Guidelines on Nonlinear Dynamic Analysis for Performance-Based Seismic Design of Steel and Concrete Moment Frames

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Abstract

Nonlinear dynamic (response history) analysis is being used increasingly in design practice for the performance-based seismic design of new buildings. In contrast to nonlinear static analysis, dynamic analysis requires more explicit modeling of cyclic response including strength and stiffness degradation as well as special consideration to selection and scaling of ground motions, definition of viscous damping, and other dynamic effects. To help bridge the gap between state-of-the-art in research and practice, the National Institute of Standards and Technology (NIST) has funded a multi-phase project through the Applied Technology Council (ATC) to develop improved modeling criteria and guidelines for nonlinear dynamic analysis. This paper highlights recently developed modeling guidelines and criteria for buildings, including both general modeling requirements as well as models and criteria that are specific to steel and concrete moment frame buildings. The general requirements address analysis and modeling requirements that are common to all material types and systems, including the relationship between modeling requirements and acceptance criteria, and the influence of modeling uncertainties. The steel and concrete moment frame guidelines incorporate the latest research information on modeling those systems. Illustrative examples are also summarized, which were used to demonstrate application of the guidelines.

Introduction

Applications of nonlinear structural analysis for seismic design of buildings have become increasingly prevalent in recent years for design and performance assessment of both new and existing buildings. Whereas nonlinear static (pushover) analysis was at the forefront of engineering practice in the mid- to late-1990's, today nonlinear dynamic (response history) analysis has become more accessible for practice. Examples of performance-based seismic design and assessment approaches that employ nonlinear analysis include:

- Building code analysis for design of new building structures, such as in ASCE/SEI 7-10, *Minimum Design Loads for Buildings and Other Structures*, (ASCE, 2010). It is noted that the forthcoming 2016 edition of ASCE/SEI 7 will have include a major update to Chapter 16, *Nonlinear Response Analyses*, which is based on draft provisions developed for the 2015 National Earthquake Hazard Reduction Program (NEHRP) *Recommended Seismic Provisions Update* (FEMA, 2015).
- Alternate analysis methods for the design of new tall buildings, such as those described in the Pacific Earthquake Engineering Research Center *Tall Buildings Initiative: Guidelines for Performance-Based Seismic Design of Tall Buildings* (PEER, 2010) and the Los Angeles Tall Buildings Structure Design Council's *An Alternative Procedure for Seismic Analysis and Design of Tall Buildings Located in the Los Angeles Region* (LATBSDC, 2015).
- Analysis to evaluate the performance of existing buildings, such as the approach presented in ASCE/SEI 41-13, *Seismic Evaluation and Retrofit of Existing Buildings*, (ASCE, 2013).
- Analysis to evaluate the overall seismic performance of buildings, including prediction of losses and other performance measures, as presented in FEMA P-58, *Seismic Performance Assessment of Buildings* (FEMA, 2012).
- Collapse analysis of structural building systems, such as the approach described in FEMA P-695, *Quantification of Building Seismic Performance Factors* (FEMA, 2009).

Utilizing the above guidelines and standards, nonlinear analysis can be used to design and assess the performance of buildings subjected to earthquake ground motions. Typical structural response measures that are output from these analyses (called "demand parameters") are the drifts of each story, the accelerations of each floor, thedeformations of yielding or "deformation-controlled" components, and the force demands in "force-controlled" components that are expected to remain elastic. These calculated demand parameters are then used to either (a) evaluate conformance to acceptance criteria using prescriptive code-based procedures (e.g., ASCE/SEI 7, ASCE/SEI 41, PEER 2010, or LATBSDC 2011), (b) predict explicit performance metrics related to functionality, losses and safety (e.g., using FEMA P-58), or (c) evaluating collapse risk (e.g., using FEMA P-695).

These previous guidelines listed above have substantially advanced the state-of-the-art in performance-based earthquake engineering, but they often lack specific guidance for creating nonlinear structural models and performing the analyses for specific material and structural systems. One exception to this is ASCE/SEI 41, which does include nonlinear modeling and acceptance criteria for specific systems, although the provisions of the current 2013 edition of ASCE/SEI 41 are geared primarily to nonlinear *static* analysis, with limited coverage of dynamic analysis and explicit modeling of cyclic behavior. This requires users to determine appropriate modeling and analysis methods for the type of building they are evaluating, which is both time consuming and can result in inconsistencies in design practice.

To help begin to remedy this, the National Institute of Standards and Technology (NIST) has funded a multi-phase project through the Applied Technology Council (ATC), through the ATC-114 project, to develop improved modeling criteria and guidelines for nonlinear dynamic analysis. Those

Guidelines, the topic of this paper, are intended to address the need to establish consistent modeling parameters and assumptions for nonlinear dynamic analysis of common types of structural systems used in buildings.

The Guidelines are intended to provide comprehensive guidelines for nonlinear analysis, and it intentionally does not repeat material from other established standards and reference documents. In addition to the reference standards cited above, users are encouraged to reference the following documents:

- NIST GCR 10-917-5, NEHRP Seismic Design Technical Brief No. 4, *Nonlinear Structural Analysis for Seismic Design, A Guide for Practicing Engineers* (NIST, 2010),
- NIST GCR 11-917-15, *Selection and Scaling Earthquake Ground Motions for Performing Response-History Analyses* (NIST, 2011), and
- NIST GCR 12-917-21, *Soil-Structure Interaction for Building Structures* (NIST, 2012).

Overview of the ATC-114 Modeling Guidelines

The ATC-114 Guidelines are composed of a series of related reports and are structured into two parts. The Part I document is the first in a series of reports to help fill this gap by providing general guidance for creating nonlinear models and conducting nonlinear analyses, with the guidance being general enough to apply to all types of structural systems. The Part II companion reports then supplement the Part I guidance by providing further details for selected structural system types. The initial Part II reports cover steel moment frames (Part IIa) and reinforced concrete moment frames (Part IIb). The future vision is for these Guidelines to be further extended to include additional Part II reports for other common structural systems such as reinforced concrete shear walls, steel braced frames, etc.

For the anticipated use-case of these Guidelines, it is envisioned that these documents (Part I and the Part II guideline appropriate to a system type of interest) will be used in conjunction with one of the available performance-assessment documents (listed in the introduction section), or their equivalent, that are appropriate for the specific circumstances. Accordingly, the Guidelines document focuses on providing practical structural modeling and analysis guidance, but it does not attempt to repeat or prescribe all of the possible performance goals and detailed numerical acceptance criteria contained in other documents.

The Guidelines are primarily intended for use by engineering practitioners, who are well versed in seismic design and behavior and are familiar with the concepts of nonlinear structural analysis, but who desire more detailed guidance on nonlinear modeling. These guidelines are written considering the analysis software capabilities that are currently available to practitioners, but also with a view towards emerging techniques that will become available in the future.

Although the Guidelines are generally applicable to nonlinear analysis of both new and existing buildings, they emphasize applications of nonlinear dynamic (response-history) analysis for the seismic design and performance assessment of new buildings over the expected range of response commonly evaluated. Thus, the Guidelines do not address all of the structural deficiencies and complex modes of failures that may be encountered in existing buildings, nor do they emphasize the highly nonlinear degrading response modes that occur during collapse. By emphasizing the practical use of nonlinear dynamic analysis for new buildings, the goal is to enable the utilization of new structural systems and response modification technologies that have the potential to transform building construction.

The Part I Guideline document includes an overview of the full process used for a building seismic performance assessment using nonlinear response-history analysis. These global aspects, including both modeling and other aspects of the process, such as acceptance criteria, are covered in Chapter 2 of the Guidelines. Chapter 3 then provides specific detail on the requirements for the *modeling* portion of this overall assessment process. Chapter 4 follows this by discussing the roles and limitations of nonlinear static analysis (which is not recommended as the final performance check for both building types), and then Chapter 5 outlines the recommended nonlinear response-history analysis procedure. Chapter 6 details how acceptance criteria are then checked to assess building performance. Appendices then supplement this material: Appendix A presenting a history of the use of nonlinear analysis for seismic design, Appendix B providing background documentation on how uncertainties should be treated in the development of acceptance criteria, and Appendix C providing instructions on calibrating a nonlinear component model using test data.

The Part II Guidelines follow the Part I Guidelines and provide additional information for a specific structural system. Chapter 2 of each Part II document provides an overview of expected structural behavior and failure modes for the building system of interest, and then Chapter 3 provides the general modeling guidelines for that system type. Chapters 4-6 then provide specific guidelines for concentrated hinge component models (Chapter 4), fiber-type models (Chapter 5), and continuum finite element models (Chapter 6). Appendices to each Part II document illustrate the use of the guidelines for a low-rise moment frame building.

Characteristics of Nonlinear Dynamic Analysis versus Static Pushover Analysis

As noted previously, nonlinear analysis for performance-based design or performance assessment is often done using a nonlinear static pushover method based on ASCE/SEI 41. One key behavioral aspect which the static pushover method does not capture is the fact that the nonlinear behavior of the building depends strongly on the cyclic loading demand (number of cycles, etc.). Figure 1 shows the cyclic response of identical steel columns under two different cyclic loading protocols and under a monotonic push; Figure 2 shows similar data for two identical reinforced concrete columns subjected to both cyclic and monotonic loading. These two figures clearly show the extreme differences in hysteretic response for the various loading protocols and it is notable that the nonlinear static modeling procedure is incapable of capturing these effects. Therefore, the ATC-114 Guidelines propose that nonlinear dynamic response-history analysis (rather than nonlinear static analysis) be used for most cases where nonlinear analysis is needed for design or performance assessment, and then provides all of the modeling guidelines to enable the engineering analyst to complete such analysis.

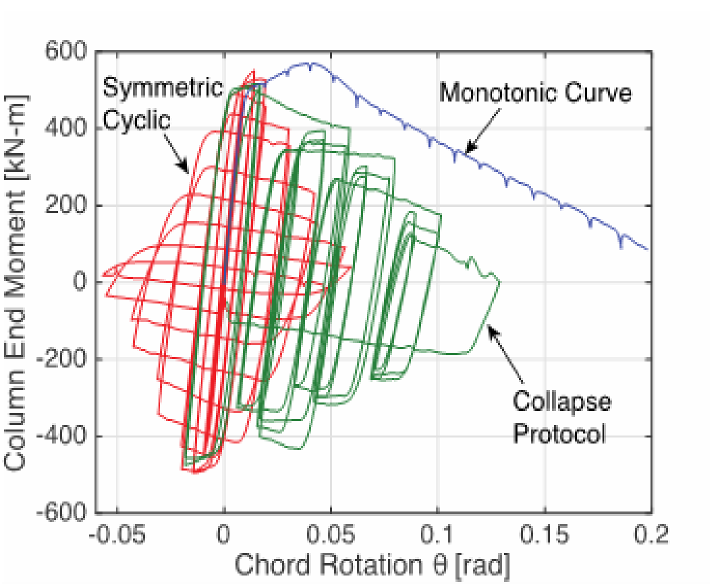

Figure 1. Response of Steel Column to Alternative Loading Histories (Suzuki and Lignos, 2015)

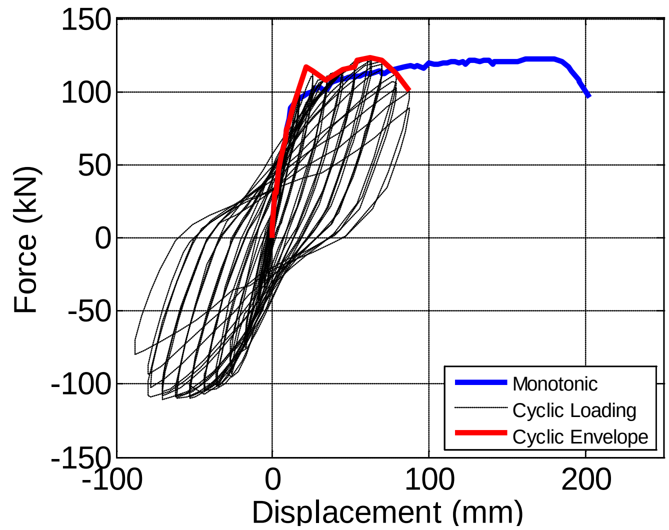

Figure 2. Experimental data from cyclic and monotonic tests of two identical RC columns (Ingham et al., 2001), illustrating definitions of the monotonic loading curve and cyclic envelope curve. (1 kN = 0.2258 kips force; 1 mm = 0.0393 inches).

To appropriately reflect nonlinear structural behavior, to enable meaningful nonlinear dynamic response-history analysis, the nonlinear component models must adequately capture the following two types of nonlinear response:

- **Cyclic strength deterioration:** Strength is lost *between subsequent cycles* of loading, due to stiffness degradation, wherein the model maintains a positive reloading stiffness in each cycle. Cyclic strength deterioration is modeled through cyclic hysteric rules.
- **In-cycle strength deterioration:** Strength is lost *during a single cycle* of loading, where the force-deformation response develops a negative tangent stiffness, i.e., strain softening response. In concentrated hinge models, thein-cycle strength deterioration is typically modeled through a negative slope in the backbone response curve.

Figure 3 shows an example of test data, and a model calibrated to that data, that demonstrates cyclic strength deterioration for most of the loading and then shows the last cycles (after 6% drift) where in-cycle strength degradation occurs. For purposes of nonlinear static analysis, a simple cyclic envelope would be fit to these data and these differences in behavior would not be reflected (note that a cyclic envelope curve was shown in Figure 2). For meaningful nonlinear dynamic response-history analysis, these two behaviors should be captured in the nonlinear components models and care should be taken to properly calibrate models to represent these behavioral modes.

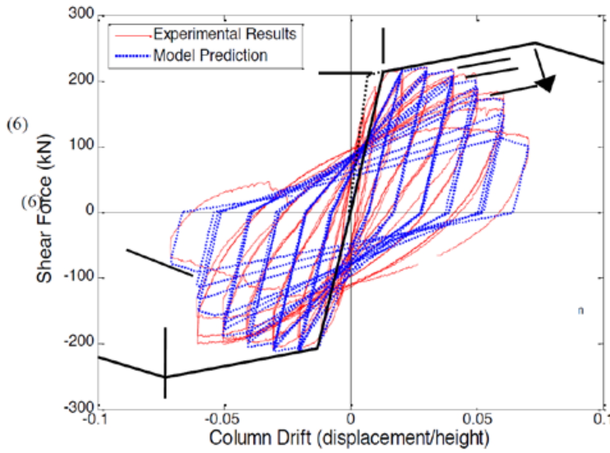

Figure 3. Example of test data and calibrated component model, illustrating the differences between cyclic and in-cycle strength deterioration. Experimental test is by Saatcioglu and Grira (1999), specimen BG-6, and the model calibration figure is after Haselton et al. (2008).

To enable this more complete treatment of inelastic behavior of structural components, the ATC-114 Guidelines introduce the concept of two backbone curves - the monotonic backbone and the cyclic backbone (Figure 4). Nonlinear component models are then created and calibrated to work for all cyclic loading cases – e.g. reflect the monotonic backbone under a monotonic pulse-type load, reflect the cyclic backbone when subjected to a prescribed loading protocol for which that backbone was developed, and reflect behavior "somewhere in the middle" for typical earthquake loading protocols. This updated framework for component backbone curves is more fully discussed and documented in a related paper on the ATC-114 Guidelines project (Hamburger et al., 2016).

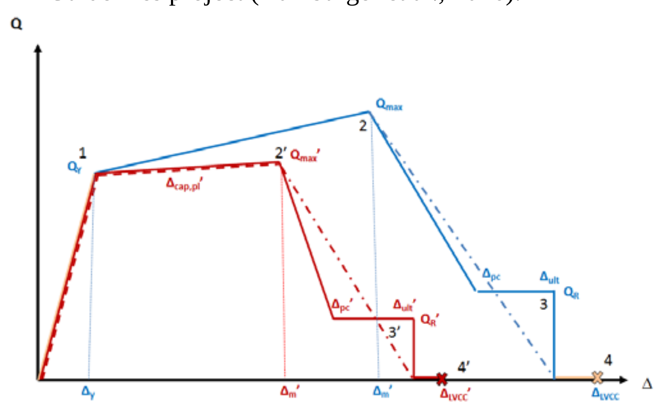

Figure 4. ATC 114 Idealized Backbone Model Descriptions

Structural Modeling Approaches Covered by the Guidelines

The ATC-114 Guidelines cover all common types of nonlinear modeling. Figure 5 shows a depiction of a steel moment frame and the following modeling approaches are supported by the Guidelines:

- Discrete concentrated hinge models (Figure 6).
- Fiber sections with distributed-inelasticity elements (Figure 7).
- Fiber sections with finite-length hinge elements (Figure 8).
- Continuum finite element modeling (Figure 9).

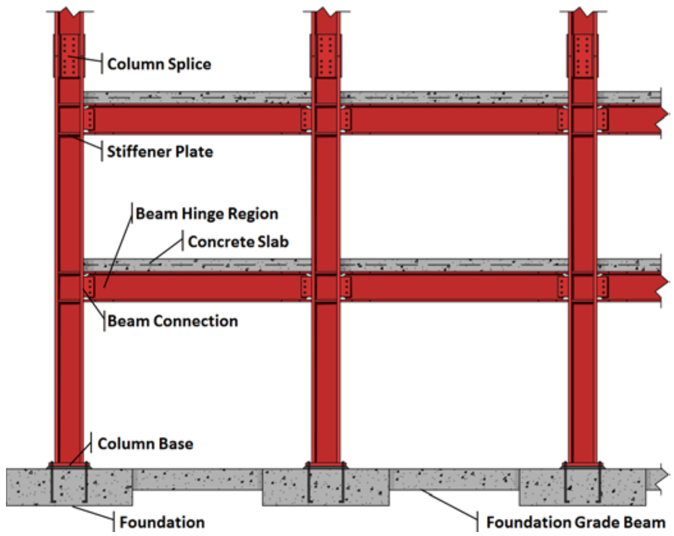

Figure 5. Overview of typical steel moment frame system.

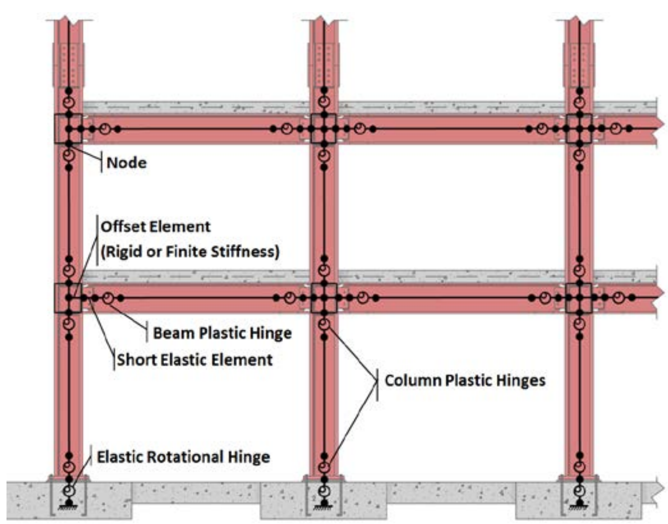

Figure 6. Discrete model: concentrated hinge (section and element).

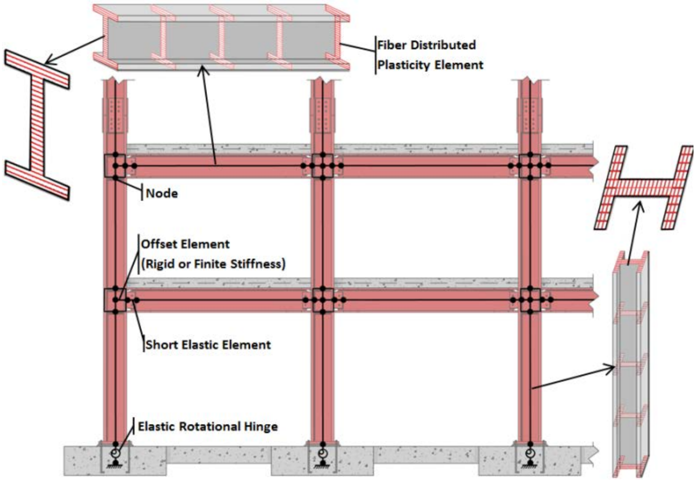

Figure 7. Fiber section in distributed-inelasticity elements.

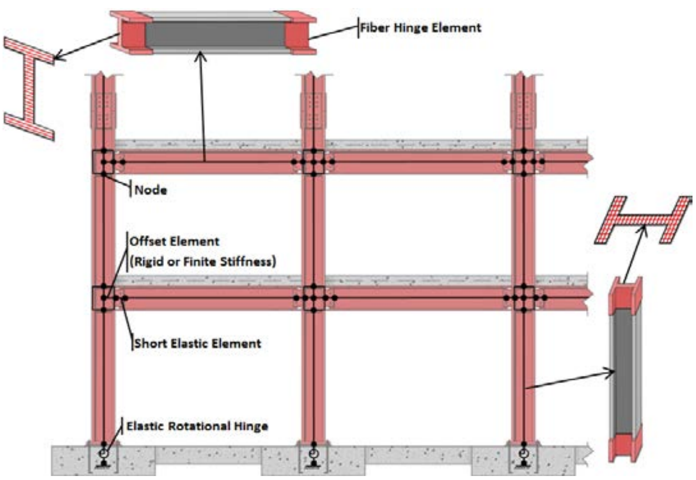

Figure 8. Fiber sections in finite length hinge elements.

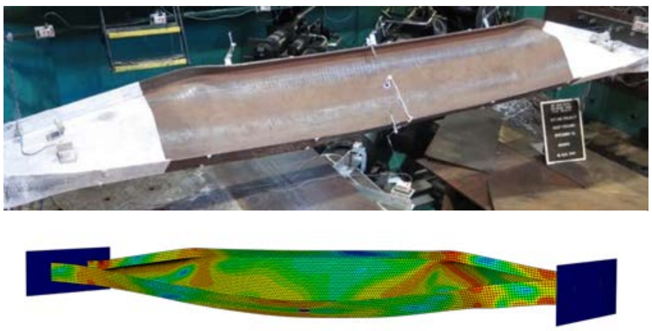

Figure 9. Simulation of cyclic response of a deep (W24) column with ABAQUS (Ozkula and Uang, 2015).

Part I – General Guidelines

The Part I document in the ATC-114 Guidelines provides all of the general requirements for nonlinear modeling, which are not specific to any type of structural systems. For details, the reader is referred to the forthcoming guidelines, which are expected to be published in 2017 (ATC, 2016a).

Part IIa – Steel Moment Frames

The Part IIa document in the ATC-114 Guidelines covers all of the detailed modeling requirements for steel moment frames. Figure 10 shows sample test data for a steel reduced beam section (RBS), and the following list of equations are examples of how the monotonic backbone curve would be quantified for this component type. Additional equations are included in the ATC-114 Guideline report for non-RBS sections and for cyclic backbones.

Figure 10. Test data for a post-Northridge reduced beam section ductile connection (Engelhardt and Sabelli, 2007)

The following are sample equations from ATC-114, which can be used to quantify the monotonic backbone curve for a RBS.

$$M_y = 1.1M_{p,exp} = 1.1\, Z\, R_y\, F_y \quad (\text{COV} = 0.1)$$

$$M_{max} = 1.1\, M_y \quad (\text{COV} = 0.1)$$

$$K_e = \alpha_e\, EI/L$$

$$EI^* = EI/(1\text{-}6/\alpha_e) = 1.1EI \text{ for } \alpha_e = 60$$

$$\theta_p = 0.09\left(\frac{h}{t_w}\right)^{-0.3}\left(\frac{b_f}{2t_f}\right)^{-0.1}\left(\frac{L}{d}\right)^{0.1}\left(\frac{d}{21''}\right)^{-0.8} (\text{COV} = 0.3)$$

$$\theta_{pc} = 6.5\left(\frac{h}{t_w}\right)^{-0.5}\left(\frac{b_f}{2t_f}\right)^{-0.9} (\text{COV} = 0.3)$$

where EI and L are the cross section stiffness and length of the beam, α_e is the stiffness coefficient, h/t_w is the web depth-to-thickness ratio, $b_f/2t_f$ is the flange width-to-thickness ratio, L_b/r_y is the laterally unbraced length divided by the weak-axis radius of gyration, L/d is the clear span-to-depth ratio, and d is the section depth in inches. It is suggested to make the hinge stiffness about 10 times the stiffness of the beam in reverse curvature (i.e., $6EI/L$), in which case α_e should be set to 60. The stiffness of the elastic beam connected to the hinges should then be increased to account for the flexibility of the hinge.

The residual strength for both RBS and non-RBS beams may be assume as $M_r = 0.4\ M_y$, although, as a practical matter the rotations are usually limited by other criteria before this limit is reached. The ultimate plastic rotation capacity is likely to be controlled by ductile fracture. In the absence of test or other data to reliably evaluate the ultimate rotation, it is recommended to assume a limiting plastic rotation of $\theta_u = 0.08$ (radians) with a COV = 0.3 under cyclic loading.

Figure 11 also shows an example of a brittle fracture of a pre-Northridge connection. The ATC-114 Guidelines also provide an appendix which outlines the modeling requirements for such a system.

Figure 11. Test data for a pre-Northridge brittle connection (Engelhardt and Sabelli, 2007)

Figure 12 and Figure 13 show recent testing of steel column components. The ATC-114 Guidelines provides detailed guidance for modeling column components, which is based on recent research in this area.

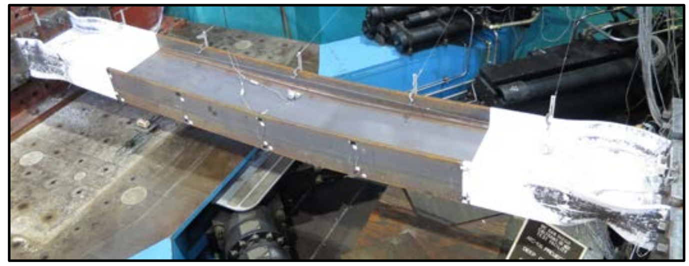

Figure 12. Failure modes of steel columns (Uang, Ozkula and Harris, 2015). W24×131 with P = 0.18Py.

Figure 13. Failure modes of steel columns (Uang, Ozkula and Harris, 2015). W24×176 with P = 0.18Py.

Components of the “gravity system” in a building can also have substantial impact on the seismic response of a building (having possible large effects on both strength and stiffness). Figure 14 shows an example of such a connection and the ATC-114 Guidelines provides detailed guidance for modeling these gravity shear tab connections.

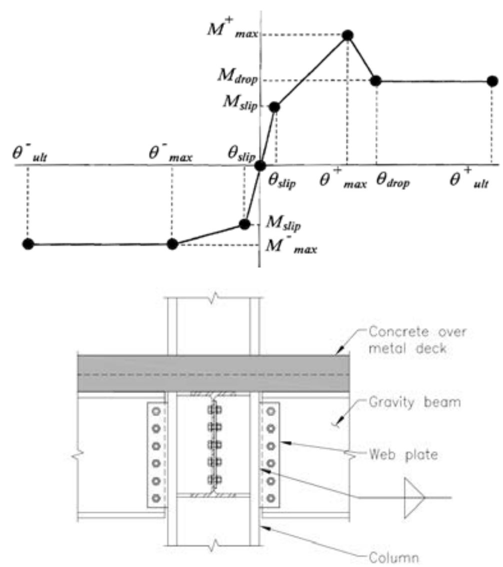

Figure 14. Cyclic skeleton curve for composite gravity framing connections.

Part IIb – Concrete Moment Frames

The Part IIa document in the ATC-114 Guidelines covers all of the detailed modeling requirements for reinforced concrete moment frames, and is structured similarly to the Part IIa section on steel moment frames. Due to space limitations, further details regarding the reinforced concrete moment frame modeling is not repeated here, and the reader is referred to the ATC-114 Part IIb Guidelines report (ATC, 2016c).

Illustrative Examples

To both beta test and illustrate the modeling Guidelines, a five-story office building was designed and evaluated for a site located in San Francisco, CA as depicted in Figure 15. The first three stories have overall plan dimensions of 120 ft by 80 ft. Above the fourth floor, the floor plate setbacks a single bay for an overall plan dimensions of 85 ft by 80 ft. The typical story height is 13'-0". A roof top garden is located at the fourth floor setback. Mechanical equipment is located on the roof. During the design development phase, a new project requirement for a large conference space in the first story at the south-east corner of the building necessitated the removal of a column to open up the space.

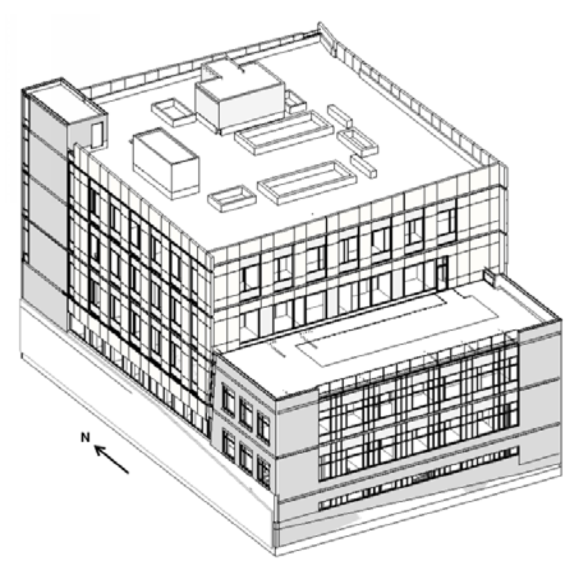

Figure 15. Overview of design example building

As shown in Figure 16 and Figure 17, a RAM Steel model was created for the elastic trial design process and a CSI Perform model was created for the nonlinear response-history analysis.

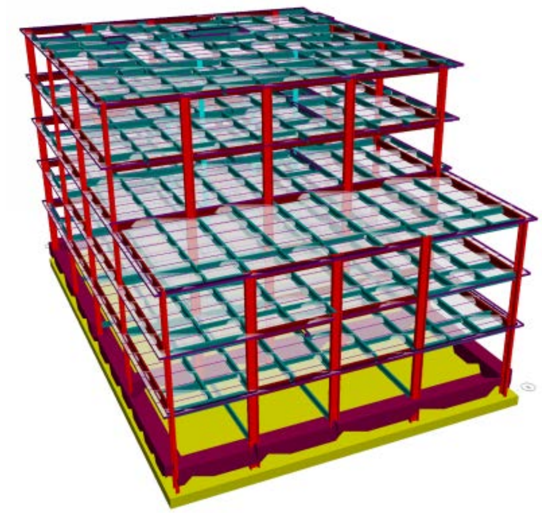

Figure 16. Overview of elastic RAM model

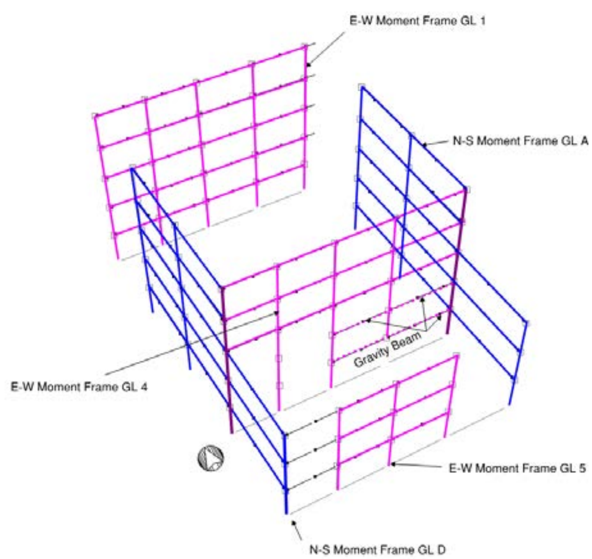

Figure 17. Overview of nonlinear CSI Perform model

For the response-history analysis, ground motions were then developed for response-history analysis based on the risk-targeted Maximum Considered Earthquake (MCE_R). Eleven horizontal ground motion pairs were selected and scaled to the MCE_R spectrum, following the new ASCE 7 Chapter 16 provisions for nonlinear response history analyses (ASCE 2016). The rest of the full performance assessment was completed for the example (including checking of all acceptance criteria, etc.) and this is documented in the ATC-114 Guidelines report.

Summary

The ATC-114 Guidelines report is at the 85% draft stage and is nearing the 95% draft stage. This report will be issued by ATC and will become publically available in the near-future.

Acknowledgments

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