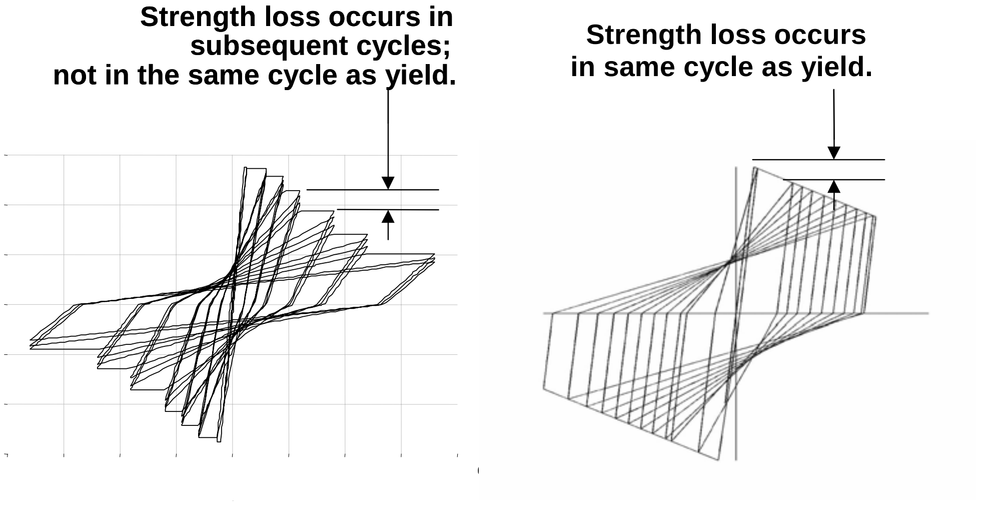
Research & Development Needs
as identified by the Applied Technology Council during development of the
FEMA 440 Report, ***Improvement of Nonlinear Static Seismic Analysis Procedures***

Under the ongoing FEMA-funded ATC-55 project, which commenced in September 2000, the Applied Technology Council (ATC) has developed guidance for improved applications of two widely used inelastic seismic analysis procedures: (1) the Coefficient Method, as defined in the FEMA 273 *Guidelines for the Seismic Rehabilitation of Buildings* (ATC/BSSC, 1997), and its successor document, the FEMA 356 *Prestandard and Commentary for the Seismic Rehabilitation of Buildings* (ASCE, 2000); and (2) the Capacity Spectrum Method, as defined in the ATC-40 Report, *Evaluation and Retrofit of Concrete Buildings* (ATC, 1996). Guidance was needed because engineers have reported that the two procedures often give different estimates for displacement demand for the same building. Recommendations for improved application of the two procedures will be published in the FEMA 440 Report, *Improvement of Nonlinear Static Seismic Analysis Procedures,* which is in the final editing stages and is expected to be published in early 2005.

In developing the improvements to be published in FEMA 440, a number of important needs for future development and improvement of inelastic seismic analysis procedures have been identified. These are summarized in the following sections.

a.) Nonlinear modeling for cyclic and in-cycle degradation of strength and stiffness

FEMA 440 makes a distinction between two types of degradation of stiffness and strength of inelastic single-degree-of-freedom oscillators (see Figure 1). This distinction had not previously been addressed explicitly by guidelines for nonlinear static procedures. Independent studies demonstrate that if strength degradation occurs cyclically, then dynamic response of single-degree-of-freedom (SDOF) systems is stable. In contrast, in-cycle loss of strength can lead to dynamic instability. It is vitally important to be able to differentiate between these two types of structural degradation. Because current nonlinear static pushover procedures cannot fully distinguish between cyclic and in-cycle strength degradation, FEMA 440 includes interim recommendations based solely on judgment for this purpose.



Strength loss occurs in subsequent cycles; not in the same cycle as yield.

Strength loss occurs in same cycle as yield.

Cyclic strength degradation

In-cyclic strength degradation

Figure 1. Force-deformation plots of cyclic response showing difference between cyclic strength degradation, which is benign, and in-cycle strength degradation, which can result in dynamic instability

Important unanswered questions include:

- What current data exist on force-deformation behavior and strength degradation of components subject to large ductility demands in a single cycle of loading?
- How does in-cycle strength loss in components affect the global dynamic stability of structural models?
- Can this effect be adequately incorporated into nonlinear static analysis procedures?
- What practical guidance can be provided for the incorporation of in-cycle degradation into nonlinear response history analysis procedures?
- How can these effects be incorporated into simplified models?

b.) Soil and foundation structure interaction

While some advances are made in FEMA 440, there is not completely adequate guidance for addressing the effects of the interaction of structures with supporting foundations and soils. This is particularly important for short-period or large footprint structures, where current models may over-predict the input ground motion. Furthermore, additional guidance on force-deformation relationships and damping characteristics of foundations is needed. Finally, there is an important need for adequate guidance on the effect of foundation rocking on structural response.

FEMA 440 supplements existing nonlinear static procedures with preliminary recommendations for the inclusion of soil-structure-interaction (SSI) effects. These recommendations augment the existing guidelines in FEMA 356 and ATC 40 for soil-foundation stiffness and strength, with approximate procedures to account for kinematic SSI and soil damping. The provisions for soil-load-deformation behavior provide a framework primarily with some default values for typical materials. The documents recommend site-specific studies if performance is significantly affected by soil properties.

Important issues include:

- Is the adaptation of linear SSI procedures for nonlinear analysis presented in FEMA 440 adequate as is, or are further adjustments warranted?
- What information is available on soil-load-deformation characteristics that might be adopted for general practical application?
- What analytical procedures are available to geotechnical engineers to estimate critical soils properties for inelastic seismic analysis?
- What are the effects of foundation rocking on inelastic seismic response and how can these effects be incorporated into practical analysis procedures?
- What are the effects of foundation sliding on inelastic seismic response and how can these effects be incorporated into practical analysis procedures?

c.) Nonlinear multi-degree of freedom simplified modeling

Current nonlinear static procedures are based on single-degree-of-freedom models, which while simple to understand, are very limited in their ability to address complex structures as well as multiple-degree-of-freedom (MDOF) effects from input seismic ground motions. FEMA 440 recognizes that current nonlinear static procedures are limited in the ability to predict reliably the effects of inelastic behavior of multi-degree-of-freedom systems. Specifically, predictions of maximum story drifts, story forces, and inelastic component demands (i.e. plastic hinge rotations) are not reliable using a single load vector. FEMA 440 also notes that current procedures for using multiple load vectors representative of the fundamental mode and one or more higher modes (multimode pushover analysis) can improve results somewhat particularly for prediction of maximum story drifts. Ongoing research suggests that multimode pushover procedures might be modified to provide better estimates of other demand parameters as well.

These improvements come at the expense of greater computational effort and less transparency, however. These barriers have been cited as obstacles to the practical application of nonlinear analysis techniques in the time domain (i.e., using response history analysis).

One of the interesting observations about multi-degree-of-freedom effects made during the preparation of FEMA 440 was that, in spite of significant dispersion among records, any single nonlinear response history analysis result often produced better estimates of maximum engineering demand parameters than any of the approximate analyses in the frequency domain. This observation suggests that there may be a viable analysis procedure that characterizes global engineering demand as the maximum displacement response of a structural model subject to shaking hazard represented by currently available regional maps (i. e., by the maps currently prepared by the U. S. Geological Survey for the National Earthquake Hazards Reduction Program). Maximum displacements might be estimated using nonlinear static procedures. Story level and component level engineering demand could then be estimated using a simplified MDOF response history analysis for a small number of ground motion records scaled to result in the same estimated global displacement demand. This approach could greatly simplify nonlinear response history analysis.

Nonlinear response history analysis might be facilitated further by the use of simplified structural models. Detailed structural models often can require hundreds of degrees of freedom making the process prone to error and complicating the interpretation of results. As noted in FEMA 440, many practitioners have used innovative sub-structuring techniques to generate “stick” or “fishbone” models that greatly simplify data management, computational effort, and visualization of results.

In summary, this issue presents the following critical questions:

- What are the limits (e.g. periods, separation of modes, mass participation) for building models when MDOF effects must be considered significant?
- Can multi-mode pushover procedures provide adequate results for systems with significant MDOF effects?
- Can maximum engineering demand below the global level (i.e. story and component levels) be predicted using a limited number of nonlinear response history analyses?
- How should ground motion records be scaled to produce global maximum displacement demands that are representative of a specific shaking hazard?
- How can MDOF structural models be simplified while still providing reliable results for practical application?
- How can strength and stiffness degradation (see item “a.” above) be adequately represented in MDOF structural models?
- How can improved methods for modeling foundations and soil structure interaction (see item “b.” above) be incorporated into MDOF structural models?
- What is the effect of concentrating masses at story levels on inelastic response, particularly for relative short structures?